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Improving the existing roadway tunnels capacity by adding new tunnels—a structural approach

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Abstract

The roadway tunnel is considered a good solution for the success of modern roadway networks. It can help to overcome possible traffic congestion and considerably reduce journey time. The continuous growth of traffic volumes leads to increase congestion and decrease safety. This leads to the need for extra tunnel space. The extra tunnel space can be achieved either by the widening of the existing tunnel or by adding a new one. The choice of the suitable method is dependent on many factors like tunnels alignment, site conditions, construction method, tunnel operation, risk assessment…etc. The current research investigates the second alternative through a specific case study as an example. The method comprises adding two new tunnels to an existing twin roadway tunnels. The investigated problem considers the new tunnels to be added vertically or horizontally. The influence of the new tunnel construction on the existing tunnels is investigated considering both the variation of relative position and spacing distance in a parametric study context. Several numerical models are employed to check the construction sequence and the tunnelling safety. These models are used to evaluate the induced stresses in surrounding ground for two different soil types, straining actions in tunnels' liner and deformations of both ground and liner. The result demonstration shows how to find out the minimum practical and safe spacing distance between the driven new tunnels and the existing ones without the need for the relatively expensive soil strengthening techniques.

Keywords Roadway tunnels · Numerical modelling · Tunnel development · Tunnelling position

Introduction

Sometimes, adding new tunnels to existing roadway tunnels becomes the only feasible development method for existing tunnels when the traffic capacities are insufficient. New tunnels relative position, the spacing distance between new and existing tunnels, and surrounding soil properties determine the impact of the new tunnel construction on existing ones. One of the primary constraints during the new tunnel construction is

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to ensure the capability of the existing tunnels to operate safely.

Commonly, safety in tunnelling engineering is indicated by the resulted ground surface settlement and induced displacements and stresses in surrounding soil and tunnel material. Many researchers have studied, generally, the deformations indictors through mathematical, experimental, or numerical approaches (Verma and Singh 2010; Kun 2015; Qiu et al. 2017; Moeinossadat et al. 2018).
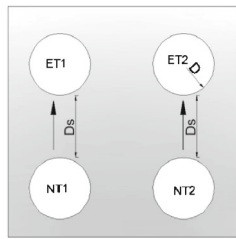
The impact of adding new tunnels to existing ones has been investigated previously many times via site observation, physical models and numerical models (Perri 1994; Kim et al. 1998; Yamaguchi et al. 1998; Karakus et al. 2007; Liu et al. 2009). In these studies, the attention was paid mainly to the induced deformation. Most of the applied numerical analyses were 2-D models with few attempts using 3-D models (Addenbrooke and Potts 2001; Koungelis and Augarde 2004). A series of systematic 3-D analyses have been conducted to investigate the interaction between hypothetical large parallel twin tunnels constructed in stiff clay using New Austrian Tunneling Method (Lee et al. 2004). The analysis

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First case: Twin tunnels added vertically underneath existing tunnels

Second case: Twin tunnels added horizontally outer to existing tunnels

Fig. 1   Tunnels relative positions

proved that, for spacing distance larger than 3D (where D is the average tunnel diameter), there is no significant impact from tunnels on each other (Hage and Shahrour 2008; Chakeri and Hasanpour 2010).

The current research introduces a parametric study to study this influence into two different cases: vertically and horizontally added tunnels. Two and three-dimensional numerical models are implemented for this parametric study. The study considers main parameters: the induced deformations in ground and tunnels and induced stress presented by plasticized zones in surrounding ground. The research investigates these parameters and checks their relation to spacing distance. The optimal distance is the minimum reliable spacing distance between driven new tunnels and existing ones without the consideration of soil strengthening. Thus, the research aims mainly to demonstrate the methodology of selecting the optimal spacing distance considering the most effective
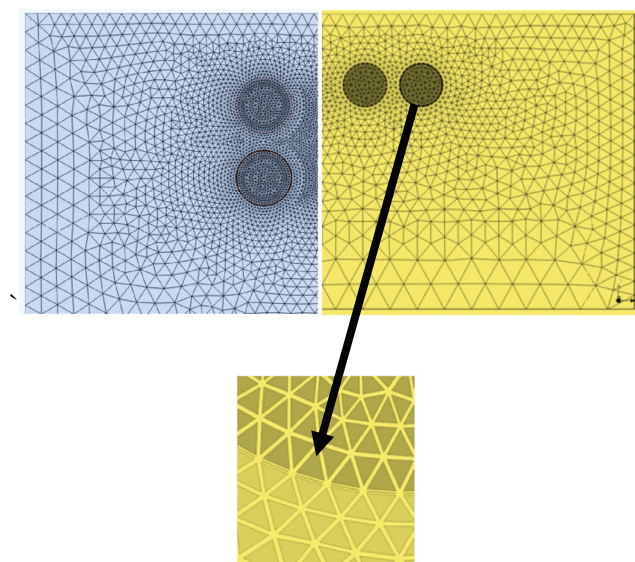

Fig. 2   Mesh layout for 2-D numerical modelling of the two types of the parametric study

Table 1   Material properties of soil parameters

	Model/parameter		Unit
Soft ground type	Sand	Clay	
Material model	Mohr-Coulomb	Mohr-Coulomb	–
Type of material behaviour	Drained	Drained	–
Soil unit weight (γ)	20	20	kN/m^3
Young's modulus (E)	40,000	60,000	kN/m^2
Poisson's ratio (ν)	0.37	0.35	–
Cohesion (C)	0.0	200.00	kN/m^2
Friction angle (Φ)	39	0.10	–

parameters. The results can be used to help the decision-making process as guidelines at the preliminary and layout design stage.

The case study

It is expected that adding new tunnels close to existing tunnels shall influence ground deformations and stabilization of the existing tunnels. Even for Tunnel Boring Machine (TBM) technique, the tunnelling process affects the existing neighbour tunnel lining during soil excavation and lining installation stages (Ezzeldine and Darrag 2006; Karakus and Fowell 2006; Abdou and Abo 2007).

The current study is performed assuming existing twin two-lane roadway tunnels run parallel to each other and shallow depth tunnels similar to El-Azhar roadway twin tunnels (Abu-Krisha 2005). The existing roadway tunnels are located at distance 15.0 m from the surface. These tunnels need development due to traffic capacity insufficiency. Thus, new two roadway tunnels shall be driven parallel to the existing ones using TBM method. All tunnels, existing and new, are assumed to have the same diameter (D) which is 9.4 m.

In this research, a parametric study considers that the clear spacing distance (Ds) between new and existing tunnels is conducted. The investigated distance ranges from 0.1D to 1D. The parametric study considers, also, two different cases of tunnel relative positions, as shown in Fig. 1. The first case is to add the new tunnels (NT1 and NT2) vertically underneath existing tunnels (ET1 and ET2). The second case is to add them horizontally at the same elevation of existing tunnels.

Table 2   Material properties of existing tunnel lining

Concrete properties	Thick. (m)	Density (γ), kN/m^3	Young's modulus (E), MPa	Poisson's ratio (ν)
Lining	0.4	25	28.5×10^3	0.2
Grout	0.125	20	150	0.25

Fig. 3 Ground surface deformation due to (Ds) variation in sandy soil
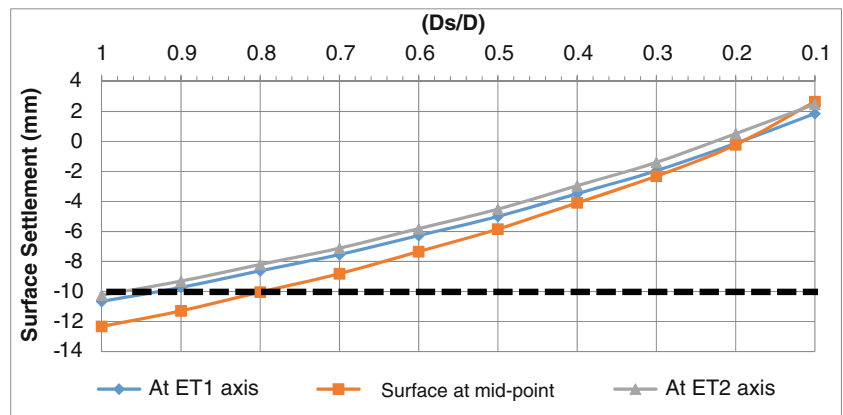
The parametric study is performed for two different soil types, cohesion-less sandy soil and cohesive clayey soil, which represent typical soil types in Egyptian ground.

