International Journal of Civil and Structural Engineering – IJCSE
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Volume 6 : Issue 2 - [ISSN : 2372-3971] - Publication Date: 27 Dec, 2019

# 2D Numerical Analysis of Deformations in diaphragm wall supported by horizontal struts

Imtiaz, H[1]., Naseer , S*[2]., Khan, Z[3]., Mahmood, H [4].

*Abstract*—**Deep excavations are becoming quite common in urban areas due to limited spaces and construction of multi-story buildings, burrows and underground storage spaces. Such excavations require special consideration due to the nearby constructions and structures. Construction work requires ground excavation with vertical cuts. The faces of the cuts need to be protected by short-term bracing mechanism to lessen the excavation area, maintain excavation stability, and to certify that movements will not cause damage to neighboring structures or to utilities in the surrounding ground. Besides, excavation support is an issue of extraordinary significance to construction safety due to the threats to life posed by earth collapse, in addition to their major influence on profitability, speed, and quality of construction projects. Due to the excavation, lateral movement of soil will occur which results in failure of neighboring structures. This paper specifically focusses on the application of struts as a support system for the deep excavations. Finite element modelling was performed using PLAXIS 2D to determine the stresses and displacements caused during excavations. Elasto-plastic beam element was used to perform the finite element analysis.**

*Keywords*—**Deep Excavation, underground construction, finite element modeling, struts, Elasto-plastic beam element**

## I. Introduction

An excavation is a man-made cut, cavity or depression in the earth’s surface formed by the removal of earth [1]. Urban growth due to industrialization, population growth and rural-urban migration has increased the demand for space in towns, cities and other centers of urbanization. The increased demand for space has led to the need to create high structures with deep foundations for positioning cars, electrical and plumbing services in the basements of these structures [2]. This has therefore resulted in the need to carry out deep excavations.

Peck [3] investigated the horizontal movement of soldier piles and concluded that when excavation is carried out, horizontal movement takes place below the lowest strut. The magnitude of the movement solely depends upon the type of soil and excavation depth.

[1] Haroon Imtiaz
Capital University of Science and Technology, Islamabad Pakistan

[2] Sohaib Naseer*
Capital University of Science and Technology, Islamabad Pakistan

[3] Zaryab Khan
Capital University of Science and Technology, Islamabad Pakistan

[4] Haider Mehmood
Capital University of Science and Technology, Islamabad Pakistan

Mana and Clough [4] suggested a basic technique for estimating the deformations of braced excavations in cohesive soils. They concluded that whether the strut spacing is decreased or wall bending stiffness is increased, it will reduce the deformations. They also stated that increasing strut stiffness also decrease the deformations. Furthermore they stated that deformations increase if the depth of excavation and width to an underlying soil layer is increased. Clough and O’Rourke [5] utilized inclinometer and presented general outline of wall deformations and adjacent ground deformations. For flexible systems, the wall deforms as a cantilever and the adjacent soil settlement increases in inverse ratio to distance from excavation edge when the excavation proceeds to deeper elevations, wall movement at upper levels is restrained by new support systems. This condition results as deep inward movement of the wall.

In deep excavations, wall displacement is analyzed to evaluate the safety of construction. Generally, the horizontal deformation of the diaphragm wall to 2% of ultimate depth of excavation is generally normal distance in buried buildings [6-8]. An insignificant horizontal displacement of the diaphragm wall is a result of uneconomical design, while large wall displacements tend to put the safety of the area surrounding the excavation at risk during construction. As such, the horizontal displacement of a diaphragm wall is recognized as a key factor for designing excavation parameters. Bose and Som [9] investigated a 13.6m deep braced cut by utilizing the finite elements method (FEM), and examined wall and soil deformations in a braced excavation. They showed that the width of excavation was adequate on wall–soil deformations and the pre-stressing of struts was also demonstrated to be adequate for such excavations. Yoo and Lee [10] utilized FEM to undertake a two-dimensional (2D) numerical study on the effect of excavation on ground movement. The results of their research were presented as a two-step method for predicting ground displacement. Hsiung [11] studied the influence of creep, soil–wall interface, and elasticity of sand on the behavior of the diaphragm wall during excavation by using finite difference numerical method, and compared the results to a case study. The numerical finite difference study by Chowdhury et al. [12] on the effects of strut stiffness, thickness of diaphragm wall, depth of wall penetration, and struts positioning ended up with a design guide for the diaphragm wall. Based on the research a conclusion was drawn which stated that the thickness of diaphragm wall was proposed as 6-7% of the depth of the excavation and the depth of wall penetration was proposed as 80-100% of the depth of the excavation for the excavations up to 20m. Zhang et al. [13] considered the influence of soil strength and stiffness properties on behaviour of the wall utilizing FEM, and proposed a simple method for predicting the excavation-induced wall deflection behavior. Goh et al. [14] performed numerical 2D and 3D studies on the properties of diaphragm wall and soil in braced excavation, and came up with a simple method for predicting wall displacement. The



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results of that study showed that the maximum horizontal displacement obtained in 3D modeling was lower than that in 2D modeling.

