Journal of Mining and Earth Sciences

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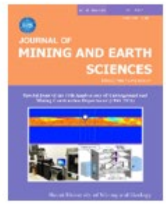


Stability of steel pile walls and tunnels excavated by shield machines in the urban areas: A case study

Minh Tuan Tran *, Thai Ngoc Do, Phong Duyen Nguyen

Hanoi University of Mining and Geology, Hanoi, Vietnam

ARTICLE INFO

Article history:
Received 15th Sept. 2021
Revised 28th Dec. 2021
Accepted 20th Feb. 2022

Keywords:
Basement,
Numerical modeling,
Settlement,
Shield machines,
Stability.

ABSTRACT

Placement of infrastructure and other facilities underground brings superior opportunities for long-term improvements in terms of the environmental impact of urban areas and more efficient use of underground space. However, underground construction in urban areas is a high-risk activity and has been considered a challenging problem for geotechnical and structural designers. Therefore, the evaluation of the stability of underground structures plays a vital role in structural and construction design. This paper presents a case study on analyzing the stability of steel piles walls and tunnels excavated by shield machines in the urban area in Vietnam in terms of the change in internal forces in the structures. The research results show that the excavated stages of the basement influence on the values of internal force in the tunnel lining. In the case of study using composite lining in the tunnel, the thickness of lining concrete 35 cm, steel frame type I-W1000×883 are applied for tunnel excavated before construction of nearby basement, and 30 cm and W1000×350 steel ribs for the opposite side. This research could be applied to evaluate the effects of tunnel excavation near the existing structures in urban such as in the geological conditions in the Ha Noi and Ho Chi Minh City in the near future. However, this analysis also has the disadvantage that it does not consider the construction time as well as the construction sequence of the works during tunnel excavation. The shapes of the tunnel only are circular tunnels and the only type of steel piles in this research. Further study, total evaluation for other types of tunnels and walls of basements should be considered.

*Corresponding author
E - mail: trantuanminh@humg.edu.vn
DOI: 10.46326/JMES.2022.63(3a).04

1. Introduction

Nowadays, construction of the basements partly or completely below the level of the ground as well as underground spaces in the cities is an inevitable trend for urban areas in Vietnam. The basements are often used for several purposes as a garage, as maintenance rooms, or as living space. There are recently two biggest cities in Vietnam, Hanoi and Ho Chi Minh city, implementing two metro lines, namely Line 3 and Line 1. The former is from Nhon to Hang Co station in Ha Noi city, and the latter is from Ben Thanh to Suoi Tien. The length of metro Line 3 in Hanoi is approximate 12.5 km long in total and consists of 12 stations, with 8.5 km on the surface and 4 km below the surface (Figure 1).

In Ho Chi Minh City Metro Line 1 connecting Ben Thanh Market and Suoi Tien Theme Park in District 9 was designed with a length of 19.7 km consisting of 2.6 km below the ground surface and 17.1 km above. Metro Line 1 comprises three underground stations and 11 stations on the surface. Under the initial plan, the Metro project Line 1 was designed to complete by the end of 2017 and put the Metro systems into operation in early 2018.

Due to civil construction density on the surface as well as building characteristics in the populated urban areas, people's houses are so close to each other, excavation and construction of deep foundations are necessary to use steel pile walls to ensure stability, safety and avoid nearby existing buildings on the surface from being affected. This work is very important in building a deep foundation and underground construction of nearly sensitive structures. Excavation subway tunnels under cities in soft soils and containing underground water usually applied shield machines with EBP (Hu et al., 2003; Do et al., 2014; Nguyen et al, 2007; Kolymbas, 2005). Subway tunnels excavated by shield machines have advantages to increase the excavation speed and decrease risks of construction on the surface and other near constructions (Pankratenko, 2002; Kartozia et al., 2001a; Kartozia et al., 2001b).

Currently, analytical methods concerned with many factors of soil layers and structures are complex, in many cases can't solve (Wang and Wang, 2015; Weng et al., 2016; Nguyen, 2008 and 2010; Nhu et al., 2020; Nguyen, 2007a; Vo, 2006; Nguyen, 2005; Tran, 2014). This paper introduces the use of the numerical method to analyze the stability of the steel pile wall of a basement, and structures of tunnel excavated by shield machines subjected to the surface structures in the urban conditions.

Figure 1. Traffic situation (a) and plan view of metro line 3 (b) in Hanoi.