Numerical modelling

Numerical simulation of TBM tunnelling should consider many factors such as machine advance, shield stiffness, grouting pressure, slurry face pressure and lining installation. These factors should be considered in 3-D numerical modelling to get realistic simulation. In the 2-D analysis, some approximation can be performed to get reasonable simulation compared to 3-D analysis. In this research, 2-D plane strain numerical models, with elastoplastic soil model based on Mohr-Coulomb failure criterion, are developed for all study cases. A 3-D modelling is employed for some critical cases. Figure 2 shows the mesh layout applied in 2-D models where the soil is represented by three-node triangular elements and the tunnel lining is represented with two-node elastic beam elements (Zaki and Abu-Krisha 2006). In the 3-D numerical model, four-node tetrahedron solid elements are used to represent soil and tunnel lining and four-node shell elements are used for shield modelling.

The Finite Element Analysis package, MIDAS-GTS, is used for both 2-D and 3-D numerical models. The main loading and construction stages considered in these models are the following:

1. Initial state: This considers the effect of soil pressure, surface load and the ground water table.
2. Soil excavation for the first existing tunnel (ET1): A load distribution factor is used for excavated soil elements elimination.
3. Lining installation for ET1: The lining elements are activated after excavation of entire tunnel section.
4. Steps 2 and 3 are repeated for the second existing tunnel (ET2).
5. The long-term effect.
6. Soil excavation for the first new added tunnel (NT1): Face pressure of the machine is applied, and load distribution factor is used for excavated soil element elimination.
7. Lining for NT1 activation: Lining and grouting elements are activated after complete tunnel soil excavation.
8. Steps 6 and 7 are repeated for the second new added tunnel (NT2).

Fig. 4 Existing tunnel deformation due to (Ds) variation in sandy soil
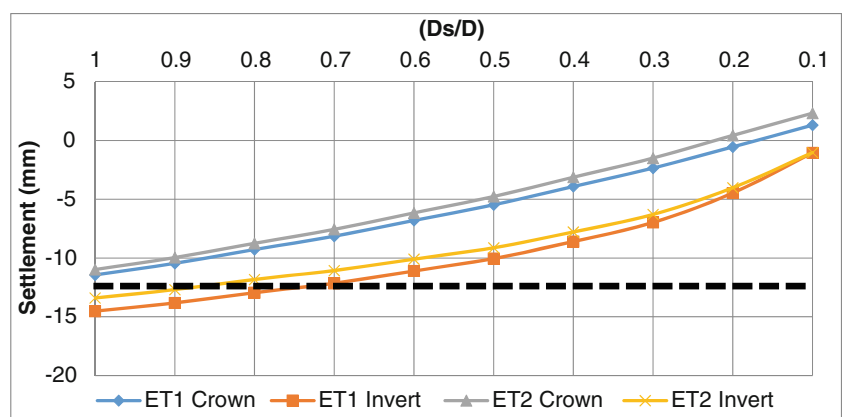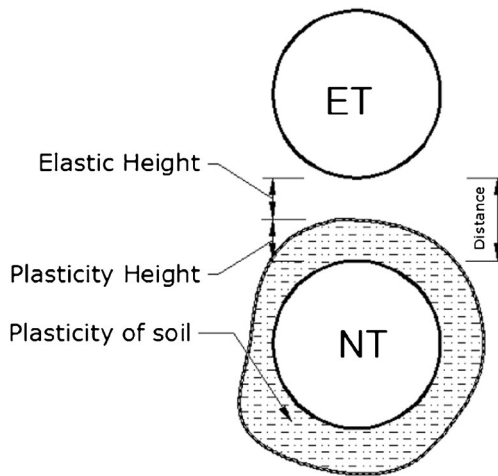
Fig. 5 Plastic and elastic height between tunnels

Material properties

Tables 1 and 2 show the used characteristic material properties for existing tunnel lining, new tunnel lining, grout and ground soil.

Analysis and results

In this section, numerical models for each value in the investigated spacing distance range are established for the described relative position cases. Results, from these models, are plotted to show the influence of new tunnel construction on existing tunnels and ground surface deformations, plasticized zone distribution in each soil, and straining actions in tunnel lining.
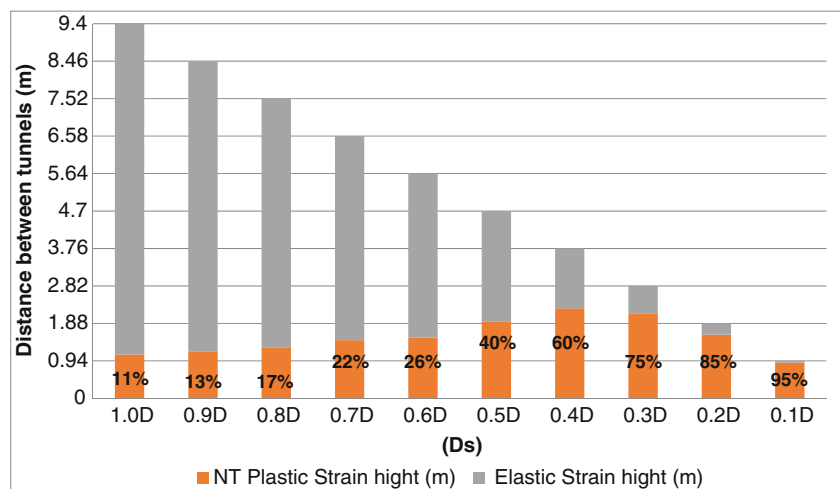
Vertically added tunnels in sandy soil

Deformations of existing tunnels and ground surface

Figure 3 shows the impact of spacing distance variation on the ground surface settlement above the tunnel's centre line and the mid-point between tunnels.

For all studied points, the settlement value decreases as spacing distance decreases. The settlement values range from 10 to 12 mm at spacing distance 1D and reach 2 mm heave at spacing distance 0.1D. The existing tunnel lining deformations at crown and inverts are shown in Fig. 4. The deformation values range from 11 to 14.5 mm downward at a 1D spacing distance and decrease to reach values range from 1 mm downward to 2.5 mm upward at a 0.1D spacing distance. Assuming that the preconditioned or allowed settlement value is 10 mm for the existing tunnels and reviewing Figs. 3 and 4, the recommended spacing between the existing and the new tunnels is 0.5D.

Plasticized zone distribution in soil

Plasticized zone distribution indicates soil failure probability due to excessive stresses. In the studied cases, this situation was found around existing tunnels due to nearby tunnelling process. The behaviour of confined soil between tunnels groups, existing and new tunnels, is either to be elastoplastic or fully plasticity. In the case of plasticity distribution occupied total confined soil height between the existing tunnel and the new one, the failure of existing tunnels is placed. In the developed 2-D numerical models, the plastic zone height is introduced as a percentage of the total spacing distance between existing and new tunnels which is shown in Fig. 5. The chart, shown in Fig. 6, shows that plasticized zone percentage is increased with the decrement of the distance (Ds).