Struts are temporary slabs that offer short-term resistance to the retaining walls in deep excavations. Ou et al. [8] stated that strutting systems are required to resist the lateral earth pressure. While selecting the type of strutting systems to be provided various factors are kept under consideration i.e. magnitude of lateral pressure, time duration and delay it might cause during construction. Kim et al. [15] compared the construction cost of braced wall system utilizing H-shaped steel and high strength steel pipe in the strut of the braced excavation. They concluded that the high strength steel pipe in the strut of braced excavation was economical as compared to H-shaped steel strut. Sabzi and Fakher [16] studied the performance of buildings adjacent to deep excavations supported by inclined struts. A series of 2D finite element analysis was performed to study the effect of struts on the deflection of adjacent buildings. It was observed that stiffness of adjacent buildings, depth of excavations and soil stiffness have a significant effect. They concluded that the application of inclined struts influenced the performance of adjacent buildings through two mechanisms. One is that they transfer a portion of adjacent building load and reduce the effect of excavation induced settlement and the other is that they limited the deflection of the adjacent building. Liu et al. [17] monitored a 15.5m multi-strutted excavation comprising of soft clay in Shanghai and concluded that the wall deflections were quite small, the measured surface ground settlement was appropriate. Further they concluded that there was no creep deflection of diaphragm wall.

Tefera et al. [18] studied the ground settlement and wall deformation of a sheet pile wall during different stages of an excavation using a large-scale model test with dry sand and compared the results with finite-element simulations. Nakai et al. [19] performed 2D model tests with aluminum rods in place of sand and analyzed them with an elastoplastic FEM. It was found that the computed results closely matched the results obtained from the model tests. Seok et al. [20] performed model tests to quantify the amount of building settlement adjacent to a braced excavation and the zone of soil improvement required to reduce building settlement when the building's centroid is located within the excavation influence zone.

In this paper, two-dimensional analysis of deep excavation in clayey soil was carried out to assess the deformations in diaphragm wall while the excavation was supported by horizontal struts. The detailed methodology has described in following sections.

## II. METHODOLOGY

In this study, a site proposed for multistory building with six (06) basements was selected. The borehole data was used to evaluate the physical and strength characteristics of subsurface soil. The soil parameters obtained from the subsurface investigation are summarized in table-1 and table-2.

Table 1 Summary of Ground Conditions

| **Depth of soil layers from Road Level (m)** | **Soil Type** |
|---|---|
| 0-24 | Soft to Medium Stiff Sandy Silt |
| 24-32 | Stiff Clay and Gravelly Clay |
| 32-49 | Medium Stiff Clay |
| Below 49 | Hard, Rocky and Sandy Clay |

The two-dimensional numerical analysis is conducted as a plain strain problem utilizing the Finite Element software Plaxis 2D. The analysis was carried out under undrained conditions and the excavation process was simulated under following sequence.

- The excavation boundary was prepared, different soil layers were defined and the mesh was generated.
- Along the periphery of the model, the lateral deformation was restricted but settlement is allowed whereas at the bottom of the model, both lateral movement and settlement are restricted.
- The excavation is carried out up to a certain depth and the diaphragm wall is installed upto the desired depth.
- After the excavation is carried out, struts are installed at the various levels to resist the lateral soil movement. The arrangement of strut is presented in table 3.

The effect of strut's stiffness was also study by varying the strut's stiffness in all arrangements. Four (04) different strut's stiffness ($k_{strut}$) (i.e. 1.0 x $10^6$ kN, 1.5 x $10^6$ kN, 2.0 x $10^6$ kN and 2.5 x $10^6$ kN) were considered in this study.