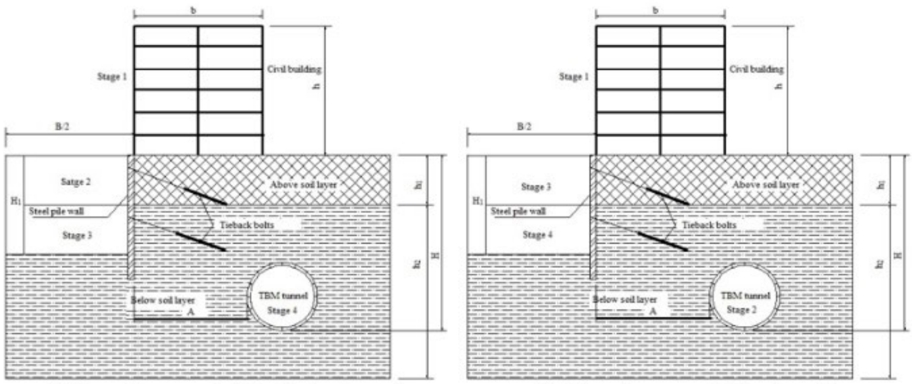
2. Model of problem

2.1. Establish the numerical model

Considering a practical case that comprises a deep basement and tunnel that are going to be constructed. Due to the urban conditions, the location of these two items is designed to be relatively close to each other. The depth of the basement is H_1, located near the civil building on the surface. The height of the civilian house h and width b respectively. The excavation of the basement is done through two soil layers, in the sidewalls of the foundations applied steel pile walls combined with tieback soil bolts, the parameters of piles and bolts will be calculated. Tunnel support is applied by concrete segments with the thickness of linings d, the diameter of tunnel D, and the distance from the steel pile wall to the TBM tunnel is A. Two cases will be considered to analyze the effects of the excavation tunnel on the steel pile walls, tieback bolts, and civil building on the surface when the tunnel is excavated in the final as in (Figure 2a). In other cases, the tunnel was excavated below the civil building in stage 1 and considered to change internal forces or the stability of the tunnel in case of the steel pile walls and tieback bolts installed after the existing tunnel (Figure 2b). In this research, the effect of underground water levels has not been considered. All of the excavation stages for deep foundation and stalling tieback bolts and tunnel excavation are simulated in this research.

2.2. Input parameters and numerical computation scenarios

Input data for analysis consist of a six-floor building with a height (h) of 22 m; width (b) of 10 m; the diameter of the tunnel (D) of 5 m; The depth of foundation (H_1) of 8 m; The width of foundation (B) of 20 m respectively; the depth of TBM tunnel (H) of 15 m; distance from pile wall to the side of TBM tunnel (A) of 10 m; the ratio of horizontal and vertical initial stress is 0.5; the properties of soil layers, steel pile walls, and bolts as well as linings presented in (Tables 1÷3). This study considered two cases:



a) Tunnel excavated finally in stage 4 b) Tunnel excavated in stage 2

Figure 2. Theoretical model.

Table 1. Properties of soil layers in the analysis.

Parameters	Symbol	Units	Above soil layer (Soft soil)	Below soil layer (Stiffness soil)
The thickness of layers	h_1; h_2	m	4.0	14.0
Unit weight	γ	MN/m^3	0.012	0.02
Young's Modulus	E	MPa	10.0	20.0
Poisson ratio	μ	-	0.35	0.32
Tensile strength	σ_k	MPa	0.10	0.10
Cohesion	c	MPa	0.25	0.30
Friction angle	φ	Degree	12.0	25.0
Dilation angle	ψ	Degree	1.0	0.5
Residual friction angle	φ_{re}	Degree	10.0	20.0
Residual cohesion	c_{re}	MPa	0.15	0.20

Table 2. The parameters of tunnel lining (https://www.rocscience.com/software/rs2).

Parameters	Symbol	Values	Units
Type of material	Behavior	Elastic	-
Thickness of lining	d	30.0	cm
Young's Modulus	E_{bt}	35000	MPa
Poisson ratio	μ	0.15	-
Compressive strength	σ_b	40.0	MPa
Tensile strength	σ_{bk}	3.0	MPa

Table 3. The properties of steel walls and bolts (https://www.rocscience.com/software/rs2).

Parameters	Symbol	Steel pile walls	Bolts in the above soil layer	Bolts in the bellow soil layer	Units
Type of material	Behavior	Elastic	Elastic	Elastic	-
Diameter of bolt steels	d	-	19	19	mm
Bond strength	C_n	-	5000	5000	MN/m
Borehole diameter	d	-	50	50	mm
Tensile capacity	P_k	-	100	100	MN/m
Pre-tensioning force	P	-	20	50	MN
Percent of length (bond length of tieback bolts)	-	-	40	40	%
The length of tieback bolts	l	-	8.5	8.5	m
The angle of bolts/vertical	α	-	69	69	Degree
Spacing of bolts in vertical plan	a	-	4.0		m
The thickness of walls	d_c	20	-	-	cm
The length of steel pile walls	L	10	-	-	m
Young's modulus of steel pile walls	E_t	30000000	-	-	MPa
The depth of excavated stages	-	4.0			m

The first case: Execute the construction of the basement, followed by the tunnel.

The second case: The construction of a tunnel using a shield machine is carried out first, the subsequent basement is constructed.

The surcharge load induced by the civil building located on the top of the model is replaced by the equivalent distribution of load 1.0 MN/m^2. The boundary conditions are modeled wherein the vertical sides of the models are fixed in X-direction; the top surface of the model is free to move in all directions, and the bottom is fixed in both vertical and horizontal directions. The finite element method is used to simulate these considering cases as shown in (Figures 3, 4).

2.3. Results and Discussions

The numerical calculation results of the distribution of total displacement around steel pile walls and tunnel structures are shown in Figures 5, 6. The values of internal forces in the steel pile with other excavated stages in the first case are indicated in Tables 4÷6. From these results, the relationship between the internal forces and the length of the steel pile wall is analyzed as shown in Figures 7÷9.

