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## Research Paper

### Comparative research on the mechanical behaviour of underground parking constructed by Top-down and Semi-Top-down method: A case study of Tran Hung Dao underground parking (Hanoi)

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#### ABSTRACT

Hanoi (Vietnam) has approximately 8.5 million inhabitants and suffers from severe traffic infrastructure insufficiency. The parking spaces in the city are lacking and have become one of the leading causes of traffic congestion. Underground parking facilities could be a solution. The Top-down, Bottom-up, and Semi-Top-down methods have been applied worldwide to construct shallow underground structures in soft soil. Comparative studies are needed to clarify their impacts on underground structures during construction. This paper presented the research on a shallow underground structure constructed by the Top-down and Semi-Top-down methods using numerical modelling. A model of 4-floor underground parking at the Tran Hung Dao station (Hanoi) was built, and the FEM analysis was realised. The behaviour of the parking structure, the diaphragm walls and the surrounding ground was investigated. The impact of the soil's bulk modulus and the wall's stiffness on the model's responses was also studied. The obtained results show the clear influence of soil and the construction procedure on the behaviour of the numerical model. The research was hoped to enrich the knowledge on the construction of shallow social infrastructures in soft soil.

## 1 Introduction

### 1.1 Research background

Hanoi, the capital of Vietnam, is the country's largest city (3,344.6km<sup>2</sup>) and the second most crowded city (approximately 8.5 million inhabitants). It is suffering from severe traffic congestion, which is constantly growing. A high-density urban infrastructure covers the downtown of Hanoi. The public parking spaces in the city are smaller than 1% of

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the city's surface [1]. The lack of parking facilities creates many problems in terms of traffic, pedestrian security and sidewalk congestion. In 2020, there were 36 million motorbikes and 3 million cars, with an increase of 10 to 15% per year [2]. The fast vehicle development leads to high traffic congestion. On-road and off-road spaces (sidewalks) have been utilised for parking purposes, contributing to traffic congestion and causing danger for pedestrians. From 2011 to 2015, the demand for parking surfaces in Hanoi for cars and motorbikes was 363,153m<sup>2</sup> and 52,118m<sup>2</sup>, respectively [3]. As people's economic life increases, inhabitants have been inclined to buy cars instead of motorbikes. Shortly, the public parking demand is expected to grow to 18,057,000m<sup>2</sup> [1]. Table 1 shows the capacity of different parking facilities near the metro stations in the downtown area of Hanoi.

**Table 1 – Capacity of parking facilities in Hanoi [4]**

| Parking type         | Area (m <sup>2</sup> ) | Parking slot |           |       |
|----------------------|------------------------|--------------|-----------|-------|
|                      |                        | Bicycle      | Motorbike | Car   |
| Parking garage       | 3,948                  | 20           | 500       | 308   |
| On-road              | 1,778                  | 0            | 0         | 320   |
| Sidewalk             | 4,836                  | 70           | 450       | 390   |
| On-road and sidewalk | 17,125                 | 140          | 880       | 1,431 |

Implementing new traffic infrastructure is essential to reduce all these traffic problems. Unfortunately, building an outdoor parking lot is very difficult due to the lack of space. The remaining solution is to construct underground parking lots. Underground parking can liberate the parking ground space and fluidise the traffic flow, besides other advantages presented by J.P. Tareau (1995) [5]. The preferable locations are under the roads to avoid intersecting with the existing building's foundations.

## 1.2 Prototype of the research

The underground parking is located on Tran Hung Dao street in the French quarter of Hanoi, crowded with traffic roads and existing buildings. The parking will be constructed next to the Tran Hung Dao station, the transit location of the Hanoi urban metro lines N<sup>o</sup>2 and N<sup>o</sup>3, under Hang Bai street.



**Fig. 1 – Location of the Tran Hung Dao underground parking on the Google map**



**Fig. 2–Tran Hung Dao underground parking structure [4]**

The underground parking is a 4-floor structure with a total capacity of 100 cars per floor or 560 motorbikes per floor. The structure is 255m long and 21.4m large, representing around 20,000m<sup>2</sup>, and is fully buried under the U-turn of the Hanoi metro Line N<sup>o</sup>3 in the Tran Hung Dao station. It will be constructed using the Cut-and-Cover method. Each floor is 4,900m<sup>2</sup>, and the total floor area will be 9,800m<sup>2</sup>, including the sanitary, machine rooms, and other facilities. The underground walkway from the 1<sup>st</sup> basement floor will directly connect to the Tran Hung Dao station concourse. Two emergency exits will be located on Hang Bai street.

