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# Evaluation of Behavior of a Deep Excavation by Three-dimensional Numerical Modeling

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**Abstract**

To stabilize the urban deep excavations, soil anchoring is one of the methods that are very common for geotechnical engineers. Most of the previous studies have used a simplified the complex interaction and often they have overlooked the effects of three-dimensional (3D) modeling. In this study, the results of 11 3D finite element (FE) analysis of a deep excavation which supported with tie-back wall are presents. For this purpose, Firstly, the Texas A&M excavation which supported by two rows of ground anchors, soldier pile and wood lagging was modeled and secondly the results obtained from 3D numerical modeling have been compared with those obtained from measured data and the results of previous study. Then, the effect of ground anchors arrangement on the excavation behavior including horizontal displacement of the wall ($\delta_h$) and surface settlement ($\delta_v$) and their maximum values have been investigated. The results showed that a change in the value of $SV_1$ does not have a significant effect on the value of maximum horizontal displacement of the wall ($\delta_{hm}$). The value of $SV_1$ has a significant effect on the value of $\delta_v$ and by increasing its value from 1.5 m to 2.5 m; the heave created at edge of the wall disappears and at $d \geq -1$ m surface settlement created. When $D_e$ = 16 m, a variation in ground anchors arrangement significantly affected the values of maximum surface settlement ($\delta_{vm}$) as compared to $\delta_{hm}$. The results presented in this study can be helpful for designers without experience and information of previous designs.

**Keywords**

deep excavation, tie-back wall, ground anchor, 3D finite-element analysis, horizontal displacement of the wall, surface settlement

## 1 Introduction

In recent years, based on the development of urban areas and limitation of ground in urban comprehensive plan and the necessity of underground spaces, excavation in urban areas is very important. According to providing the stability of excavations especially with considering to the load from adjacent structures, geotechnical engineering's are faced with the challenge to use the retaining structures. One of the methods which are very common for urban deep excavations is tie-back wall. In this method, the excavation process is stage construction and performed from top to down. After reaching the desired level, the strands are placed inside the boreholes located in the excavation wall and the bonded length is filled with slurry and then pre-stress force were applied to ground anchors. The pre-stress force makes the soil more compacted and then the shear strength of the soil increase and displacements around the excavation decrease. The design of tie-back wall is a very wide subject and some assumption have to be made and the performance of it is significantly affected due to the complex mutual interaction between its main components such as the native soil, the unbonded and bonded length of ground anchors, the retaining structure (sheet piles, soldier piles and lagging walls and concrete diaphragm or slurry walls) and the facing.

To control and limit the wall deflections and ground surface settlements caused by deep excavations, a number of numerical studies have been performed in the past research [1–23]. Some researchers by conducting 3D analysis found that movements caused by excavation reduced near the corners of the excavation (Bono et al. [24], Wong and Parton [25], Chew et al. [26], Finno and Bryson [27], Finno and Roboski [28]). Finno and Roboski [28] proposed

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parallel distributions of settlement and lateral ground movement for deep excavations in soft to medium clays. Also, they found that by using the complementary error function, just geometry and maximum movement parameters are necessary for defining the parallel distributions of ground movement. In the previous studies, several works have been reported the performance of tie-back wall in deep excavations. Most of these studies are based on analytical and numerical modeling (Clough et al. [29], Simpson et al. [30], Matos Fernandes and Falcao [31], Caliendo et al. [32], Mosher and Knowles [33], Briaud and Lim [34], Dawkins et al. [35], Abraham [36], Orazalin [37], Tabaroei et al. [38]). Caliendo et al. [32] studied on performance of the soldier pile tie-back and founded that after the final level of the excavation, the maximum deformation of the wall occurred at approximately two-thirds of the length down the wall. Mosher and Knowles [33] studied on the 15.24 m high temporary tie-back reinforced concrete diaphragm wall by finite element analysis (FEA) and showed that the relative value of the hyperbolic soil stiffness modulus in an influential parameter in the FE results. Briaud and Lim [34] founded that the location of the tendon bonded length only had a small effect on the bending moment and axial load in the soldier piles as long as the beginning of the tendon bonded zone is outside the failure wedge.

The limitations of two-dimensional (2D) numerical modeling in some parts of excavation walls indicate the importance of 3D numerical modeling of the excavation problem. With 3D numerical modeling, we can predict the value of $\delta_h$ and $\delta_v$ in accordance with the actual conditions at the project site. For this purpose, this study focused on 3D analysis of a deep excavation which supported with tie-back wall. The effects of different values vertical distance of ground anchors relative with each other on excavation response were evaluated.

## 2 Case study and 3D numerical model

### 2.1 Texas A&M excavation case study

The Texas A&M full scale model wall was constructed and tested as a four-part research that focused on the improved design of permanent ground anchor walls for highway applications (Abraham [36], Weatherby et al. [39]). A test section wall contained sections which supported by one row and two rows of ground anchors, respectively (Briaud and Lim [34], Abraham [36], Weatherby et al. [39]). In addition, the length and height of the wall were 60 m and 7.5 m, respectively and built by driving H piles in a line on 2.4 m center for one part of the wall and by drilling and grouting H piles in a line on 2.4 m center for the other part of the wall (Briaud and Lim [34], Abraham [36], Weatherby et al. [39]). The cross section of two levels of tie-back wall