The received results in Figures 7÷9 show that the excavated stages and the excavation of the tunnel have a significant influence on the internal forces of the steel pile wall. With the axial force the values changed arrange from 0.12÷2.68% between stage 3 and stage 4, shear forces arrange from 0.40÷3.67%, and bending moment from 0.31÷3.67% in the case of the newly installed tunnel (minus in the tables indicates that the decreased level of internal force values in steel pile wall). These comments indicate the design of steel pile walls of basements must be considered by unfortunately risks from new tunnels. The factor of safety in the design of walls will be much more because of the increase of internal forces to 3.67%. In the case of existing basements, the designers should decrease the effects of tunnel excavation on the walls with new excavated technologies or reinforce existing walls with artificial solutions.

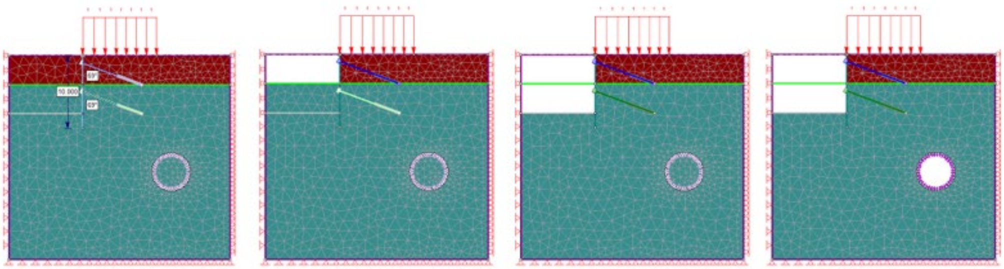

a) Stage 1 b) Stage 2 c) Stage 3 d) Stage 4

Figure 3. Modeling stages in the first case.

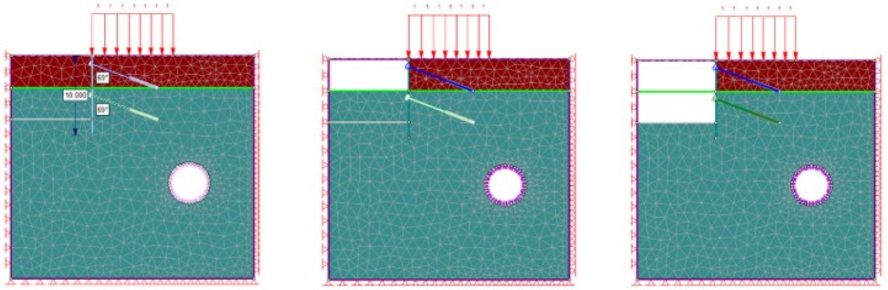

a) Stage 1 b) Stage 2 c) Stage 3

Figure 4. Modeling stages in the second case.

Table 4. The values of axial forces in the steel pile wall in the different stages in the first case.

Distance (m)	Stage 2	Stage 3	Stage 4	Variability (%)
0.69	-0.54	-1.71	-1.76	2.68
2.06	1.46	-3.52	-3.48	-1.03
3.36	1.43	-3.98	-3.94	-0.97
4.70	1.31	-1.84	-1.88	2.37
6.06	1.14	4.72	4.68	-0.74
7.36	1.25	3.77	3.75	-0.55
8.50	1.16	3.31	3.29	-0.36
9.50	0.81	3.00	3.01	0.12

Table 5. The values of shear forces in the steel pile wall in the different stages in the first case.

Distance (m)	Stage 2	Stage 3	Stage 4	Variability (%)
0.69	0.62	-2.57	-2.66	3.67
2.06	3.46	-8.72	-8.58	-1.62
3.36	1.57	-10.47	-10.35	-1.12
4.70	-0.18	-4.40	-4.46	1.35
6.06	-1.35	11.87	11.80	-0.56
7.36	-1.83	7.95	7.96	0.14
8.50	-1.77	5.55	5.53	-0.40
9.50	-1.34	3.26	3.23	-0.87

Table 6. The changing of bending moment in the steel pile wall.

Distance (m)	Stage 2	Stage 3	Stage 4	Variability (%)
0.00	-0.43	1.78	1.84	3.67
0.69	-0.43	1.78	1.84	3.67
1.38	-1.80	5.60	5.65	0.90
1.38	-1.80	5.60	5.65	0.90
2.06	-3.17	9.42	9.45	0.38

Distance (m)	Stage 2	Stage 3	Stage 4	Variability (%)
2.73	-4.83	15.68	15.63	-0.31
2.73	-4.83	15.68	15.63	-0.31
3.36	-6.49	21.93	21.80	-0.61
4.00	-6.93	26.79	26.64	-0.56
4.00	-6.93	26.79	26.64	-0.56
4.70	-7.36	31.66	31.49	-0.52
5.40	-6.85	29.25	29.12	-0.42
5.40	-6.85	29.25	29.12	-0.42
6.06	-6.34	26.84	26.76	-0.30
6.73	-5.30	20.36	20.30	-0.30
6.73	-5.30	20.36	20.30	-0.30
7.36	-4.27	13.89	13.84	-0.32
8.00	-3.25	9.96	9.92	-0.42
8.00	-3.25	9.96	9.92	-0.42
8.50	-2.22	6.03	5.99	-0.65
9.01	-1.44	3.82	3.80	-0.70
9.01	-1.44	3.82	3.80	-0.70
9.50	-0.67	1.62	1.60	-0.87
10.00	-0.67	1.62	1.60	-0.87