### 1.3 Research methodology

The Cut-and-Cover method has been widely applied to construct the urban underground infrastructure. The construction sequence consists of the following main stages: soil excavation to create the trench (Cut), soil mucking, structure construction in the trench, and soil backfilling (Cover). It belongs to the Trench technology in tunnelling and is preferable for shallow buried structures. The Top-down and Bottom-up are two Cut-and-Cover method types. In the former, the diaphragm walls belong to the permanent supporting structures, whereas in the latter, they belong to the temporal supporting structures. C. Behniya *et al.* summarised the research bibliography of the two methods [6], while Y. Tan *et al.* compared two methods and presented the predominant characteristics and limitations of the Top-down method [7]. The Top-down method has been successfully applied to construct many metro stations and the basements of high-rise buildings in soft ground worldwide thanks to the early ground surface recovery on the excavation trench. The Semi-Top-down is the hybrid method that takes advantage of the Top-down and Bottom-up methods [7]. However, the published works on the comparison of the distinct differences between the Semi-Top-down method and its parent methods are limited. Analysing the case study of the Shanghai metro station, the paper of Y. Tan *et al.* is a representative work [7]. The behaviour of the diaphragm walls and the underground structure constructed by the three mentioned methods (Top-down, Bottom-up and Semi-Top-down) has caught the attention of many researchers. The actual projects' in-situ monitoring data and the numerical (theoretical and modelling) data were investigated, independently or simultaneously, to understand the performance of the diaphragm walls as a part of the supporting system of the underground structure during the construction phase.

A study on the diaphragm wall deformations of an urban underground facility during the underground construction procedure was launched, and the 4-floor underground parking at the Tran Hung Dao station of the Hanoi urban metro network was chosen as the prototype. Since the construction project has not been started, only a numerical modelling approach can be applied. However, this fact led us to the idea of comparing the two construction cases using the Top-down and Semi-Top-down methods. The research was hoped to enrich the comparative understanding of urban underground construction solutions. In this study, a Finite Element Method (FEM) in a Plaxis 2D modelling was realised for the prototype during the construction by the two mentioned methods. The geological and geotechnical data of a similar project were utilised. The deformations of the diaphragm walls and the underground parking structure were analysed. The effect of the geotechnical characteristics of the surrounding soil on the model behaviour was investigated with the variation of the bulk modulus of the soil layers in the modelling. The impact of the diaphragm walls' stiffness was also studied with three different elastic modulus values of the wall's concrete. The results obtained from two construction cases showed the distinction between the Top-down and Semi-Top-down methods. The research details are presented in the following parts of the paper.

## 2 Numerical modelling

### 2.1 Model size and element meshing

In a FEM analysis, the model's boundaries are determined to avoid any distortion and wrong calculation. It should be large enough to ignore all boundary effects on the model and the modelling results. The boundary's horizontal side was 600m, and the boundary's vertical side was 75m. The equivalent parameters of the parking model were 255m and 21.4m, respectively. The model was bi-directional fixed at the bottom boundary, and bi-directional free at the upper boundary. The numerical model comprised the linked triangle elements, and each triangle was divided into nodes. When the model was loaded, the model's geometry was moved, and the modelling accuracy depended on the model's node number. In this paper, the 6-node models were chosen. The goal for this setting was to avoid high time consumption calculations while providing reasonable accuracy for the modelling results.

## 2.2 Geological conditions

To create a numerical model with a reasonable similarity, the actual geotechnical parameters of the site were needed for the soil media in the model. However, since the construction of the prototype (the parking and urban metro station) was always in preparation, the required data were absent. Luckily, a building that stayed 5km from the parking area and contained a similar parking structure was found. Its geological investigation documents provided us with the input data for the modelisation. The numerical soil media contained eleven soil layers, and the Hardening soil type was applied to all soil layers. The clay layers were set in undrained conditions, and the sand layers were set in drained conditions. The reason for the choice was that the clay's low permeability reduced the water's movement in the soil, which induced the pore pressure from the water. The model's ground characteristics are shown in Table 2.