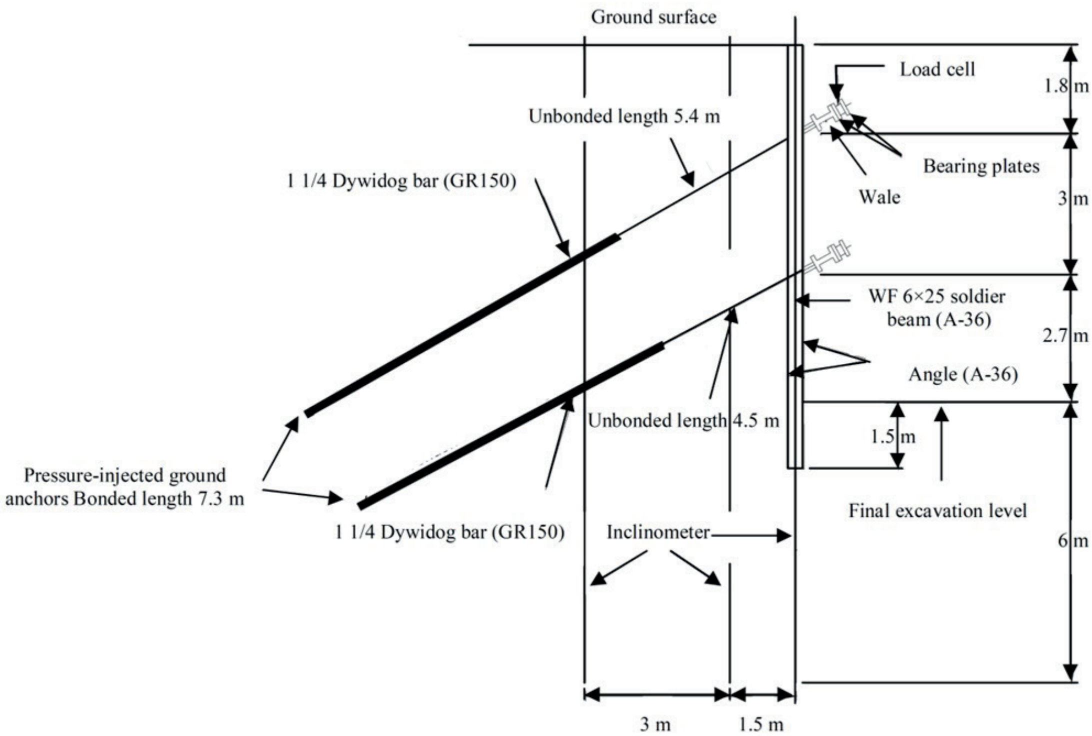


**Fig. 1** Section of two levels of tie-back wall of the Texas A&M University excavation (Abraham [36])

of the Texas A&M excavation is shown in Fig. 1. In this project, the ground anchors were high pressure type and inclined 30° relative to the horizontal direction and located at 1.8 and 4.8 m below the top of the wall (Briaud and Lim [34]). For supporting the soil between soldier beams the wood lagging were used. The length, height and thickness of the wood lagging boards were 2.4 m, 0.3 m, and 75 mm, respectively. More detail of the Texas A&M full scale excavation reported by in the literature (Briaud and Lim [34], Abraham [36], Weatherby et al. [39]). In order to simulate of 3D numerical model of this study, the two levels of tie-back wall of the Texas A&M excavation are used.

### 2.2 3D numerical model

To consider the real conditions of the excavation, 3D numerical modeling has been used. The FE program PLAXIS 3D was used in the analysis of this study. This software is a FE package specially developed for analysis of deformation and stability in different geotechnical engineering problems. In order to model a tie-back wall of the Texas A&M excavation, this software is capable to model the soil, the unbonded and bonded length of ground anchors, soldier beams, wood lagging, wale and especially the SSI interaction. The dimensions of the 3D numerical model were considered based on Abraham [36] study.

FE calculations steps in PLAXIS 3D are according to the construction activities of two levels of tie-back wall at Texas A&M excavation. In 3D analysis of this study, the hardening soil (HS) model is used to simulate the behavior of the soil. The HS model can predict the values of wall displacement and surface settlement very well, in excavation problems. The soil layers and soil parameters used in the numerical modeling are illustrated in Table 1. These parameters were taken from Abraham [36] study.

In order to model soldier beam and wood lagging in numerical modeling, plate element is used. Plates are composed of six nodes triangular plate elements with three translational degrees of freedom and thee-rotational degree of freedom per node. Wales were simulated by beam element. The beam elements are three node line elements with three translational degrees of freedom and three rotational degrees of freedom per node. The interaction between soldier beam and wood lagging with surrounding soil elements were simulated by interface element. In PLAXIS 3D, ground anchors were simulated by means of a node-to-node anchor and an embedded beam elements. An embedded beam element consists of beam elements with special interface elements providing the interaction between the beam and the surrounding soil. In Fig. 2, 3D FE model of two levels of tie-back wall at Texas A&M excavation and elements used in numerical modeling is displayed. In this model, the number of elements (ten-node triangular) and nodes are 24473 and 39468, respectively.