For (Ds) equal to tunnel diameter D, the plasticized zone percentage distance is about 11% of the total spacing distance,

Fig. 6 Percentage of plasticized zone height to total spacing distance (Ds)
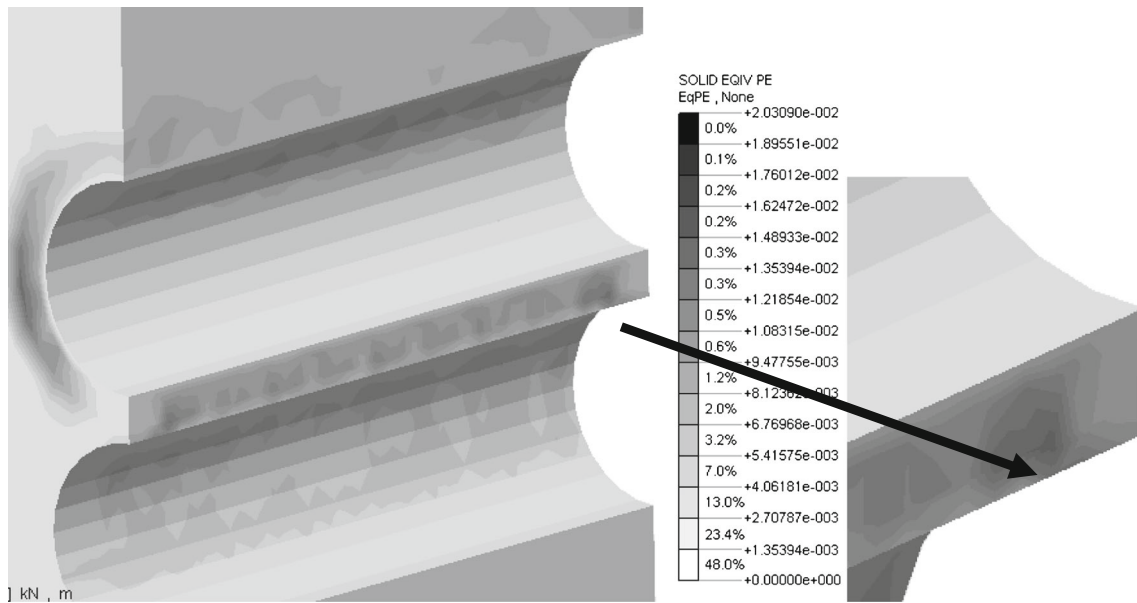
Fig. 7 Plasticized zone distribution at (Ds) equal to 0.1D

and this percentage is increased to be 95% at (Ds) equal to 0.1D which indicates soil failure. These results are compared and confirmed with two 3-D models for the spacing distance equal to 0.1D and 0.5D. Figures 7 and 8 show the contour lines for plasticized zone distribution along the spacing distance in these models.

Straining actions in existing tunnel lining

For different spacing distance values, the maximum normal force value in the existing tunnel (ET1) lining is reduced during first new tunnel (NT1) execution and increased during
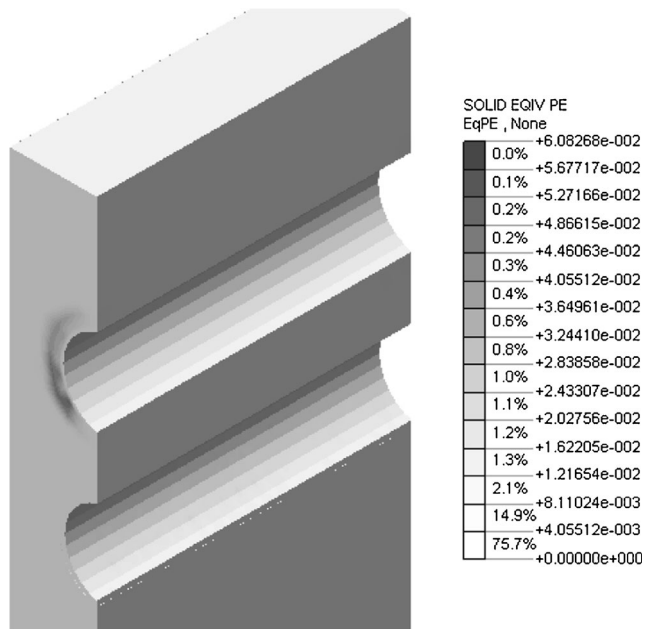
Fig. 8 Plasticized zone distribution at (Ds) equal to 0.5D

second new tunnel (NT2) execution. This trend is reversed for the maximum normal force value in the existing tunnel (ET2). The value is increased during first new tunnel (NT1) execution and decreased during second new tunnel (NT2) execution. These values are presented in bar charts shown in Figs. 9 and 10.

Induced bending moments' maximum value follows the same trend for induced normal forces in existing tunnels' lining, with an exception for small spacing distance cases. For the existing tunnel (ET1) with spacing distance 0.1D, the maximum bending moment value is increased during first new tunnel excavation and is reduced during lining installation. For the existing tunnel (ET2), the value variation, during new tunnel execution, is reduced with spacing distance reduction. At spacing distances 0.2D and 0.1D, the value is almost settled during first new tunnel execution. These results are shown in Figs. 11 and 12.

Vertically added tunnels in clayey soil

Deformations of existing tunnels and ground surface

Figure 13 shows the impact of spacing distance variation on the ground surface settlement above the tunnel's centre and the mid-point between tunnels. For all studied points, the settlement value is decreased with spacing distance decreases. The settlement values range from 13.1 to 14.6 mm at spacing distance 1D and reach 5.4 mm at spacing distance 0.1D. The existing lining deformations at crown and inverts are shown in Fig. 14. The deformation values range from 13 to 14.5 mm downward at a 1D spacing distance and decrease to reach values range from 5.2 to 8.2 mm downward at a 0.1D spacing distance.

Fig. 9 Maximum normal force induced in existing tunnel ET1
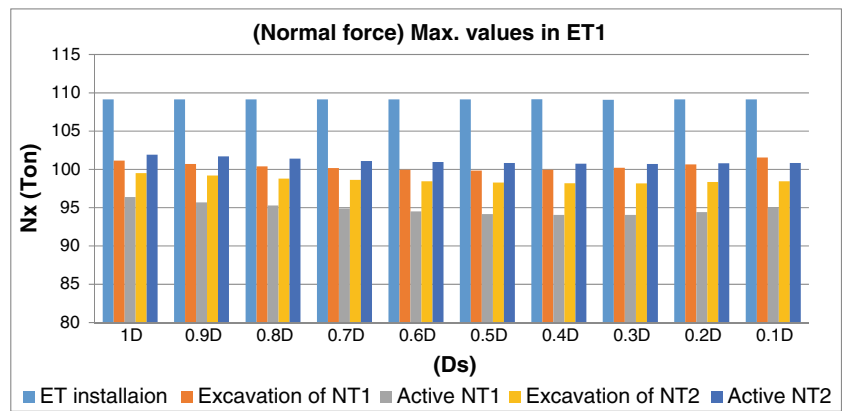
For the same assumed settlement limitation and reviewing Figs. 13 and 14, the recommended spacing between the existing and the new tunnels is 0.4D.

Plasticized zone distribution in soil

The chart, shown in Fig. 15, indicates that plasticized zone percentage is increased with the degradation of distance (*D*s). For (*D*s) ranges from tunnel diameter D to 0.8D, the plasticized zone percentage distance is almost neglected, and this percentage is slightly increased to be 100% at (*D*s) equal to 0.2D and 0.1D which indicates soil failure. Also, the plasticized zone height percentage is recognized as 45% of distance (*D*s) at a spacing distance equal to 0.5D. Comparing the plasticized zones in the two types of soil, which are shown in Figs. 6 and 15, it is recognized that the variation of plasticity zone in clayey soil is steeper than sandy soil.