**Table 2 – Geotechnical parameters of the parking's surrounding ground**

| Soil layer            | Thickness (m) | Density (kN/m <sup>3</sup> ) | Poisson's ratio | Bulk modulus (kPa) | Friction angle (°) | SPT value |
|-----------------------|---------------|------------------------------|-----------------|--------------------|--------------------|-----------|
| Soft clay             | 2.6           | 18.3                         | 0.30            | 5.0                | 5.0                | 3.7       |
| Clay                  | 2.2           | 18.3                         | 0.35            | 20.0               | 1.0                | 5.6       |
| Soft soil             | 3.1           | 14.2                         | 0.35            | 4.7                | 2.5                | 3.9       |
| Light clay/Sandy soil | 2.2           | 20.4                         | 0.35            | 15.0               | 3.5                | 4.6       |
| Silty sand            | 5.2           | 18.0                         | 0.30            | 0.0                | 35.0               | 9.3       |
| Clayey soil 1         | 2.6           | 19.3                         | 0.35            | 34.9               | 6.2                | 8.9       |
| Clayey soil 2         | 5.1           | 20.0                         | 0.35            | 52.8               | 7.3                | 14.5      |
| Clayey soil 3         | 4.1           | 18.7                         | 0.35            | 16.2               | 6.4                | 7.6       |
| Coarse sand           | 7.3           | 18.0                         | 0.25            | 0.0                | 36.0               | 33.0      |
| Gravel/Cobble         | 6.2           | 18.0                         | 0.25            | 0.0                | 36.0               | 50.0      |
| Gravel/Sand           | 19.1          | 22.0                         | 0.25            | 0.0                | 38.0               | 100.0     |

The relationship between the SPT value (N, blows) and the bulk modulus (E, kN/m<sup>2</sup>) of the soil layer was taken as

$$E = \alpha \cdot N \quad (1)$$

where  $\alpha$  was an empirical coefficient, which was in the range of [2000; 5000] for sandy soil and [1000; 3500] for clay soil. By changing the  $\alpha$  value, the value of the bulk modulus of the soil layers could be modified. Five cases of soil's bulk modulus for the modelling are shown in Table 3, in which the  $E_{ur}$  was the bulk modulus obtained from the unloading, reloading triaxial drained test.

**Table 3 – Five cases of soil's bulk modulus for the modelling**

| Parameter                           | Case 1 | Case 2 | Case 3 | Case 4 | Case 5           |
|-------------------------------------|--------|--------|--------|--------|------------------|
| $\alpha$                            | 2000   | 2500   | 3000   | 3500   | 3500/5           |
| Bulk modulus E (kN/m <sup>2</sup> ) | 2000N  | 2500N  | 3000N  | 3500N  | 3500N/5 $E_{ur}$ |

The groundwater in Hanoi is primarily sourced from two principal aquifers: the Holocene and Pleistocene. Its level depends on the season: higher during the rainy season (from May to August), lower in the dry season and will also be affected by the Red River. However, most of the time, the level can be approximately around 3.0m under the ground. This water level and the water table lowering in each excavation phase of the parking construction were described in the modelling.

## 2.3 Structural element modelling

The numerical model of the parking structure included the following elements: the diaphragm wall, slab, intermediate column, lateral column, road, and bored pile. The diaphragm wall elements were linked to each floor's slab and column elements. They were linked with the bored pile element at the bottom and with the road element at the top. The plate

models were selected to model the five first elements, while the embedded beams were used for the last element. The slab, column, road and bored piles were made of reinforced concrete with the elastic modulus  $E=30\text{GPa}$ . Directly applied by the earth pushing, the diaphragm wall was made of High-Performance Concrete with the elastic modulus  $E=50\text{GPa}$ . The lateral column had a higher stiffness than the intermediate column. This choice was made to avoid extreme displacements of the diaphragm wall since the lateral column received the stress transferring from the diaphragm wall. The parameters of the model's elements are listed in Tables 4 and 5.