**Table 1** Soil parameters used in 3D FEA (Abraham [36])

| Parameter | Symbol | Unit | Value | | | |
|---|---|---|---|---|---|---|
| | | | Layer 1 Silty sand | Layer 2 Medium dense sand | Layer 3 Clayey sand | Layer 4 Hard clay |
| Unit weight | $\gamma$ | kN/m³ | 18 | 18 | 19.6 | 20.5 |
| Elasticity modules | $E_{50}^{ref}$ | kPa | 35000 | 15000 | 15000 | 49250 |
| | $E_{oed}^{ref}$ | | 35000 | 15000 | 15000 | 49250 |
| | $E_{ur}^{ref}$ | | 105000 | 45000 | 45000 | 147750 |
| Cohesion | $c$ | kPa | 0 | 0 | 0.5 | 500 |
| Friction angle | $\varphi$ | ° | 32 | 32 | 32 | 30 |
| Power for stress level dependency of stiffness | $m$ | - | 0.8 | 0.8 | 0.8 | 0.8 |
| Poisson ratio | $\nu$ | - | 0.2 | 0.2 | 0.2 | 0.2 |
| Failure ratio | $R_f$ | - | 0.7 | 0.7 | 0.7 | 0.7 |
| Interface reduction factor | $R_{int}$ | - | 0.9 | 0.9 | 0.9 | 0.9 |

### 3 Validation of numerical modeling results

In this study the results obtained from numerical modeling have been compared and validated with those from measured data and the results of Briaud and Lim [34] study. A comparison between the results obtained from this study and measured data and the results of Briaud and Lim [34] at final stage of excavation shows in Fig. 3. This figure indicates that the results obtained from the Briaud and Lim [34] study and this study are greater than the measured data. As the distance from the depth to the ground level increases, the value of deflection of the wall increases and the wall tends to behave in cantilever shape. The lower part of the wall ($z = -9.16$ m) tends to have an initial small displacement to towards inside of the excavation zone, which, the values of deflection from measured data, Briaud and Lim [34] study and this study are 3.40 mm, 10.50 mm, and 5.97 mm, respectively. As illustrate in Fig. 3, the results of this study are largely consistent with the results obtained from Briaud and Lim [34] study, so that the deflection values obtained at the excavation edge for current study and Briaud and Lim [34] study are 36.88 mm and 34.80 mm,

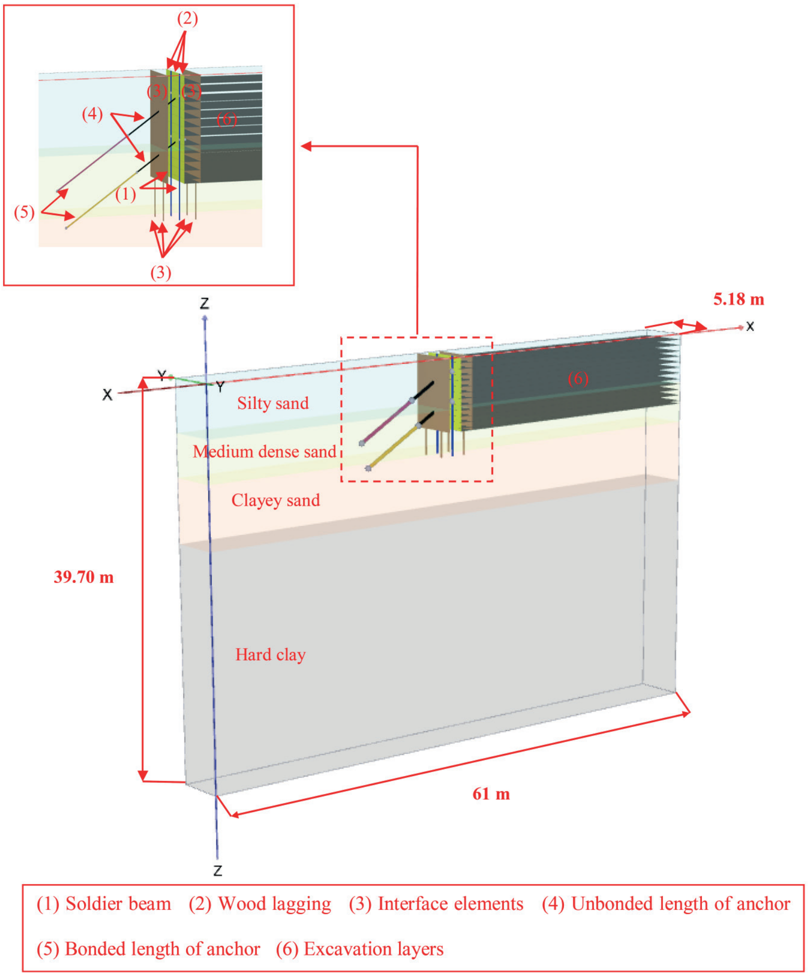


**Fig. 2** 3D FE model of two levels of tie-back wall at the Texas A&M excavation and elements used in numerical modeling

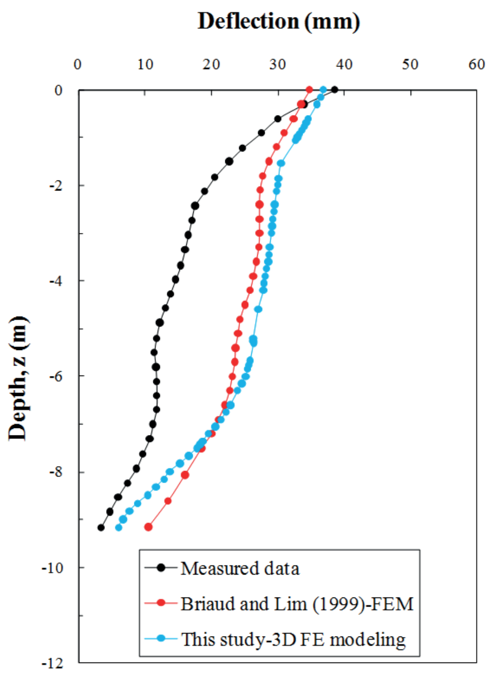


**Fig. 3** Comparison between the results obtained from this study and those obtained from measured data and the results of Briaud and Lim [34] study

respectively, which indicates an acceptable difference of 5.90%. By comparing the results obtained from current study and the results of Briaud and Lim [34] study and measured data, it can be seen that there is a good agreement exists between the results.