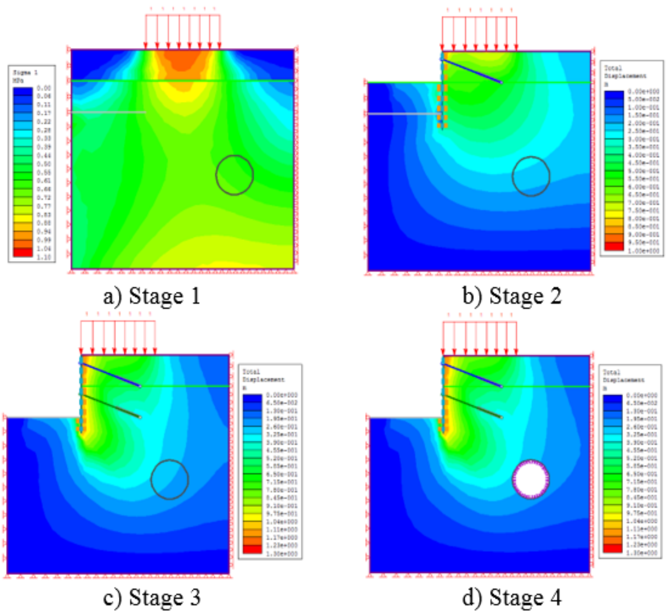


Figure 5. The distribution of total displacement in the first case.

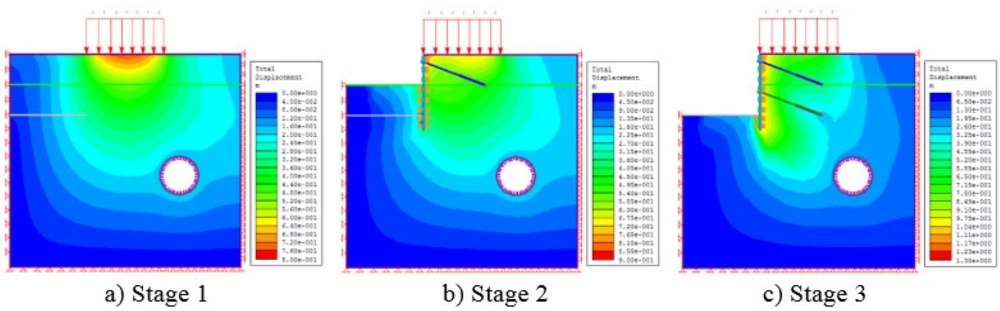


Figure 6. The distribution of total displacement in the second case.

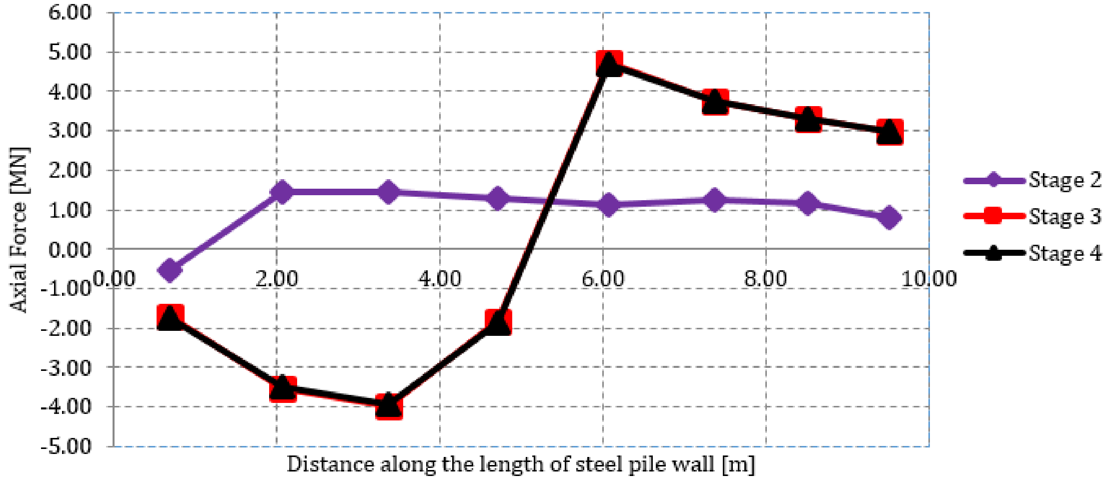


Figure 7. Axial force distributed along the length of steel pile wall in the first case.