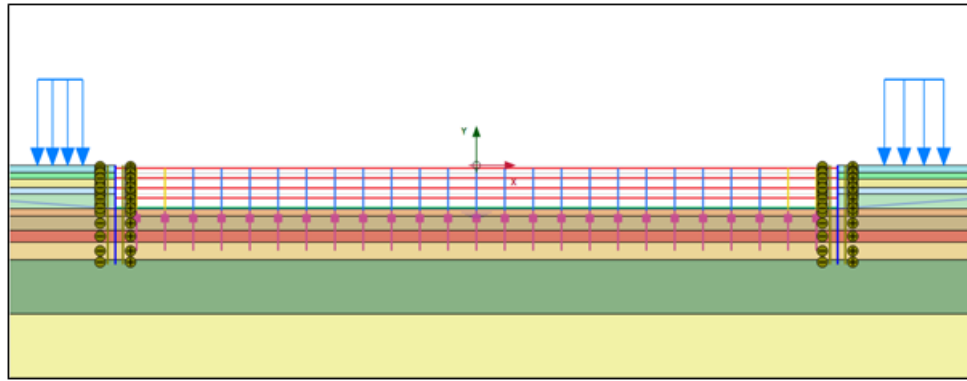


**Fig. 3 – Numerical model of the Tran Hung Dao underground parking and the surrounding ground**

**Table 4 – Mechanical parameters of the plate models**

| Element             | Type    | Axial stiffness<br>(kN/m) | Specific bending<br>stiffness<br>(kN/m <sup>2</sup> /m) | Thickness<br>(m) | Specific unit weight<br>(kN/m/m) | Poisson's<br>ratio |
|---------------------|---------|---------------------------|---------------------------------------------------------|------------------|----------------------------------|--------------------|
| Diaphragm wall      | elastic | $5.00 \times 10^7$        | $4.17 \times 10^6$                                      | 1.0              | 30.0                             | 0.2                |
| Slab                | elastic | $1.05 \times 10^7$        | $1.07 \times 10^6$                                      | 0.35             | 8.75                             | 0.2                |
| Intermediate column | elastic | $1.20 \times 10^7$        | $1.60 \times 10^6$                                      | 0.4              | 9.0                              | 0.2                |
| Lateral column      | elastic | $3.00 \times 10^7$        | $2.50 \times 10^6$                                      | 1.0              | 20.0                             | 0.2                |
| Road                | elastic | $2.40 \times 10^7$        | $1.28 \times 10^6$                                      | 0.8              | 18.0                             | 0.2                |

**Table 5 – Mechanical parameters of the Embedded beam models**

| Element    | Type    | Axial stiffness<br>(kN/m) | Specific bending stiffness<br>(kN/m <sup>2</sup> /m) | Thickness<br>(m) | Specific unit weight<br>(kN/m/m) | Poisson ratio |
|------------|---------|---------------------------|------------------------------------------------------|------------------|----------------------------------|---------------|
| Bored pile | elastic | $2.40 \times 10^7$        | $1.28 \times 10^6$                                   | 0.8              | 18.0                             | 0.2           |

## 2.4 Model's loadings

The principal loadings of the numerical model were the earth pressures caused by the surrounding soil. Besides the earth pressures, additional loadings were applied to the model. The parking, road, and lateral building loadings were self-weighted and acted as distributed loadings on the parking structure. The traffic loadings were caused by the on-road upstream and downstream traffic flows, which were 10m from the parking. They were taken as 10kN/m distributed loadings applied on the 20m-width.

## 2.5 Construction modelling

Two construction methods were applied for the numerical modelling of the 4-floor parking: the Top-down and Semi-Top-Down method. For the Top-down method case, nine continuous construction stages were modelled. For the Semi-Top-down method case, fifteen continuous construction stages were modelled. The number of construction stages in the second case was higher than in the first case, so a high level of coordination for every stage was required.

The construction procedure using the Top-down method was simulated in the following stages: (1) Stage 1: Install the diaphragm wall and apply the lateral building load; (2) Stage 2: Excavate until -2.6m; (3) Stage 3: Install the bored piles,

columns, and 1<sup>st</sup> concrete slab; (4) Stage 4: Lower the water table and excavate until -8m; (5) Stage 5: Install the 2<sup>nd</sup> concrete slab; (6) Stage 6: Lower the water table and excavate until -11.5m; (7) Stage 7: Install the 3<sup>rd</sup> concrete slab; (8) Stage 8: Lower the water table to -15.8m and excavate to the final depth; (9) Final stage: Install the last slab and apply the traffic load.

The construction procedure using the Semi-Top-down method was simulated in the following stages: (1) Stage 1: Instal the 1<sup>st</sup> diaphragm walls and apply the buildings loads; (2) Stage 2: Lower the water table, excavate until -4.5m, and install the 2<sup>nd</sup> diaphragm walls; (3) Stage 3: Lower the water table, excavate until -8.0m between the two diaphragm walls; (4) Stage 4: Lower the water table, excavate until -11.5m, and install the 3<sup>rd</sup> diaphragm walls; (5) Stage 5: Excavate until the final level, lower the water table at -15.8m, and start the floor's construction; (6) Stage 6: Construct the 3<sup>rd</sup> and 4<sup>th</sup> floor between the 3<sup>rd</sup> diaphragm walls; (7) Stage 7: Excavate until the final depth between the 2<sup>nd</sup> diaphragm walls; (8) Stage 8: Construct the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> floor between the 2<sup>nd</sup> diaphragm walls; (9) Stage 9: Construct the 1<sup>st</sup> floor between the diaphragm walls; Stage 10 to 14: Use the Bottom-down method for raising the floors between the 3<sup>rd</sup> diaphragm walls; (15) Stage 15: Raise the last slab and apply the traffic load.

### 3 Modelling results and discussions

The numerical model was set, and the loadings were applied to the model. Five cases of the soil's bulk modulus were applied to the numerical model to investigate the effects of soil stiffness on the underground structure's behaviour. The responses of the numerical model were collected. Some of the results are presented in the following sub-parts.