## 4 Numerical results and discussion

In order to study the response of tie-back wall in deep excavations, a total of 11 3D FE analysis were performed. The parameter used in the parametric study is ground anchors arrangement. In order to evaluate the behavior of the wall during excavation, geotechnical engineers usually control horizontal displacement of the wall and surface settlement. For this goal, in this study result of 3D FE analysis in terms of the horizontal displacement profiles of the wall and the ground surface settlement profiles are presented. In Fig. 4, the detail of the variable parameter and notations used in 3D FE modeling is illustrated. As it exhibited in Fig. 4, in all analysis the values of excavation depth ($D_e$) and number of ground anchors were kept constant 16 m and five,

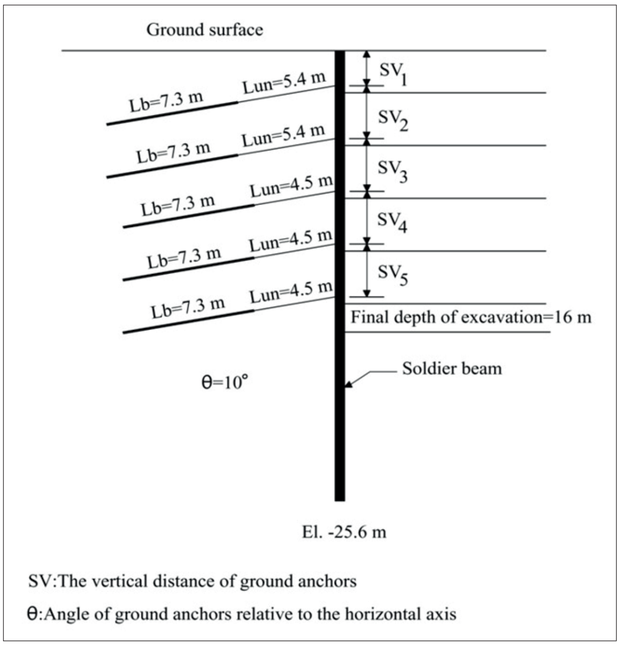


**Fig. 4** Parameter and notations used in 3D FE analysis

respectively. The detail of the numerical models and different types of ground anchors arrangement used in parametric study are shown in Table 2. As illustrate in Table 2, the vertical distance of ground anchors ($SV_1$, $SV_2$, $SV_3$, $SV_4$ and $SV_5$) was considered variable. In all of 3D analysis the depth of the model and the distance of lateral boundaries of the model from the wall were considered to be 4 $D_e$ and 6.7 $D_e$, respectively, which these values suggested by Shi et al. [40], [41–54]. Also, the width of the excavation was assumed to be 30.5 m. The soil parameters were those values that presented in Table 1. The effect of the vertical distance of ground anchors on performance of the excavation and interpretation of the results obtained from 3D FE analysis are presented in the later sections. Different 3D numerical models (numbers 1 to 11) which simulated in PLAXIS 3D, displays in Fig. 5. It should be noted that model number 2 is the base model and the values $\delta_h$, $\delta_v$, $\delta_{hm}$ and $\delta_{vm}$ of other models have been compared with this model.

### 4.1 Effect of ground anchors arrangement on $\delta_h$ and $\delta_{hm}$

In the parametric study, after determining the variable parameter (for example $SV_1$ or $SV_2$ or $SV_3$ or $SV_4$ or $SV_5$), the vertical distance of other anchors were considered 3 m to investigate the effect of this parameter on performance of excavation. The results of the horizontal displacement profiles of the wall for different values of ground anchors arrangement are displayed in Fig. 6. As seen in Figs. 6(a) to 6(e), the horizontal displacement profile of the wall is convex shape for all models. In addition, the value of $\delta_{hm}$ occurs

**Table 2** The detail of the numerical models and different types of ground anchors arrangement used in parametric study

| Model No. | Depth of each ground anchor below the ground surface (m) | | | | |
|---|---|---|---|---|---|
| | First anchor | Second anchor | Third anchor | Fourth anchor | Fifth anchor |
| 1 | 1.5 | 4.5 | 7.5 | 10.5 | 13.5 |
| 2 | 2 | 5 | 8 | 11 | 14 |
| 3 | 2.5 | 5.5 | 8.5 | 11.5 | 14.5 |
| 4 | 2 | 4.5 | 7.5 | 10.5 | 13.5 |
| 5 | 2 | 5.5 | 8.5 | 11.5 | 14.5 |
| 6 | 2 | 5 | 7.5 | 10.5 | 13.5 |
| 7 | 2 | 5 | 8.5 | 11.5 | 14.5 |
| 8 | 2 | 5 | 8 | 10.5 | 13.5 |
| 9 | 2 | 5 | 8 | 11.5 | 14.5 |
| 10 | 2 | 5 | 8 | 11 | 13.5 |
| 11 | 2 | 5 | 8 | 11 | 14.5 |

at a depth of 10 m below the ground surface. To study the effect of $SV_1$ on the horizontal displacement profiles of the wall, three 3D analysis have been performed. In these analyses, the value of $SV_1$ is 1.5 m, 2 m, and 2.5 m, respectively.