Straining actions in existing tunnel lining

The maximum normal force in theET1 lining is decreased, during tunnelling of NT1, as shown in Fig. 16. A slight increase occurred during tunnelling of NT2. The final normal force, compared to original value, is decreased. This behaviour is recognized at each step of (*D*s) degradation with negligible differences in values. This means that spacing distance

degradation has no significant effect on the normal force, compared to its impact on ET1 deformation. Figure 17 shows that normal force in ET2 is increased due to tunnelling of NT1 which is followed by a reduction during NT2 tunnelling. The normal force in ET2, due to varying distance (*D*s) from D to 0.1D, may also be neglected.

Figure 18 shows that maximum bending moment value is decreased in ET1 during tunnelling of NT1 followed by a slight increase during tunnelling of NT2 at distance 1D. Distance degradation (*D*s) causes a noticeable increase of bending moment in ET1 lining values after adding new tunnels. The maximum value of bending moment in ET2 is increased due to tunnelling NT1 at 1D, as shown in Fig. 19, followed by a reduction due to NT2 tunnelling. Finally, maximum bending moment induced in existing tunnel lining is lower than original value after adding new tunnels.

Horizontally added tunnels in sandy soil

Deformations of existing tunnels and ground surface

Figure 20 shows the surface deformation during new tunnel installation with different spacing distance. The deformation is plotted at five different points: above existing tunnels, at mid-point between existing tunnels and above new tunnels. The general behaviour of the ground surface

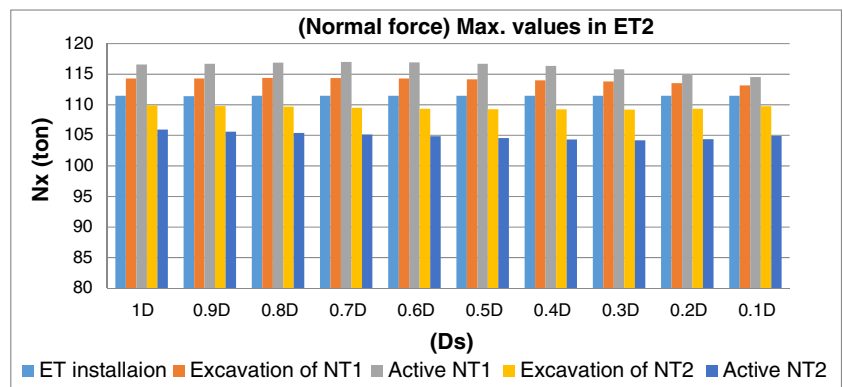**Fig. 10** Maximum normal force induced in existing tunnel ET2

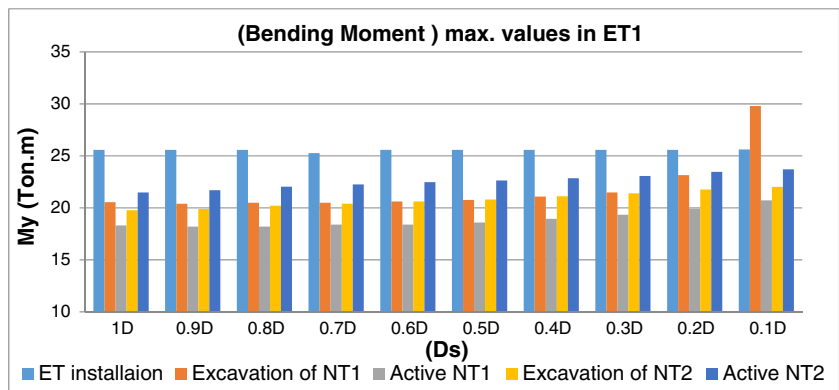**Fig. 11** Maximum bending moment induced in existing tunnel ET1

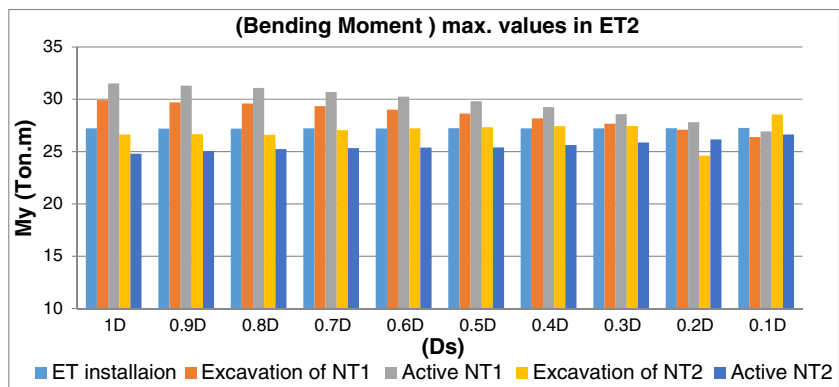**Fig. 12** Maximum bending moment induced in existing tunnel ET2

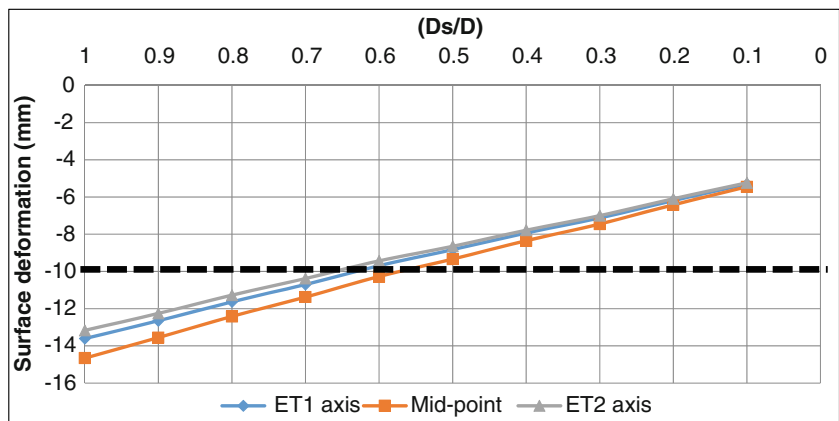**Fig. 13** Surface deformation due to (*D*s) variation in clayey soil

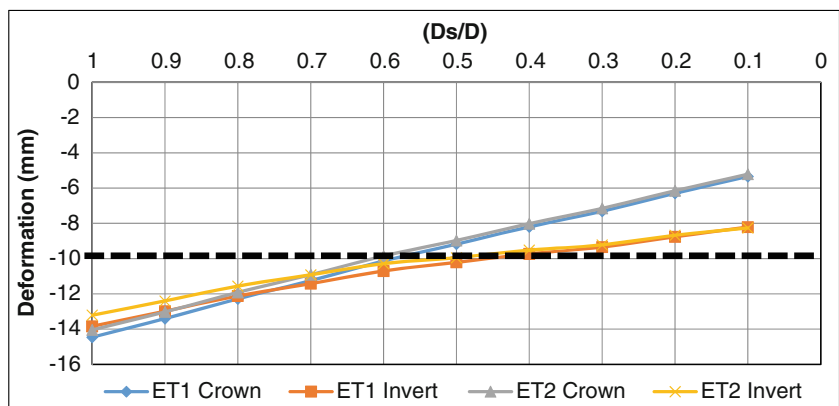**Fig. 14** Existing tunnel deformation due to (*D*s) variation in clayey soil