Table 2 Summary of Design Parameters

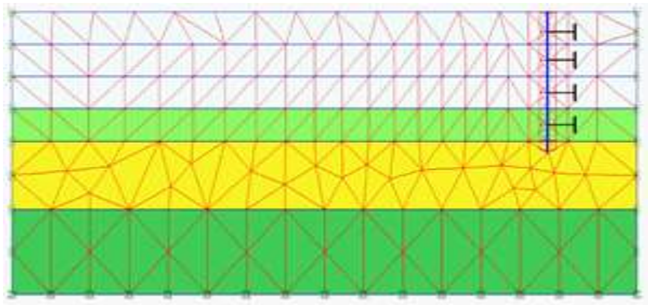
| **Parameters** | **Soil Layers** | | | |
|---|---|---|---|---|
| | **Soft to Medium Stiff Sandy Silt** | **Stiff Clay and Gravelly Clay** | **Medium Stiff Clay** | **Hard, Rocky and Sandy Clay** |
| Unit Weight ($kN/m^3$) | 15.8 | 16.3 | 15.9 | 19.5 |
| SPT 'N' value | 4 | 7 | 8 | > 50 |
| Moisture Content | 13 | 21 | 26 | 8 |
| $C_u$ (kPa) | 20 | 50 | 33 | 200 |
| $\varphi_u$ (Degree) | 22.5 | 0 | 0 | 0 |
| $M_v$ ($m^2/MN$) | - | 0.123 | 0.127 | 0.05 |
| $E_u$ ($MN/m^2$) | 6 | 15 | 9 | 36 |
| $K_s$ ($kN/m^3$) | - | 15000 | 11500 | 31000 |

Table 3 Struts Arrangements for parametric study

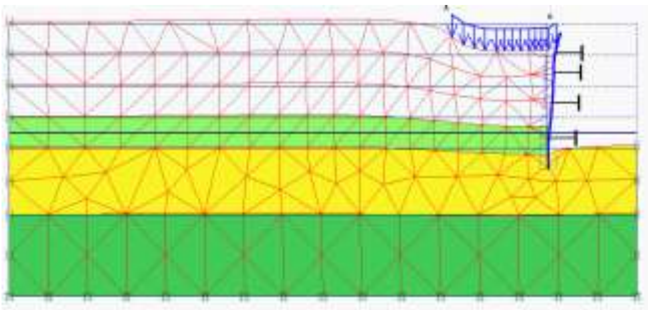
| Arrangement Type | Embedded Depth (m) | Depth of each strut below Ground Level (m) | | | |
|---|---|---|---|---|---|
| | | Strut No. 01 | Strut No. 02 | Strut No. 03 | Strut No. 04 |
| **A** | 32 | 5 | 12 | 19 | 26 |
| **B** | 32 | 4 | 10 | 18 | 27 |
| **C** | 32 | 6 | 14 | 22 | 28 |

# III. ANALYSIS AND RESULTS

Three different arrangements for struts were considered at different positions. The diaphragm wall was installed up to the depth of 34m from ground level and four struts were applied in each case to support the diaphragm wall. Figure 1 (a & b) shows the undeformed and deformed mesh of struts supported diaphragm wall.



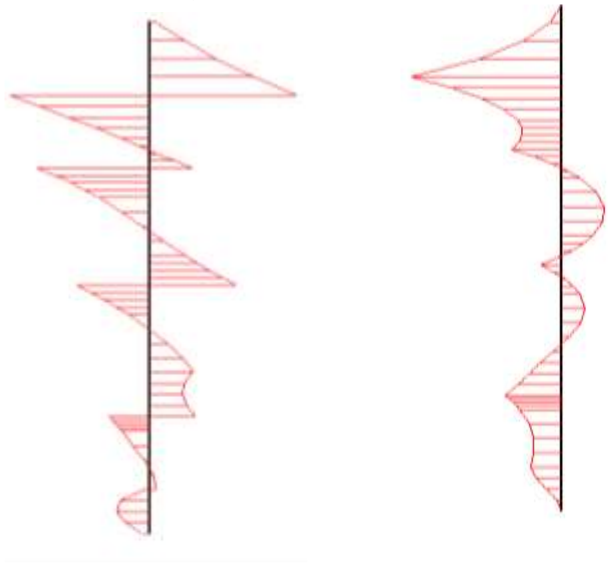
a) Undeformed Mesh



b) Deformed Mesh

Figure 1: Mesh generation of diaphragm wall supported with horizontal struts

Figure 2 shows the typical free body diaphragm of shear force and bending moment of diaphragm wall. The forces in diaphragm wall such as horizontal displacement (*u*), vertical displacement (*v*), shear force (*V*) and bending moment (*M*) are determined and summarized in table 4, table 5 and table 6 for arrangement A, arrangement B and arrangement C respectively, whereas, the forces in struts (*F*) are tabulated in table 6. It can be observed that the forces in wall significantly influenced by the position of struts. Also, the forces in struts depends on the location of struts. It can also be seen that the maximum force in a strut at a particular level depended on the vertical distance between two consecutive struts. As the vertical distance between two consecutive struts increased, the force in the top strut also increased. This is because a strut experiences maximum force when the excavation is done, before installation of the next strut. Thus, the greater the difference in height between the two struts, the greater the force in the top strut.