As illustrate in Fig. 6(a), the value of horizontal displacement at upper part of the wall ($z > –5$ m) is highly sensitive to the value of $SV_1$, so that at $z \approx –3$ m, the value of $\delta_h$ increases from 45.9 mm to 54.8 mm by an increase in the value of $SV_1$ from 1.5 m to 2.5 m. In other words, by increasing the value of $SV_1$, the upper part of the wall tends to behave in cantilever shape. In contrast to the results related to $SV_1$ effect (Fig. 6(a)), the results presented in Fig. 6(b) indicated that by an increase in the value of $SV_2$ (from 2.5 m to 3.5 m), the horizontal displacement of the upper part of the wall is not in cantilever shape. As the values of $SV_3$ (models No. 6, 2 and 7) and $SV_4$ (models No. 8, 2 and 9) increase, the value of $\delta_h$ increases significantly.

The effect of different value of ground anchors arrangement on $\delta_{hm}$ variations is illustrated in Fig. 7. The results of the 3D analysis showed that the value of $\delta_{hm}$ under the different ground anchors arrangement was varied between 73 mm and 91.4 mm. A change in the value of $SV_1$ does not have a significant effect on the value of $\delta_{hm}$ (see the first three red columns on the left side of Fig. 7). With an increase in the value of $SV_2$ from 2.5 m to 3.5 m, value of $\delta_{hm}$ increases from 78.7 mm to 82.1 mm. But by an increase in the value of $SV_5$ from 2.5 m to 3.5 m, variation in the value of $\delta_{hm}$ was more dramatic (75.5 mm for $SV_5 = –13.5$ m to 87.5 mm for $SV_5 = –14.5$ m).

The results of the analysis clearly showed that under different value of ground anchors arrangement, models number 8 and 9 have the minimum and maximum value