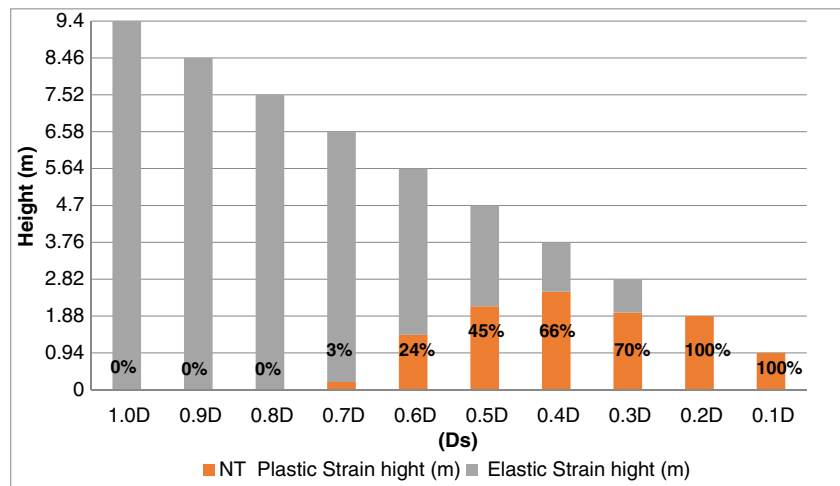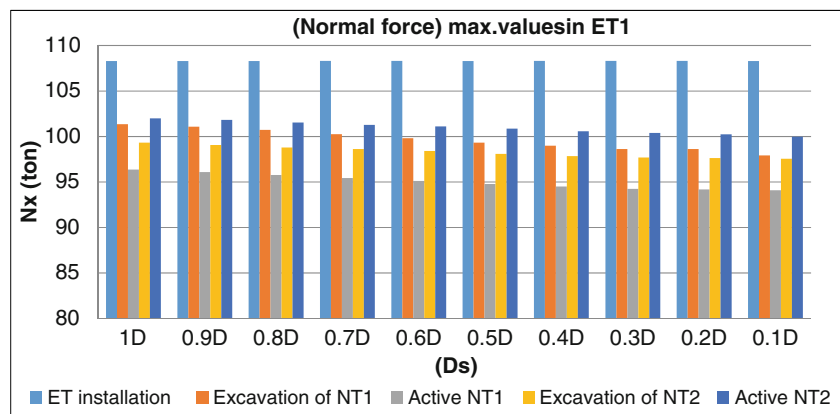**Fig. 15** Percentage of plasticized zone height to total spacing distance (Ds)

Fig. 15 chart: Percentage of plasticized zone height to total spacing distance (Ds). Y-axis: Height (m) from 0 to 9.4. X-axis: (Ds) from 1.0D to 0.1D. Percentages shown: 1.0D 0%, 0.9D 0%, 0.8D 0%, 0.7D 3%, 0.6D 24%, 0.5D 45%, 0.4D 66%, 0.3D 70%, 0.2D 100%, 0.1D 100%. Legend: NT Plastic Strain hight (m), Elastic Strain hight (m)

Fig. 16 Maximum normal force induced in existing tunnel ET1

Fig. 16 chart: (Normal force) max. values in ET1. Y-axis: Nx (ton) from 80 to 110. X-axis: (Ds) from 1D to 0.1D. Legend: ET installation, Excavation of NT1, Active NT1, Excavation of NT2, Active NT2

is heaving with peak values between mid-point and existing tunnel (ET1). The existing tunnel lining deformations at crown and inverts are shown in Fig. 21. The deformation values range from 8.5 to 9 mm upward at 1D spacing distance and range from 9 to 12.5 mm upward at a 0.1D spacing distance.

Plasticized zone distribution in soil

The plasticized zone distribution shows critical stability at the spacing distance equal to 1D, as shown in Fig. 22. It also indicates probable soil failure for smaller spacing distances. An example is given in Fig. 23.

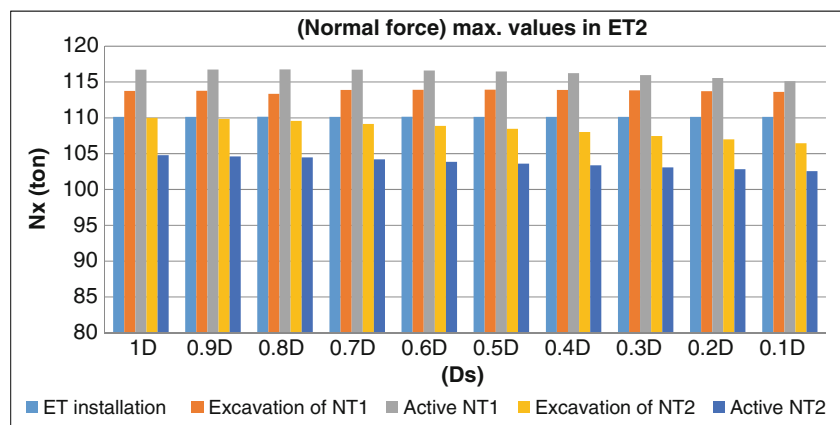**Fig. 17** Maximum normal force induced in existing tunnel ET2

Fig. 17 chart: (Normal force) max. values in ET2. Y-axis: Nx (ton) from 80 to 120. X-axis: (Ds) from 1D to 0.1D. Legend: ET installation, Excavation of NT1, Active NT1, Excavation of NT2, Active NT2

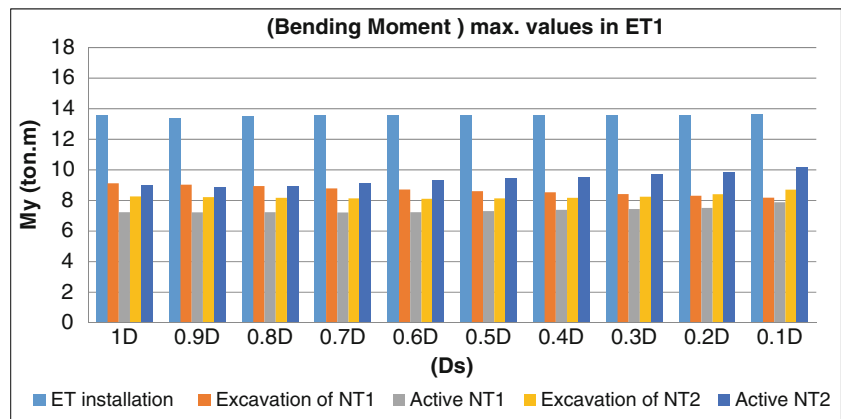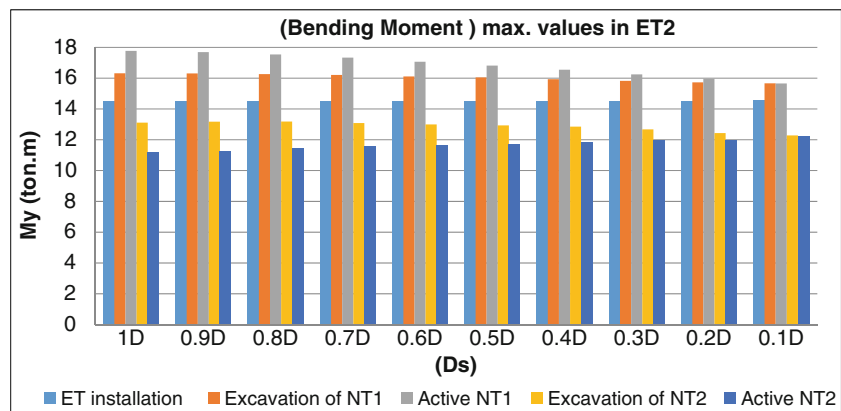**Fig. 18** Maximum bending moment induced in existing tunnel ET1

Fig. 19 Maximum bending moment induced in existing tunnel ET2

Straining actions in existing tunnel lining

For larger spacing distances (0.7D–1.0D), the induced normal force maximum value, in ET1, is constant during new tunnel execution. For smaller spacing distances, the value is increased during execution. A significant increase occurs at a spacing distance of 0.1D, as shown in Fig. 24. This is the same behaviour for normal force maximum values in ET2 due to new tunnel NT2 execution, as shown in Fig. 25.

In general, the induced bending moment maximum value in existing tunnel lining is constant during new tunnel execution except for small spacing distances (0.1D–0.3D) (Figs. 26 and 27).