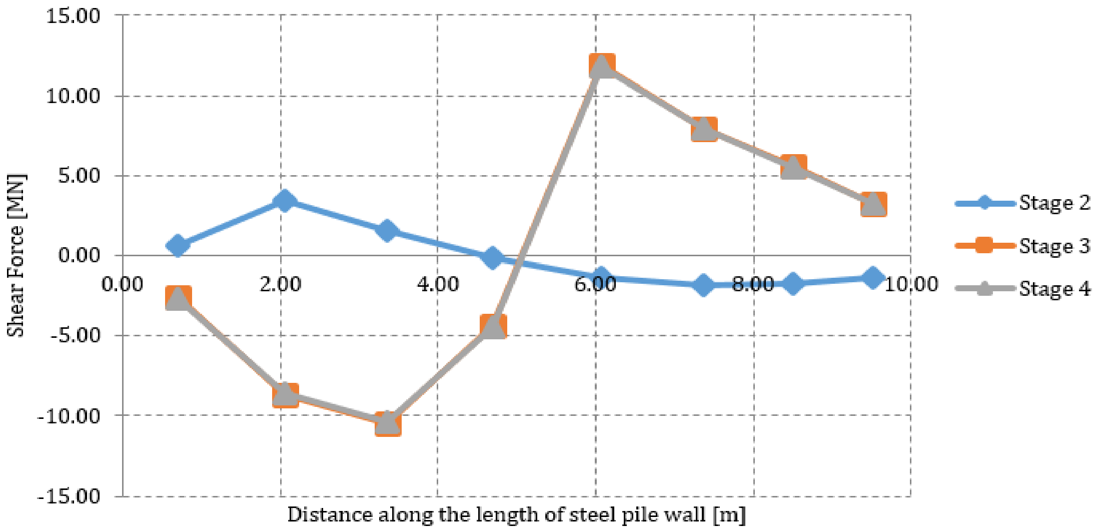


Figure 8. Diagram of shear force in the steel pile wall.

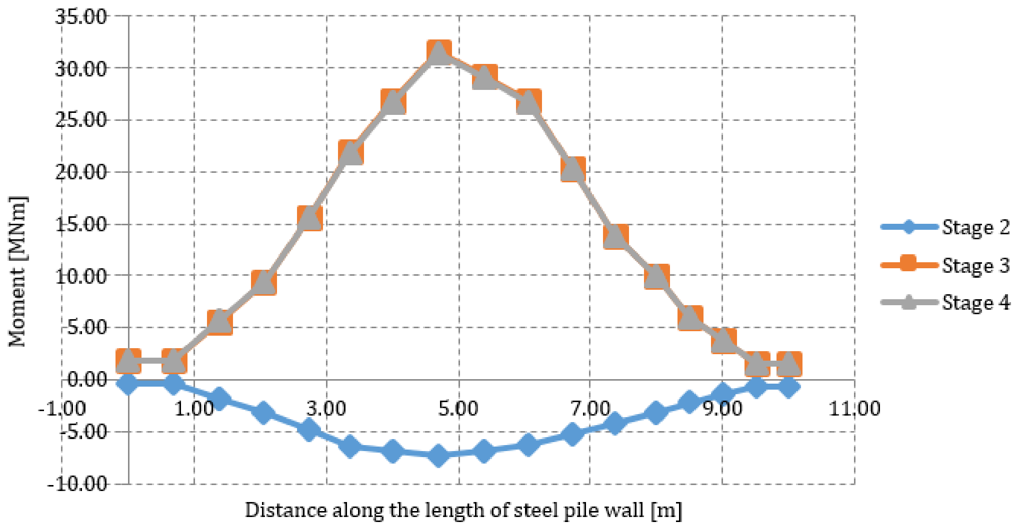


Figure 9. The distribution of bending moment of steel pile wall in the first case.

In the other case, basements of new houses are built near the existing tunnels as in Figure 4. The effects of the excavation of new basements and steel pile walls on the stability of tunnel linings are examined. The statistic method allows us received the relationship between the internal forces in the lining elements and the tunnel perimeter in other excavated stages of basements as in Figures 10÷12, and the diagram of bending moment in the lining layer of the tunnel in Figure 13 respectively.

The results of Figures 10÷13 show that the axial force in the second stage will be changed compared with the first stage from 1.67÷20.34%, in the third stage from 1.03÷66.03%. The final shear force in the tunnel lining changed from 3.64÷18.56% at the top and bottom of the tunnel, 84.29÷88.76% at the horizontal location from the

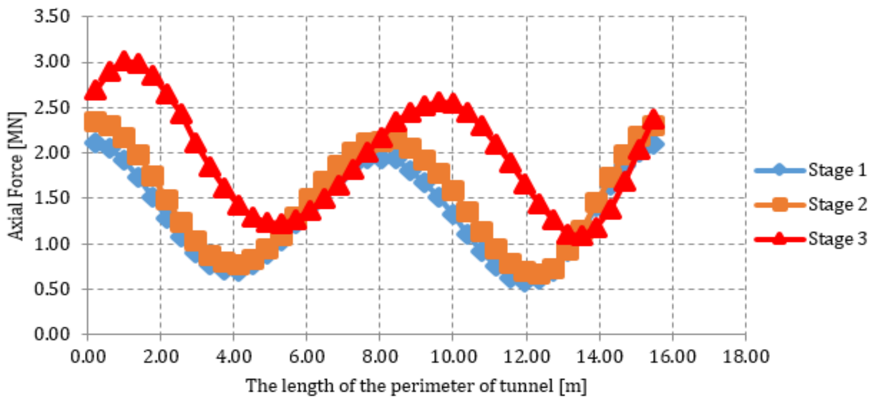


Figure 10. Axial forces of the tunnel lining in the second case.