#### 3.1 Displacements of the underground parking structure

The horizontal displacements and the vertical displacements, which were called the settlement, of the underground parking model in every construction stage were collected. The displacement curves of the structure's model constructed by each method were sketched.

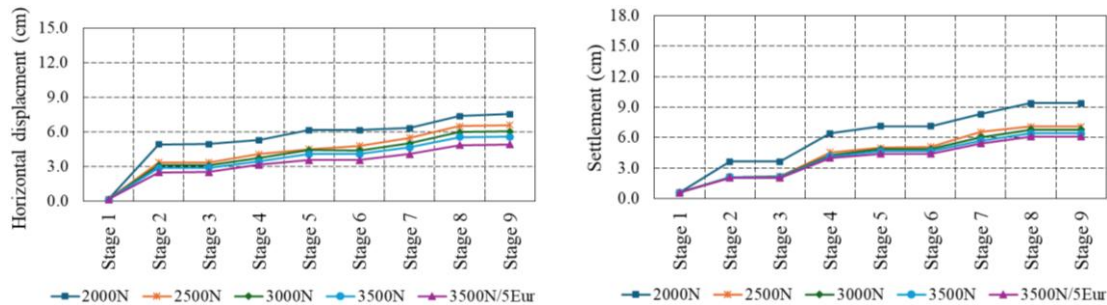


Fig. 4 – Displacements of the underground parking constructed by the Top-down method

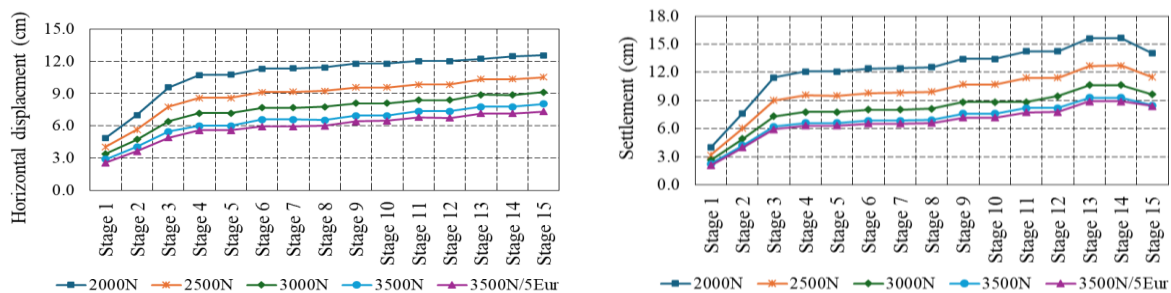


Fig. 5 – Displacements of the underground parking constructed by the Semi-Top-down method

In the Top-down method construction, the model's displacements were raised immediately from Stage 1 to Stage 2, then kept nearly horizontally from Stage 2 to Stage 3. From Stage 3 to Stage 9, the model's displacements continued to develop, but the increment was faster for settlements than for horizontal displacements. The soil stiffness significantly affected the model's deformation when the stiffer soil reduced the structure's displacement in both directions. The displacement gap between the smallest and the highest soil stiffness at Stage 9 (where the values were maximal in the construction procedure) was 2.6m in the horizontal direction and 3.3m in the vertical direction.

In the Semi-Top-down method construction, the model's displacements were elevated quickly from Stage 1 to Stage 4. From Stage 4 to Stage 8, the model's displacements continued to rise with the smaller slope. From Stage 8 to Stage 15, the horizontal displacements kept that variation rule while the settlements boosted more quickly. During the last four stages, the model's settlement showed a recovery trend when the values climbed and fell back. The soil stiffness had the same impact on the model's displacement as in the case of the Top-down method. The displacement gap between the smallest and the highest soil stiffness at the last stage was 5.2m in the horizontal direction and 5.6m in the vertical direction.

The overall geometrical appearances of all displacement curves by the two construction methods were similar. Since every curve consisted of multiple segments, its variation tendency was investigated through the non-linear regression analysis. The theoretical functions and their R-squared values of the numerical modelling data were found. The case results with  $\alpha = 2000$  are shown in the paper as the representative of the other cases.