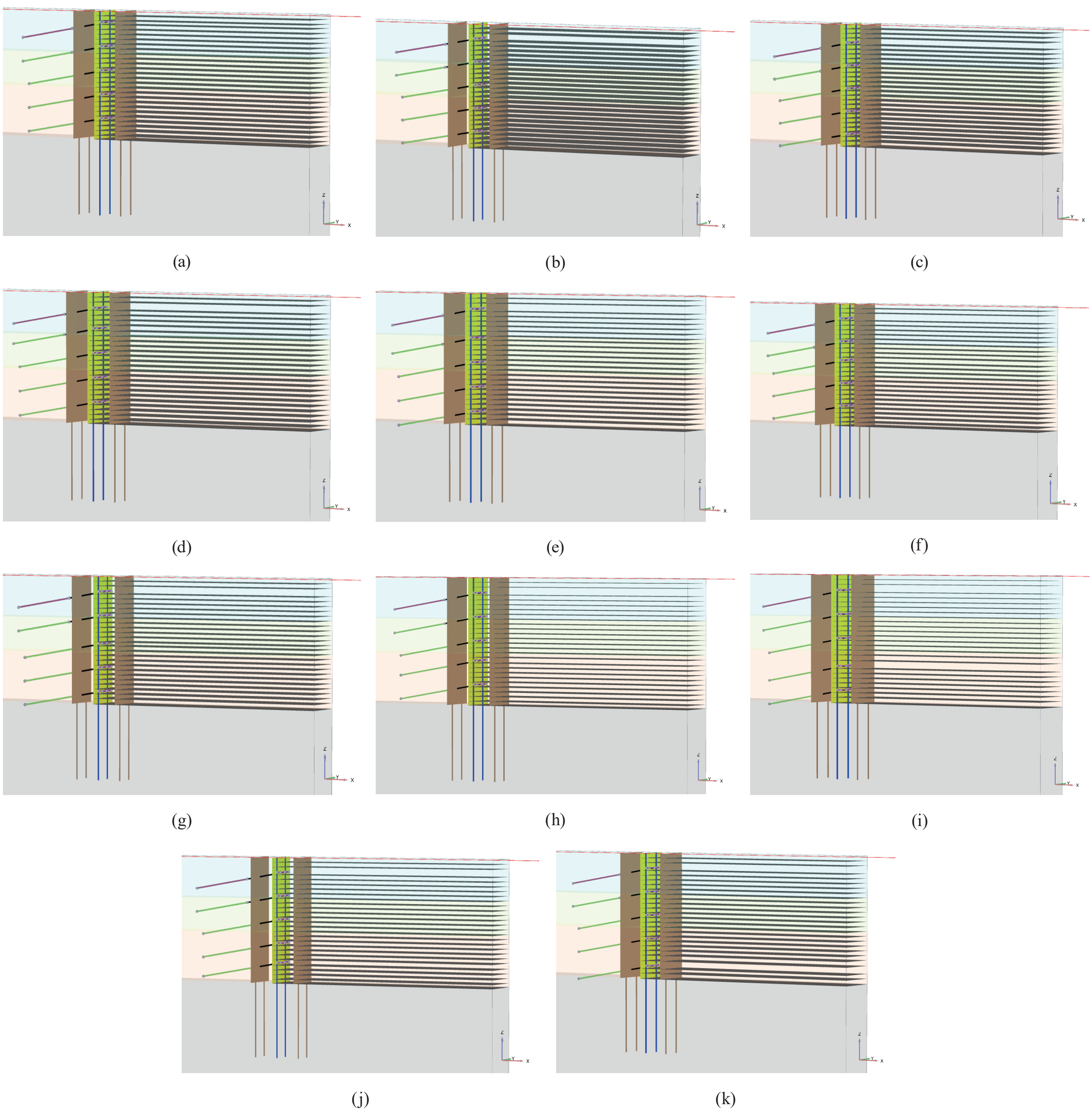


**Fig. 5** Different 3D numerical models which simulated in PLAXIS 3D: (a) Model 1 (anchors position: -1.5 m. -4.5 m, -7.5 m, -10.5 m and -13.5 m), (b) Model 2 (anchors position: -2 m. -5 m, -8 m, -11 m and -14 m), (c) Model 3 (anchors position: -2.5 m. -5.5 m, -8.5 m, -11.5 m and -14.5 m), (d) Model 4 (anchors position: -2 m. -4.5 m, -7.5 m, -10.5 m and -13.5 m), (e) Model 5 (anchors position: -2 m. -5.5 m, -8.5 m, -11.5 m and -14.5 m), (f) Model 6 (anchors position: -2 m. -5 m, -7.5 m, -10.5 m and -13.5 m), (g) Model 7 (anchors position: -2 m. -5 m, -8.5 m, -11.5 m and -14.5 m), (h) Model 8 (anchors position: -2 m. -5 m, -8 m, -10.5 m and -13.5 m), (i) Model 9 (anchors position: -2 m. -5 m, -8 m, -11.5 m and -14.5 m), (j) Model 10 (anchors position: -2 m. -5 m, -8 m, -11 m and -13.5 m), (k) Model 11 (anchors position: -2 m. -5 m, -8 m, -11 m and -14.5 m)

of $\delta_{hm}$, respectively. In model number 8 the first, second, third, fourth and fifth row of anchors are located at 0.12, 0.31, 0.50, 0.65 and 0.84 of $D_e$ below the ground surface, respectively. However, in model number 9 the first, second, third, fourth and fifth row of anchors are located at 0.12, 0.31, 0.50, 0.71 and 0.90 of $D_e$ below the ground surface, respectively. In other words, the results of 3D analysis showed that when the vertical distance between the third and fourth rows of anchors ($SV_4$) was small, the lower value of $\delta_{hm}$ is reached. It can be stated that when $D_e$ = 16 m, the ground anchor located at 1/3 lower part of $D_e$, plays an essential role in reducing or increasing the value of $\delta_{hm}$.

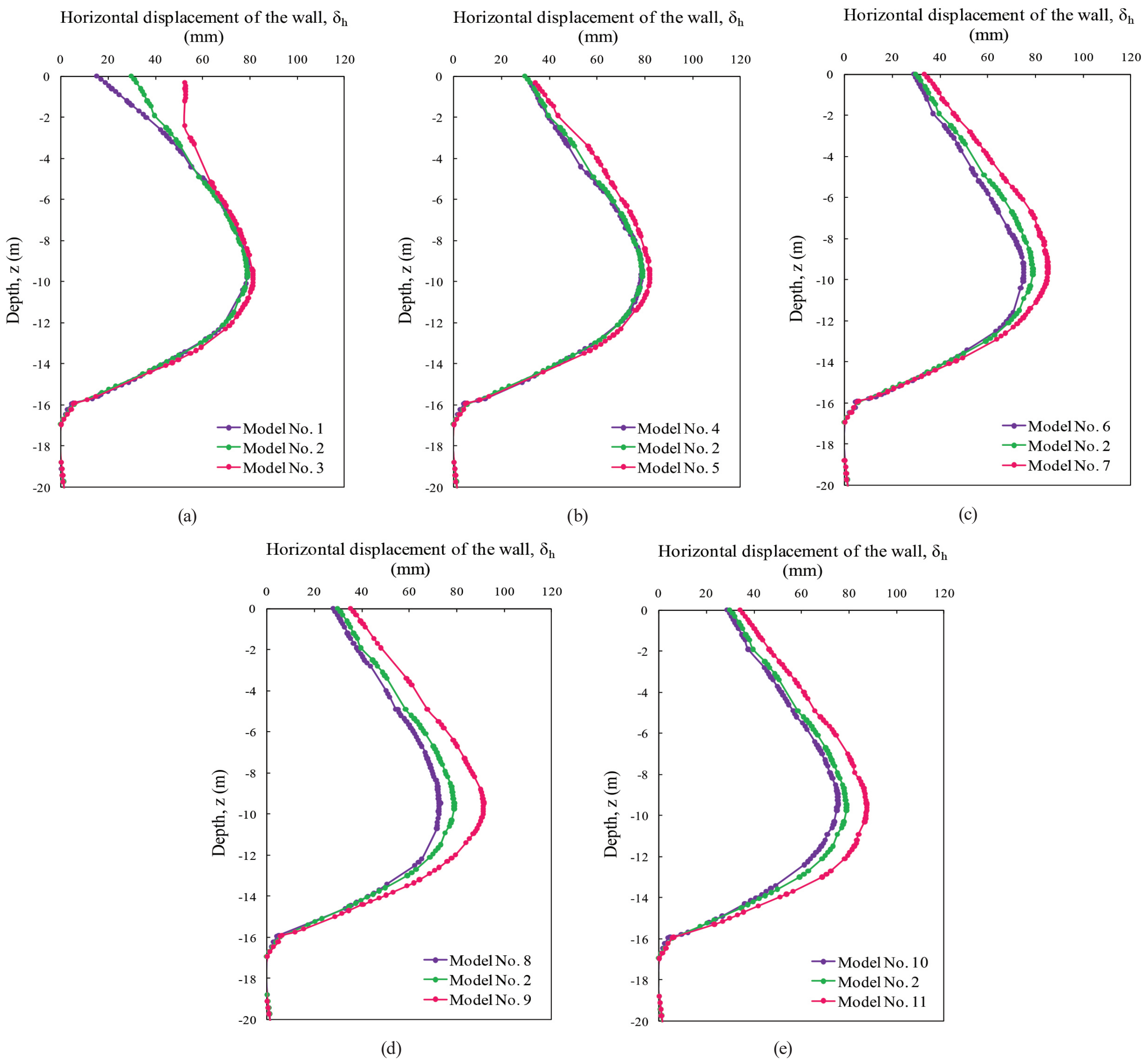


**Fig. 6** Effect of different values of ground anchors arrangement on the horizontal displacement profiles of the wall, (a) Models No. 1 to 3, (b) Models No. 4 and 5, (c) Models No. 6 and 7, (d) Models No. 8 and 9, (e) Models No. 10 and 11