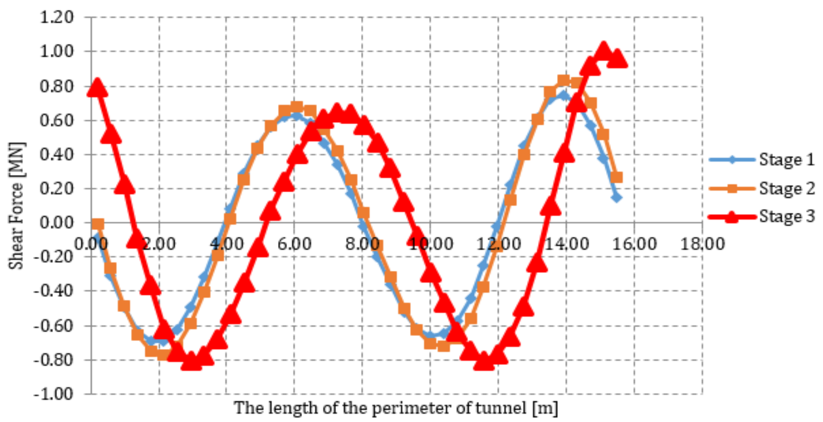


Figure 11. Shear forces of the tunnel lining in the second case.

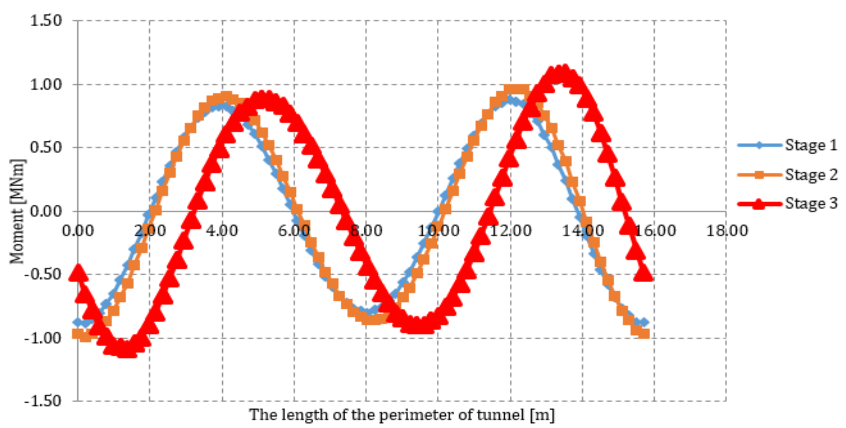
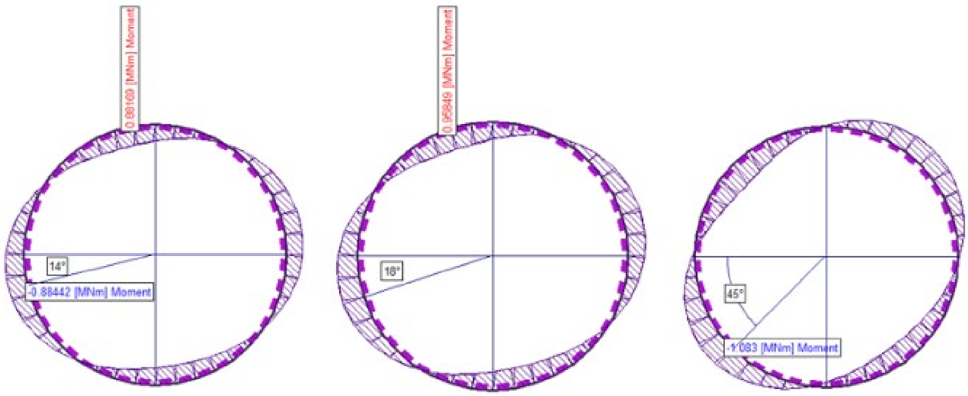


Figure 12. Bending moment of the tunnel lining in the second case.



a) Stage 1 b) Stage 2 c) Stage 3

Figure 13. Changing of bending moment of the tunnel lining in different excavated stages of the basement.

center of the tunnel compared with the case without a basement. Final values of bending moment changed about 55% at angles of 0^0 and 180^0 (Figure 13) on the horizontal axis at the center of the tunnel lining, and 7.6% on the top and bottom of the lining. In the second excavated stage of the basement, these values are 11.12% and 8.96% respectively. These comments explained that the excavation process of the basement affects the lining of the existing tunnel, designers must be investigated the working of the lining during the excavation of the basement to avoid risks for tunnel lining.

2.4. In the case of using composite linings

In other cases of research, the application of composite linings by concrete lining and steel ribs, evaluation of the capacity of linings in two cases as following are conducted:

1 - In case the tunnel is excavated before the excavation of the basement, the excavation of the deep foundation affects the selection of linings in the tunnel. The supporting structure for the tunnel will be adjusted to ensure safety because of the excavation of the deep foundation and pile wall. The results of the research show that basement excavation influences the design of tunnel linings. In the first case, the thickness of the lining of 30 cm was applied. The numerical modeling results show that the tunnel lining is not durable. In the next step, it is necessary to find another type of tunnel support.