**Table 6 – Theoretical function and its R-squared value of the displacement curves of the underground parking model with  $\alpha = 2000$**

| Displacement                | Top-down method                                                        | Semi-Top-down method                                                   |
|-----------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| Horizontal (m)              | $y = -0.005x^4 + 0.16x^3 - 1.62x^2 + 6.96x - 4.89$<br>( $R^2 = 0.96$ ) | $y = -0.001x^4 + 0.05x^3 - 0.72x^2 + 4.55x + 0.88$<br>( $R^2 = 0.99$ ) |
| Vertical<br>(Settlement, m) | $y = -0.002x^4 + 0.05x^3 - 0.57x^2 + 3.67x - 2.42$<br>( $R^2 = 0.98$ ) | $y = -0.004x^4 + 0.13x^3 - 1.63x^2 + 8.39x - 3.02$<br>( $R^2 = 0.98$ ) |

All the theoretical functions were polynomials of degree 4 that accurately represented the nonlinear variation tendencies of the displacement over all the construction stages. The high R-squared values ( $R^2 > 0.95$ ) indicated an excellent fit, so the theoretical curves were closely aligned with the numerical modelling data. The comparison of the model's displacements between the two construction methods was executed. The Semi-Top-down method showed larger initial horizontal displacements that stabilised later and exhibited a more pronounced settlement with a higher initial growth rate. Meanwhile, the Top-down method exhibited more consistent horizontal displacement throughout the construction procedure and achieved more gradual settlements, which might imply better stability for the parking structure during construction. This result proved the advantage of the Top-down method when the rigid underground structures take responsibility for the suppression of the structure movement during the construction [7]. The maximal settlements appeared in the last period of the underground construction by both methods. The recommendation of Eurocode 7 for the acceptable differential settlement of up to 1/500 of the building length was utilised [8]. The parking's length was 255m, so all settlements smaller than 51cm were considered normal. No vertical displacements of the Tran Hung Dao underground parking in the numerical modelling exceeded the limit.

### 3.2 Soil displacement from the diaphragm walls

The parking structure stayed in a dense urban place overcrowded by the surrounding buildings and traffic roads. Due to that fact, the soil displacements from the diaphragm walls in the model were studied. The evolutions of the soil displacements from the diaphragm wall in the horizontal and vertical directions by the two construction methods were investigated. The soil displacement curves by the Top-down and Semi-Top-down method is shown in Figures 6 and 7, respectively.

The overall geometrical appearance of the horizontal displacement curves was similar and in a convex shape. In both cases of the construction methods, the maximal horizontal displacement values were reached at the diaphragm wall and then gradually reduced when the distance from the wall increased. The maximal horizontal displacement varied between [-5.95; -8.62] (cm) in the Top-down method case and [-7.36; -12.27] (cm) in the Semi-Top-down method case. According to R. Frank *et al.* (2022), a horizontal displacement of around 0.2% to 0.5% of the height of concrete retaining

walls could be considered acceptable [9]. For the Tran Hung Dao underground parking, the wall was 30m-high with acceptable horizontal displacements of [-6; -15] (cm). The calculated maximal horizontal displacement values in the modelling were in this interval, which meant the normal working condition of the parking.