Horizontally added tunnels in clayey soil

Deformations of existing tunnels and ground surface

Figure 28 shows the surface deformations during new tunnel installation with different spacing distances. The deformation

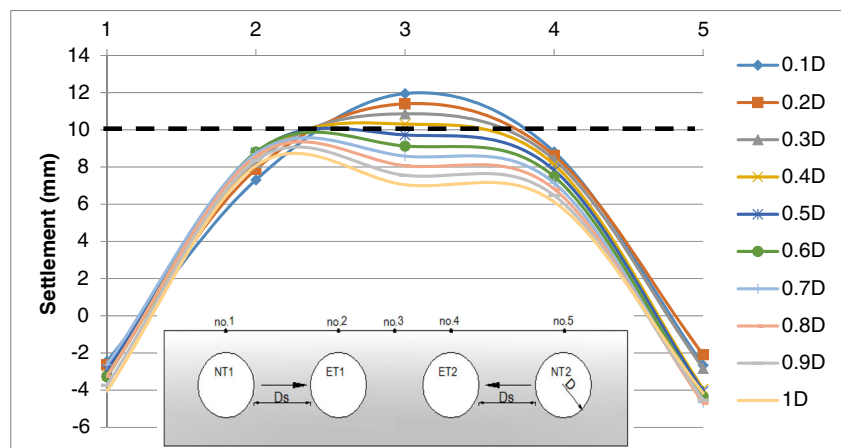**Fig. 20** Surface deformations due to (Ds) variation in sandy soil

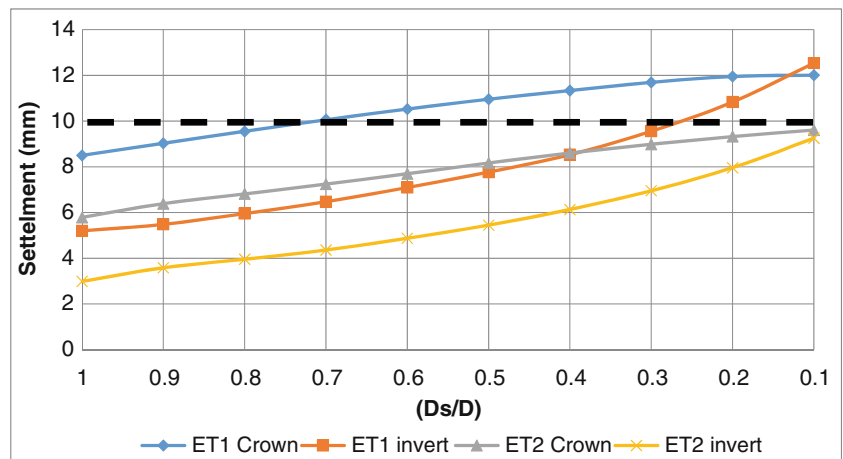**Fig. 21** Existing tunnel deformations due to (*D*s) variation in sandy soil

Fig. 22 Plasticized zone distribution at (*D*s) = 1D
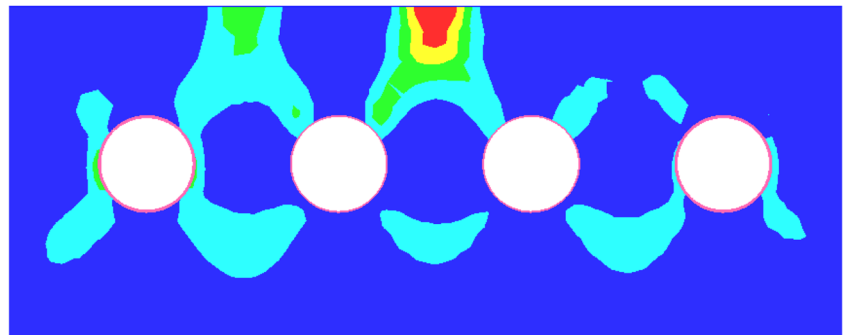

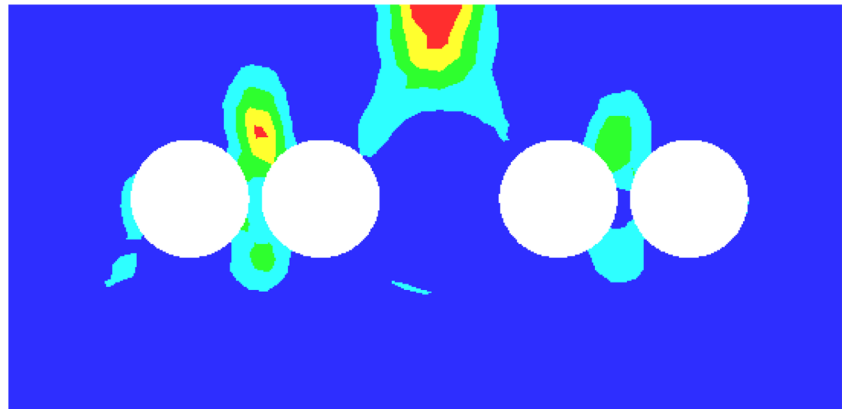**Fig. 23** Plasticized zone distribution at (*D*s) = 0.1D

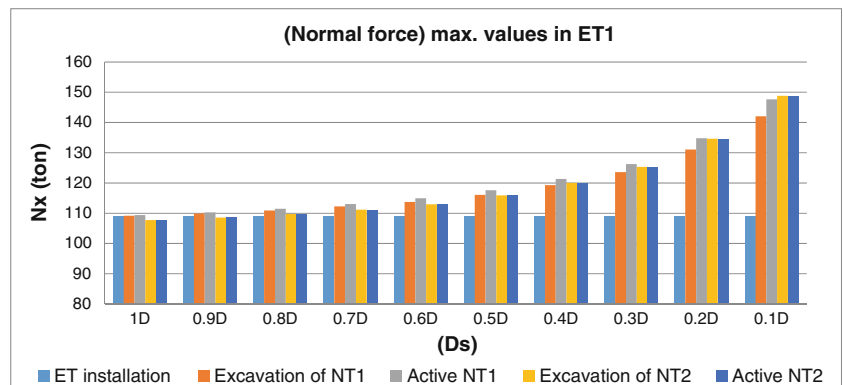**Fig. 24** Maximum normal force induced in existing tunnel ET1
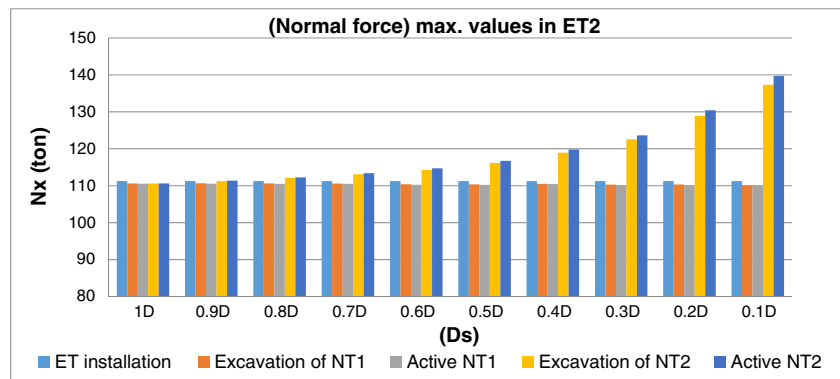
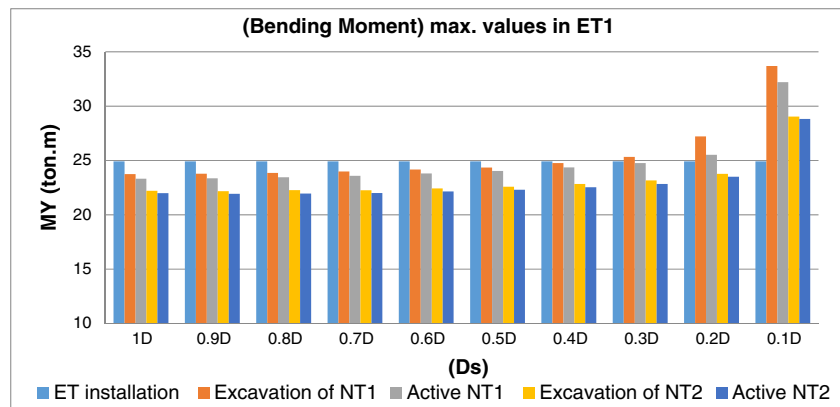**Fig. 25** Maximum normal force induced in existing tunnel ET2