In the next step of research, numerical modeling is conducted to select appropriate composite lining. By many numerical models can be received composite lining with concrete liner 35 cm and steel ribs number W1000×883. The properties of concrete can be seen in the above section, the mechanical properties of the steel ribs can be chosen by tests or as defaults of numerical modeling such as the section depth of 1.09 m, area of 0.112 m^2, Young's modulus of 200,000 MPa, Poisson's ratio of 0.25, compressive strength of 400 MPa, tensile strength of 400 MPa. In this case, tunnel lining will be durable and ensure the carrying capacity, the loading capacity chart of lining will be described as shown in Figure 14.

The results in Figure14 show that by the above parameters of linings, the factor of load capacity of lining is satisfied to more than 1.8 or 2.0 times the capacity of the external force. This means using the durability factor in the design will be up to 2.0.

2 - In another case, when the tunnel is excavated after excavated stages of the foundation and pile walls, the tunnel will be installed with a 30 cm concrete liner, using I-shaped steel ribs W1000×350 with spacing of 0.75 m for the permanent support of the tunnel. The mechanical properties of the steel ribs W1000×350 are the section depth of 1.01 m, area of 0.0445 m^2, Young's modulus 200,000 MPa, Poisson's ratio of 0.25, compressive strength of 400 MPa, and tensile strength of 400 MPa. The loading-capacity chart can be received in this case as in Figure 15, the factor of support capacity will be 1.5.

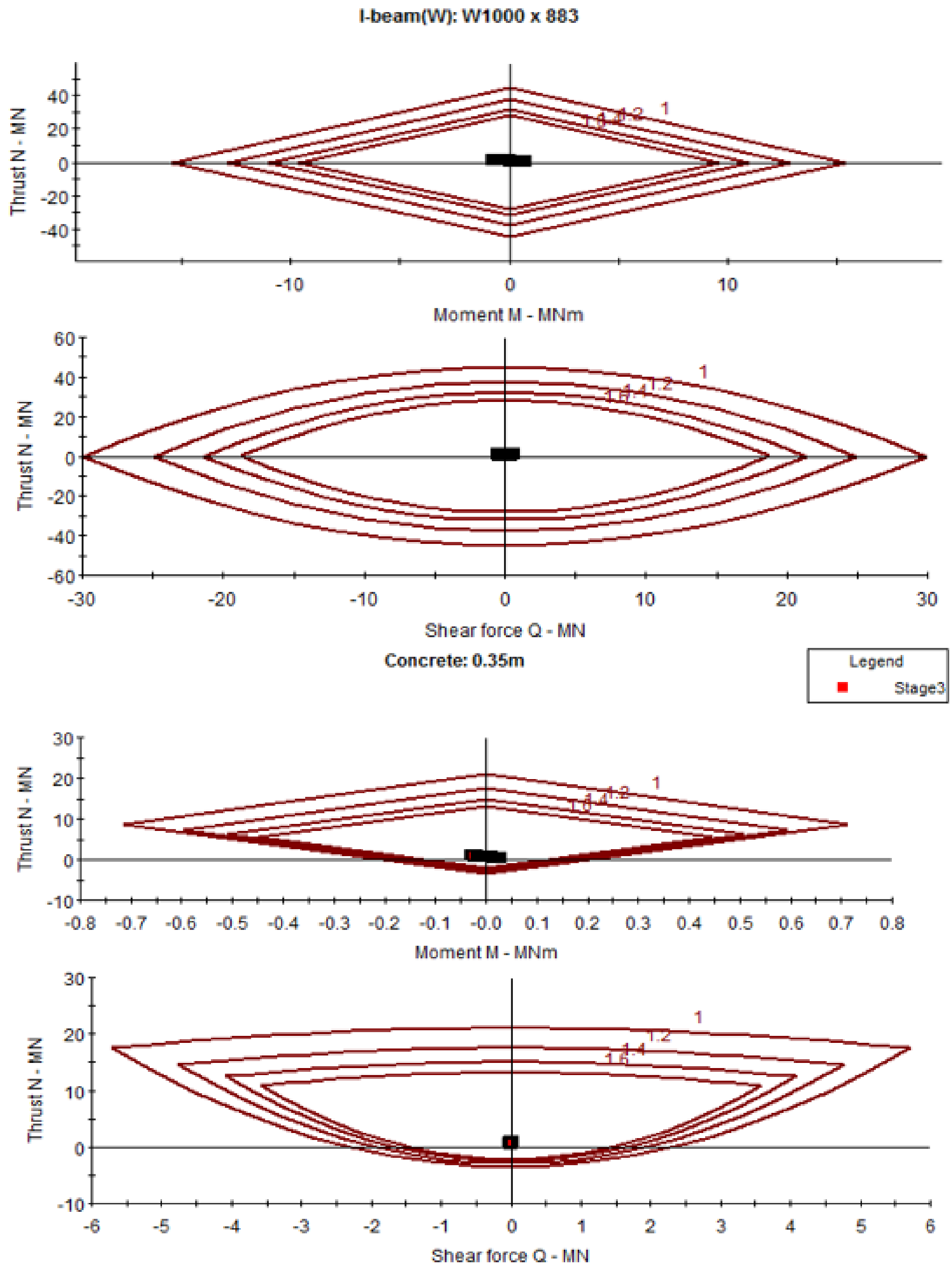


Figure 14. The loading carrying capacity of tunnel lining in case of tunnel excavated before deep foundation stage.