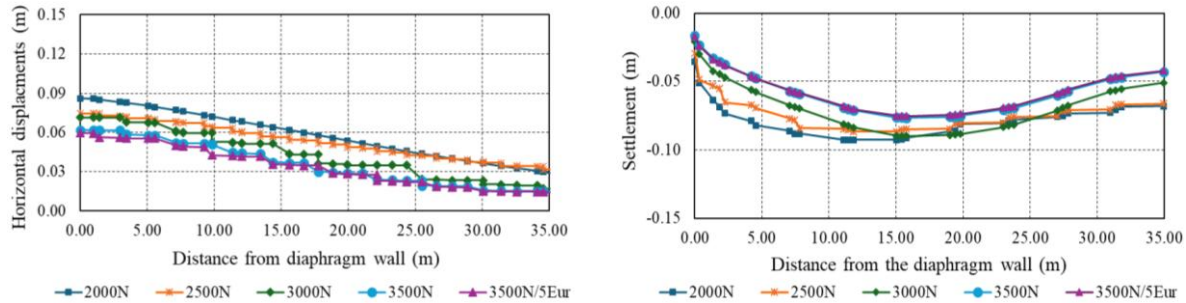


**Fig. 6 – Soil displacements from the diaphragm wall caused by the Top-down method**

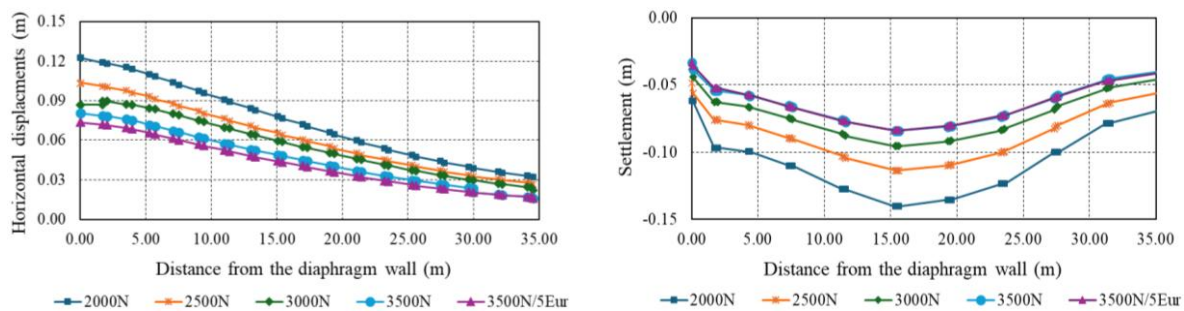


**Fig. 7 – Soil displacements from the diaphragm wall caused by the Semi-Top-down method**

The overall geometrical appearance of the settlement curves was alike and in a concave shape. In both cases of the construction methods, the maximal settlement values were reached at the location 15.35m from the diaphragm wall, which was the application location of the traffic loadings. It showed the evident influence of the loadings on the ground surface on the shallow underground structures. The maximal settlement oscillated between [-7.54; -9.27] (cm) in the Top-down method case and [-8.39; -14.03] (cm) in the Semi-Top-down method case. These high horizontal displacements and settlements could cause problems for the existing foundations and buildings near the underground parking. Moreover, it was noted that the parking is located in the old quarter where all the buildings are old and weaker than the new ones. A deeper analysis was recommended to evaluate the displacements of the old adjacent structures.

The impacts of the soil stiffness on the soil displacement from the diaphragm wall in two directions were similar. When the soil stiffness increased, the soil displacements reduced. This tendency led us to recommend the soil stabilisation and improvement solutions in the vicinity of the excavation, especially for the urban soft ground of Hanoi. The numerical results showed that the Semi-Top-down method created more significant displacements of the parking structure in the horizontal and vertical direction than the Top-down method. However, the Semi-Top-down method's curves were smoother without a gap in collation with the Top-down method's curves. It could be understood that the Semi-Top-down construction generated better soil displacement development without sudden changes than the Top-down construction.

### 3.3 Displacement of the diaphragm walls

To investigate the correlation between the concrete stiffness and the displacement of the diaphragm walls, three different values of the concrete elastic modulus of the diaphragm walls were used for the modelling. The displacements of the diaphragm walls in the numerical model were collected. The following table presents the diaphragm wall's total displacement results at Stage 9 of the Top-down method case as the representative.

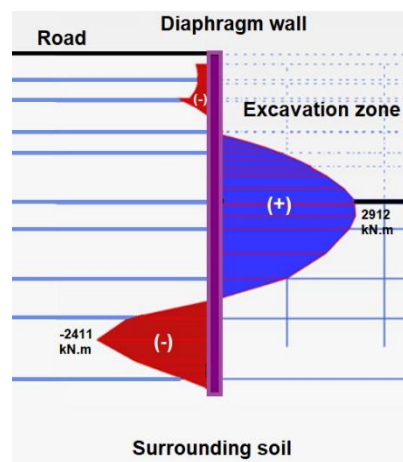
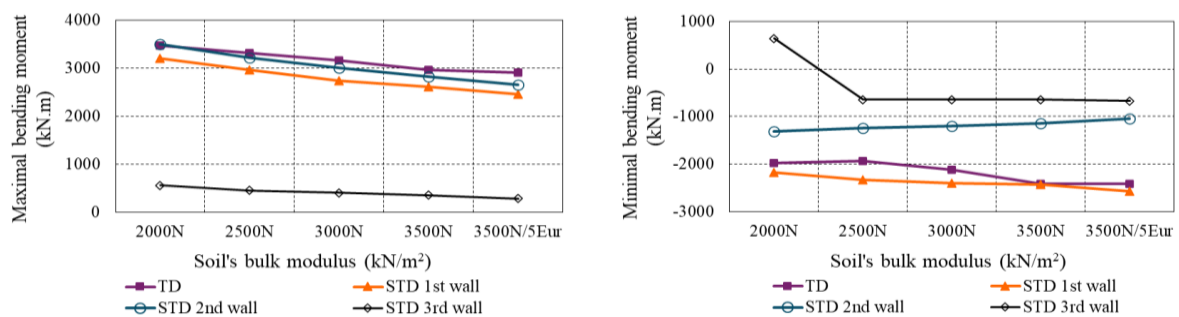
**Table 7 – Correlation between the concrete elastic modulus and the diaphragm wall's displacement at Stage 9 of the Top-down method case**

| Concrete elastic modulus (GPa)    | 30   | 40   | 50   |
|-----------------------------------|------|------|------|
| Diaphragm wall's displacement (m) | 8.89 | 8.56 | 7.59 |

The wall's total displacements were inversely proportional to the wall concrete's elastic modulus. With a normal-strength concrete ( $E = 30\text{GPa}$ ), the displacement was 8.89m. With the High-Strength Concrete ( $E = 40\text{GPa}$  and  $50\text{GPa}$ ), the wall's total displacement fell into 8.56m and 7.59m, respectively. Accordingly, the displacement reduction was 0.33m and 1.30m. The result could be understood as the proposition of the High-Strength Concrete utilisation for the diaphragm walls to diminish the structure's displacement.