Fig. 26 Maximum bending moment induced in existing tunnel ET1

is plotted at five different points: above existing tunnels, at mid-point between existing tunnels and above new tunnels. The general behaviour of the ground surface is heaving with peak values between mid-point and existing tunnel (ET1). The heave value is 1.2 mm at a distance Ds equal to 1D and increased to be 3.37 mm at Ds equal to 0.1D. The existing lining deformations at crown and invertare are shown in Fig. 29. The deformation values range from 0.17 to 2.14 mm upward at 1D spacing distance and range from 2.9 to 5.7 mm upward at a 0.1D spacing distance.

Plasticized zone distribution in soil

The plasticized zone is increased with the degradation of distance (Ds), as shown in Figs. 30 and 31. For (Ds) range from tunnel diameter 1D to 0.1D, the plasticized zone is distributed widely between tunnels. So, in the clayey soil also, it is recognized that adding new tunnels horizontally to existing tunnels has a high impact on the soil stability. Hence, a spacing distance between new and existing tunnels must exceed tunnel diameter.

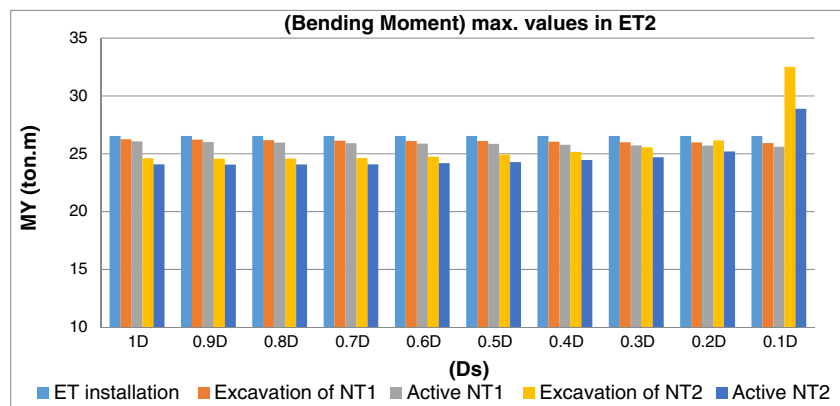**Fig. 27** Maximum bending moment induced in existing tunnel ET2

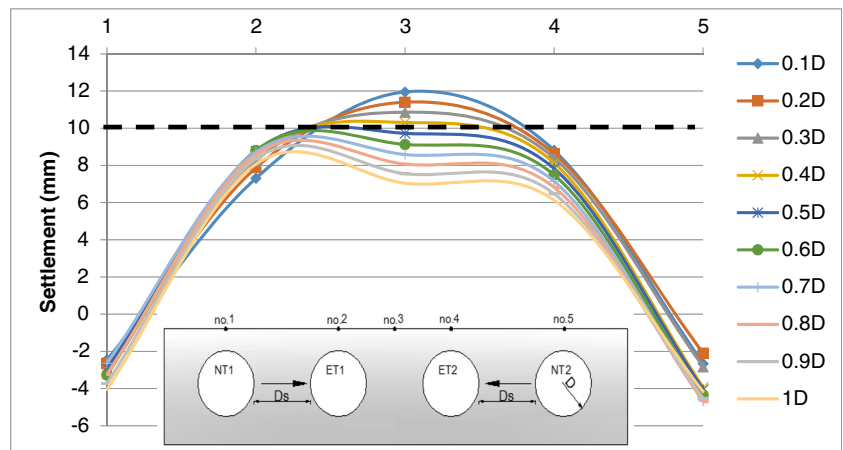**Fig. 28** Surface deformations due to (Ds) variation in clayey soil

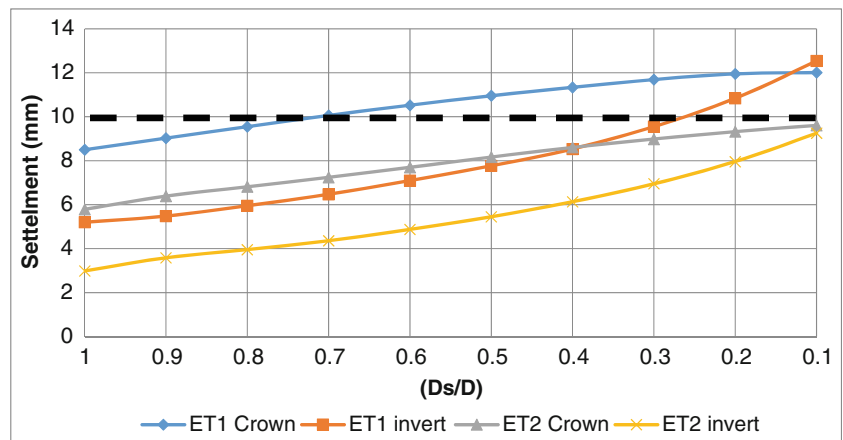**Fig. 29** Existing tunnel deformations due to (Ds) variation in clayey soil

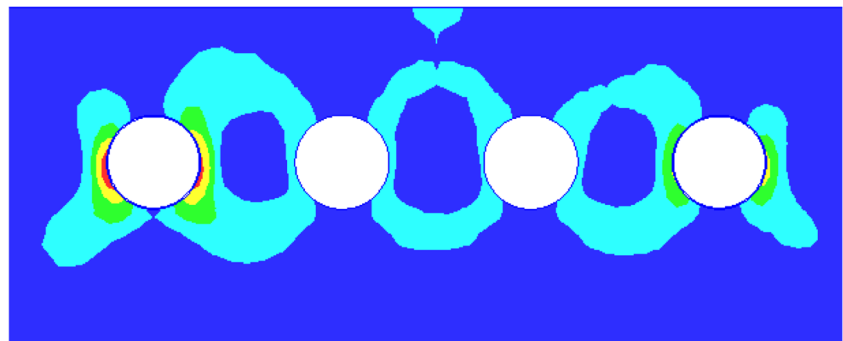**Fig. 30** Plasticized zone distribution at (Ds) = 1D

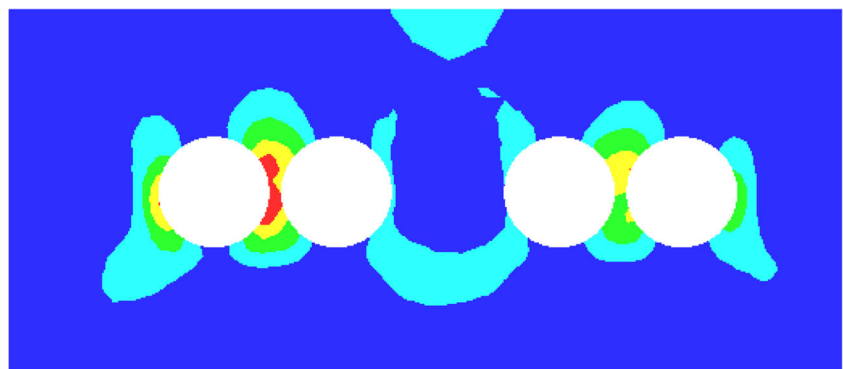**Fig. 31** Plasticized zone distribution at (Ds) = 0.1D