3. Conclusion

The stability of steel pile walls and tunnel were analyzed in terms of internal forces. Numerical computation results show that construction activities of the basement and the new tunnel have a significant influence on the internal forces of the steel pile wall of the basement. With the axial force the values changed up to 2.67%, shear forces 3.67%, and bending moment 3.67% in the case of the installed tunnel. Designers thus need to consider the alternative method that could be used to eliminate the effects of tunnel excavation activities on the stability of

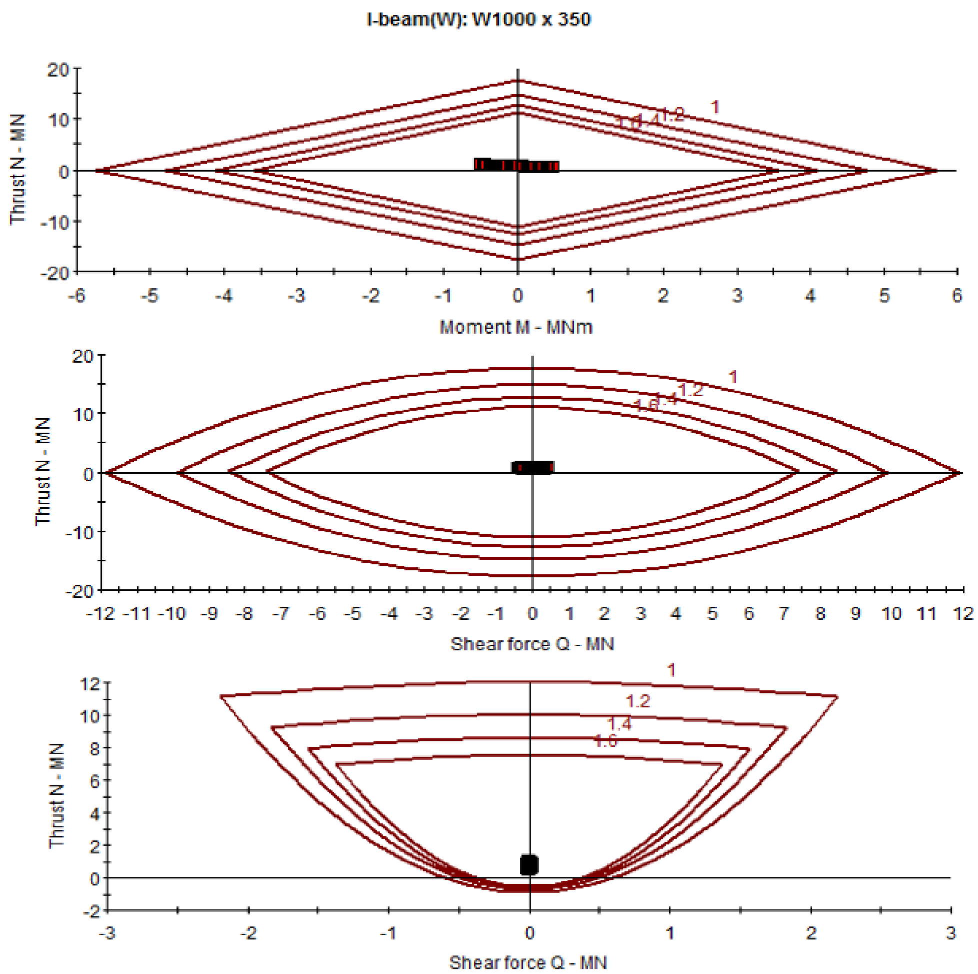


Figure 15. Support capacity chart in the case of the tunnel excavated after cutting stage of deep foundation.

nearby walls, such as applying new excavated technologies or reinforcing existing walls with geotechnical solutions.

When basements of new houses are built near the existing tunnels the axial force in the lining of the tunnel will be changed compared with the existing lining from 1.03÷66.03%. The final shear force in the lining changed from 3.64÷18.56% at the top and bottom of the tunnel, 84.29÷88.76% at the horizontal location from the center of the tunnel. The final values of bending moment changed about 55% at the angles 0^0 and 180^0 on the horizontal axis of the tunnel lining, and 7.6% on the top and bottom of the lining. These comments indicated that designers must be investigated and controlled the working of the existing lining to avoid risks for tunnel operation.

In the case of using composite lining, the first case should be applied supports in the inner tunnel with the thickness of concrete 35 cm, steel frame type I - W1000×883. In the second case, the tunnel composite lining should consist of concrete lining with a thickness of 30 cm and W1000×350 steel ribs.

Contribution of authors

Minh Tuan Tran - proposes ideas and contributes to the manuscript; Thai Ngoc Do and Phong Duyen Nguyen - constructs the manuscript and contribute to the material analyses.

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