### 3.4 Bending moments of the diaphragm walls

The evolution of the bending moments in the diaphragm walls of the underground parking was studied. Figure 8 presents the bending moment envelope of the diaphragm walls in the case of the maximal soil's bulk modulus. The bending moment reached the maximal value at the last basement floor at the level -15m. After that point, the bending moment decreased, returned to null at the level -25m and reached the minimum value at the level -29m. The bending moment signs indicated the diaphragm wall was divided into the compression and tension zones. It could be deduced that the wall's reinforcements should be positioned on the excavation side at the level from -9m to -25m and on the ground side for the rest of the wall's height.

**Fig. 8 – Bending moment envelop of the diaphragm walls in the case of the maximal soil's bulk modulus****Fig. 9 – Extreme values of the bending moments in the diaphragm walls**

The bending moments of diaphragm walls were collected and analysed in five cases of soil stiffness. The extreme values of the bending moments in the diaphragm walls of the parking structure constructed by the Top-down method and the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> diaphragm walls of the underground parking structure constructed by the Semi-Top-down method were

plotted. The abbreviation “TD” was used for “Top-down method” and “STD” for “Semi-Top-down method”. They are presented in Figure 9.

The impact of the soil stiffness on the maximal bending moments of the diaphragm walls in all construction cases was evident since the moments were reduced when the soil’s bulk modulus increased. No clear and reasonable relationship between the two quantities could be discovered for the minimal bending moments. It was found that the inversely proportional relationship between the soil’s bulk modulus and the bending moment on the excavation side of the diaphragm walls and the proportional relationship between the soil’s bulk modulus and the bending moment on the groundside of the diaphragm walls. This observation resulted from the soil pushing less on the diaphragm wall due to its higher compacity. The Semi-Top-down method with smaller bending moment values was more advantageous than the Top-down method. Among the three diaphragm walls, the 3<sup>rd</sup> had minuscule extreme bending moments. It could be a starting point for choosing the smaller dimensions for this diaphragm wall compared to the two other walls.

## 4 Conclusions

The paper studied the numerical modelling of the 4-floor underground parking excavated in the multi-layered ground at the Tran Hung Dao station of the Hanoi urban metro network in downtown Hanoi (Vietnam). The behaviour of the parking structure, the diaphragm walls and the surrounding soil in the numerical model was investigated. The numerical model of the Tran Hung Dao underground parking was in normal condition since no dangerous displacements were found, referring to the recommendations from Eurocode 7 [8] and R. Frank *et al* [9]. The obvious impact of the soil stiffness on the underground parking structure was found: the parking structure’s displacements, the surrounding soil (in the horizontal and vertical direction) and the bending moments in the diaphragm walls were inversely proportional to the soil’s bulk modulus. Hence, soil improvement and stabilisation for underground tunnelling in urban soft ground areas were recommended. It could augment the safeness of the construction and the operation of the underground structures by weakening the displacement of the ground and the structures. The influence of the concrete elastic modulus on the diaphragm wall’s displacement was also captured by an inverse proportion. Replacing the normal-strength concrete with High-Strength Concrete could significantly reduce the diaphragm wall’s displacement. The use of High-Strength Concrete for the diaphragm wall and the other components of the underground parking was proposed. The responses of the numerical model and the surrounding soil were investigated by comparing the Top-down and Semi-Top-down construction methods. The first method created fewer displacements in the two directions, which could be understood as better stability for the parking structure during the construction. The results proved the advantage of the Top-down method, which was the smaller movements of the underground structure and surrounding ground thanks to the stronger supporting structures in collation with the Semi-Top-down method. However, the second method caused smoother soil displacement evolution. It generated lower internal forces in the parking structure, which could lead to a slighter structure configuration. The research was hoped to enrich the knowledge on the construction of shallow social infrastructures in soft soil by comparing the Top-down and Semi-Top-down methods. It was also dedicated to preparing knowledge for the solid and reliable underground facilities in Hanoi (Vietnam).

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