## 4.2 Effect of ground anchors arrangement on $\delta_v$ and $\delta_{vm}$

In Fig. 8, the results of the surface settlement profiles for different values of ground anchors arrangement are presented. As observed in this figure, the selected influence area of the settlement which considered in numerical analysis is correct (6.7 $D_e$) and for the value of $d \leq -43.7$ m, the value of $\delta_v$ is insignificant. As seen, for all models the surface settlement curves are concave type and the value of $\delta_{vm}$ occurs at $d$ = 12.6 m. As the vertical distance of anchors increases ($SV_1$ to $SV_5$), the value of $\delta_v$ increase, which by increasing the vertical distance of anchors from 2 m to 2.5 m (for $SV_1$) and 3 m to 3.5 m (for $SV_2$ to $SV_5$) this

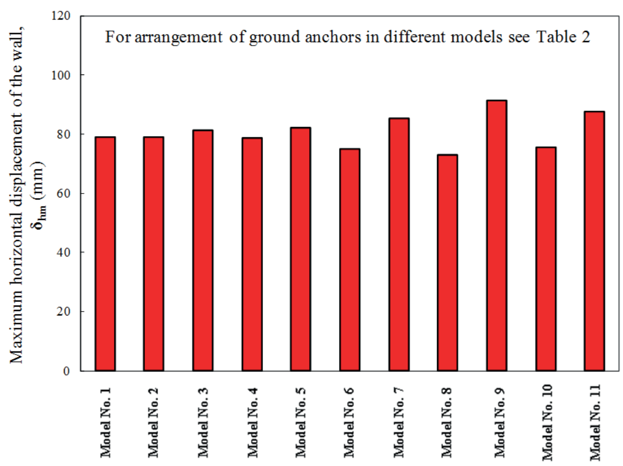


**Fig. 7** Effect different value of ground anchors arrangement on $\delta_{hm}$ variations

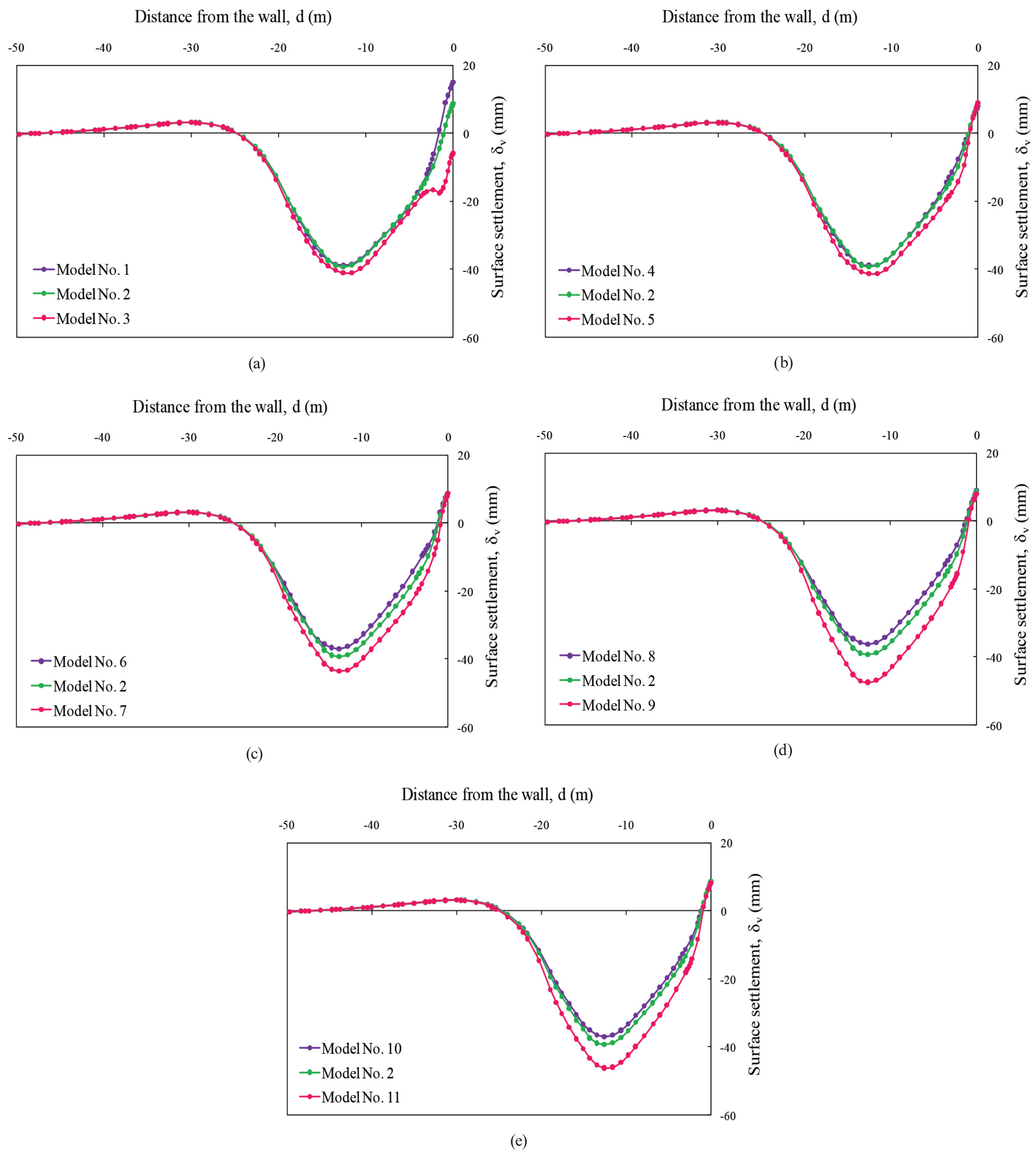


**Fig. 8** Effect of different values of ground anchors arrangement on the surface settlement profiles, (a) Models No. 1 to 3, (b) Models No. 4 and 5, (c) Models No. 6 and 7, (d) Models No. 8 and 9, (e) Models No. 10 and 11