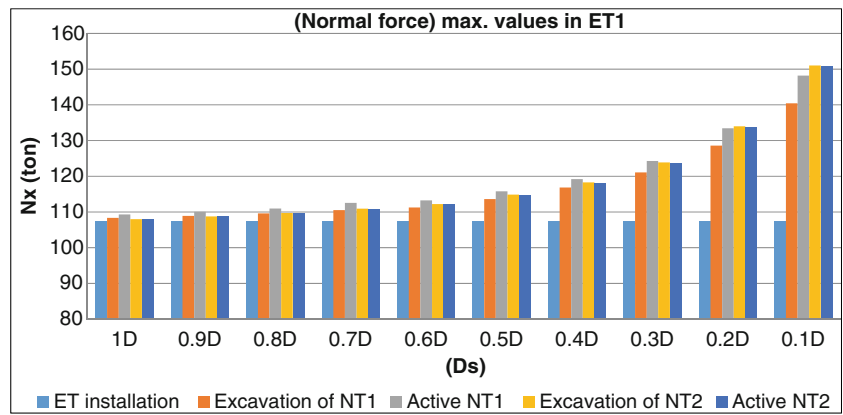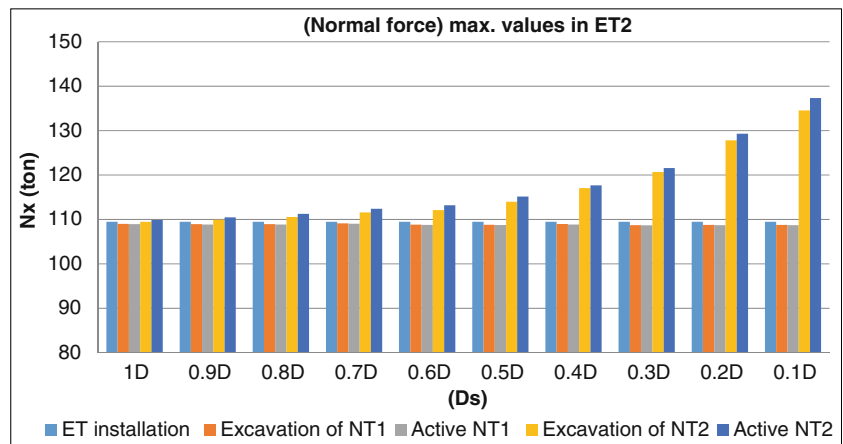**Fig. 32** Maximum normal force induced in existing tunnel ET1

Fig. 33 Maximum normal force induced in existing tunnel ET2

Straining actions in existing tunnel lining

Figure 32 shows that the normal forces in ET1 are almost constant during adding new tunnels at distance 1D. A significant increase occurred during spacing distance degradation and realized the maximum at a distance 0.1D. The bending moment maximum value is increased, at small spacing

distances (0.3D–0.1D), by 70% with the first tunnel excavation as shown in Fig. 34.

A similar behaviour for ET2 is shown in Figs. 33 and 35. The maximum value of normal force in ET2 is influenced by adding NT2 higher than NT1. Also, the maximum bending moment in ET2 is decreased during adding new tunnels in wide spacing distance range (1D–0.3D), and it is increased by 65.5% at a distance of 0.1D (Figs. 34 and 35).

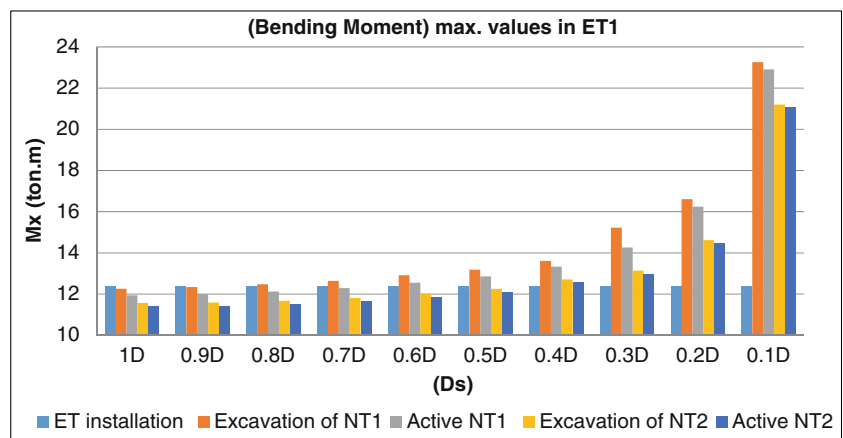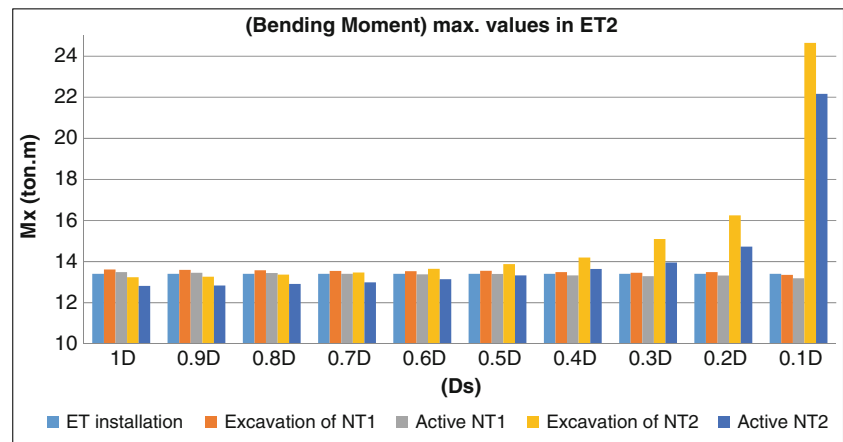**Fig. 34** Maximum bending moment induced in existing tunnel ET1

Fig. 35 Maximum bending moment induced in existing tunnel ET2

Conclusions

For the investigated case study, defined with soil type, tunnelling depth and tunnels diameter, the following conclusions may be drawn:

- The process of adding new tunnels generally does not affect the straining actions induced in existing tunnel lining beyond the safety limits. For all studied cases, lining internal stresses due to induced straining actions did not exceed the allowable material stress. Thus, existing lining internal stresses may not be considered as a constraint in spacing distance determination.
- Induced deformations and plasticized zone percentage are intensively affected with the spacing distance for both tunnelling positions and both soil types. Thus, these parameters have high impacts in decision making for optimal spacing distance selection.
- In the case of vertically added tunnels, due to preconditioned deformation constraint, the recommended spacing distance is 0.5D in sandy soil and 0.4D in clayey soil. Attention should be paid to soil plastic zones in addition to settlement value to choose the recommended spacing. Spacing can be further reduced with the use of soil strengthen technique.
- In the other case of horizontally added tunnels and due to preconditioned deformation constraint, it is recognized that existing tunnel deformation limits the spacing distance to 0.3D in sandy soil and 0.1D in clayey soil. Also, the plasticized zone distribution indicates probable soil failure for a spacing distance less than 1D.
- The comparison between constraint values, for adding new tunnels in sandy soil at a selected spacing distance with different positions, shows no advantages for any position over the other. Both vertical and horizontal positions, at a selected spacing distance, give safe results and close values. On the other hand, the same comparison between constraint values, for adding new tunnels in

clayey soil at a selected spacing distance with different positions, shows that horizontal position gives better results in deformation constraint than vertical position and close values in straining action constraints. Although results for both positions are safe, this may give the advantage to the horizontal position.

The research does not aim to present specific values for the optimal spacing distance as it differs with different soil and tunnelling properties. It aims mainly to demonstrate the selection process and investigate the effective parameters showing their weight and impact on the selection process and decision making.

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