increasing rate is more evident. At $-44.7$ m $\leq$ d $\leq -25.4$ m, a little heave occurs at the soil located at this area which its value is less than 5 mm for all models.

From Fig. 8, it clearly observed that a little heave occurs at the soil located at the edge of the wall which its value for model No. 1, i.e., the model in which the anchors are located at 0.09, 0.28, 0.46, 0.65 and 0.84 of $D_e$ below the ground surface is more than other models ($\delta_v = 15.1$ mm). The value of $SV_1$ has a significant effect on the value of $\delta_v$ and by increasing its value from 1.5 m to 2.5 m; the heave created at edge of the wall disappears and at $d \geq -1$ m surface settlement created.

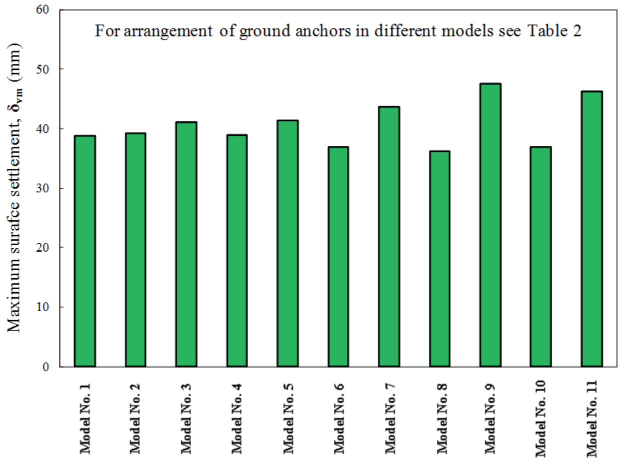


**Fig. 9** Effect different value of ground anchors arrangement on δvm variations

The effect of different value of ground anchors arrangement on $\delta_{vm}$ variations is shown in Fig. 9. The results indicated that the value of $\delta_{vm}$ under the different ground anchors arrangement was varied between 36.1 mm and 47.4 mm. Similar to the results obtained from $\delta_{vm}$ variations, models number 8 and 9 have the minimum and maximum value of $\delta_{vm}$, respectively. In model number 8 the first, second, third, fourth and fifth row of anchors are located at 0.12, 0.31, 0.50, 0.65 and 0.84 of $D_e$ below the ground surface, respectively. However, in model number 9 the first, second, third, fourth and fifth row of anchors are located at 0.12, 0.31, 0.50, 0.71 and 0.90 of $D_e$ below the ground surface, respectively. By comparing the results obtained from Figs. 7 and 9, it can conclude that when $D_e$ = 16 m, a variation in ground anchors arrangement significantly affected the values of $\delta_{vm}$.

## 5 Conclusions

In this study, the results of 11 3D FE analysis presents. To validate the 3D numerical model results, the results obtained from numerical modeling have been compared with those obtained from measured data and the results of Briaud and Lim [34] study. Based on the results obtained from 3D numerical modeling, the following conclusions are derived:

- By comparing the results of 3D numerical modeling with those obtained from measured data and the results of Briaud and Lim [34] study, it can be stated that 3D FE model used in this study can predict the response of a deep excavation very well.
- The value of horizontal displacement at upper part of the wall ($z > -5$ m) is highly sensitive to the value of $SV_1$.
- By an increase in the value of $SV_2$ (from 2.5 m to 3.5 m), the horizontal displacement of the upper part of the wall is not in cantilever shape.
- A change in the value of $SV_1$ does not have a significant effect on the value of $\delta_{hm}$. But by an increase in the value of $SV_5$ from 2.5 m to 3.5 m, variation in the value of $\delta_{hm}$ was more dramatic.
- When the vertical distance between the third and fourth rows of anchors ($SV_4$) was small, the lower value of $\delta_{hm}$ is reached. It can be stated that when $D_e$ = 16 m, the ground anchor located at 1/3 lower part of $D_e$, plays an important role in reducing or increasing the value of $\delta_{hm}$.
- The selected influence area of the settlement which considered in numerical analysis is correct and for the value of $d \leq -43.7$ m, the value of $\delta_v$ is insignificant.
- The surface settlement curves for all models are concave type and the value of $\delta_{vm}$ occurs at $d$ = 12.6 m. As the vertical distance of anchors increases ($SV_1$ to $SV_5$), the value of $\delta_v$ increase, which by increasing the vertical distance of anchors from 2 m to 2.5 m (for $SV_1$) and 3 m to 3.5 m (for $SV_2$ to $SV_5$) this increasing rate is more evident.
- The value of $SV_1$ has a significant effect on the value of $\delta_v$ and by increasing its value from 1.5 m to 2.5 m; the heave created at edge of the wall disappears and at $d \geq -1$ m surface settlement created.
- When $D_e$ = 16 m, a variation in ground anchors arrangement significantly affected the values of $\delta_{vm}$ as compared to $\delta_{hm}$.

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