a) Shear Force b) Bending Moment

Figure 2: Free body diagram of diaphragm wall

Table 4: Variation in *u*, *v*, *V*, *M* and *F* with different $K_{strut}$ for arrangement A

| Strut's Stiffness K x $10^6$ KN | Strut No. | Horizontal Displacement $10^{-3}$ (m) | Vertical Displacement $10^{-3}$ (m) | Shear Force (kN/m) | Bending Moment (kN-m/m) |
|---|---|---|---|---|---|
| 1.0 | 1A | 1200 | 133.83 | 267 | 651.30 |
| | 2A | | | | |
| | 3A | | | | |
| | 4A | | | | |
| 1.5 | 1A | 1190 | 127 | 283 | 685 |
| | 2A | | | | |
| | 3A | | | | |
| | 4A | | | | |
| 2.0 | 1A | 1170 | 120.8 | 290 | 690 |
| | 2A | | | | |
| | 3A | | | | |
| | 4A | | | | |
| 2.5 | 1A | 1160 | 121.0 | 296 | 714 |
| | 2A | | | | |
| | 3A | | | | |
| | 4A | | | | |



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The effect of strut stiffness was also studied on the horizontal and vertical deformations, shear force and bending moment. Four varying strut stiffness were considered i.e. ($1x10^6$, $1.5x10^6$, $2x10^6$ and $2.5x10^6$) for all the strut arrangements. It was observed that as the strut's stiffness increased, there was a considerable decrease in the horizontal and vertical deformations, however a rise in shear force and bending moment of the wall was observed. Table 4, table 5 and table 6 clearly summarize this behavior.

Figure 3 shows the variation in horizontal displacement of diaphragm wall with different strut' stiffness at all arrangements. It can be noted that, while increasing the strut's strength and stiffness, the horizontal displacement in wall decreases. The location of strut did not significantly affect the horizontal displacement of wall. Figure 4 and figure 5 shows the variation in shear force and bending movement of diaphragm wall respectively for all types of arrangements. It was observed that the values of shear force and bending moment increases as strut stiffness increases.

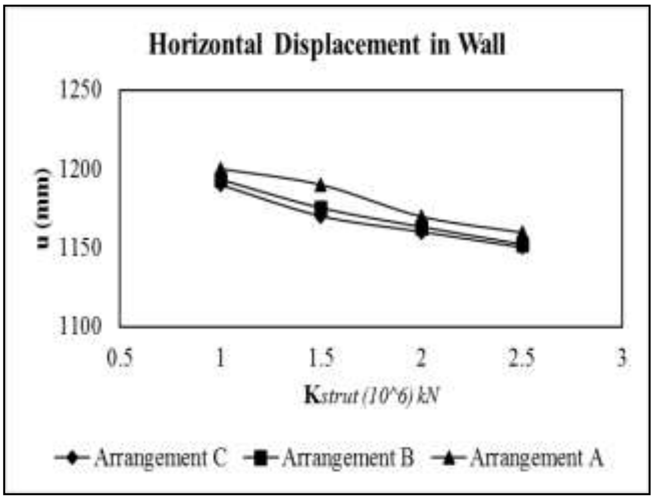


*Figure 3: Effect of $K_{strut}$ on horizontal displacement of diaphragm wall*

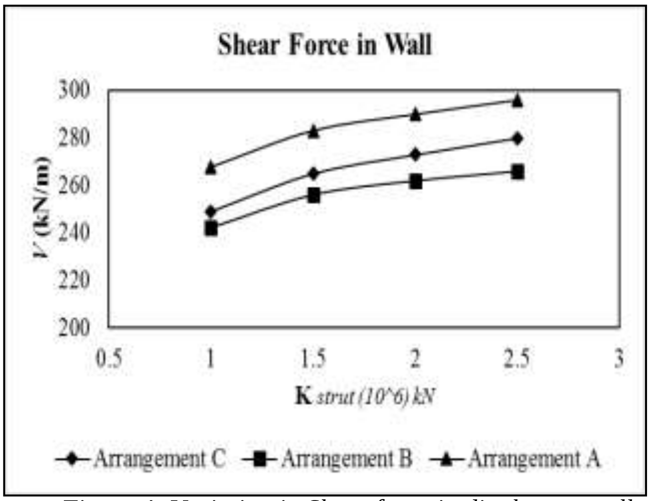


*Figure 4: Variation in Shear force in diaphragm wall with varying $K_{strut}$*

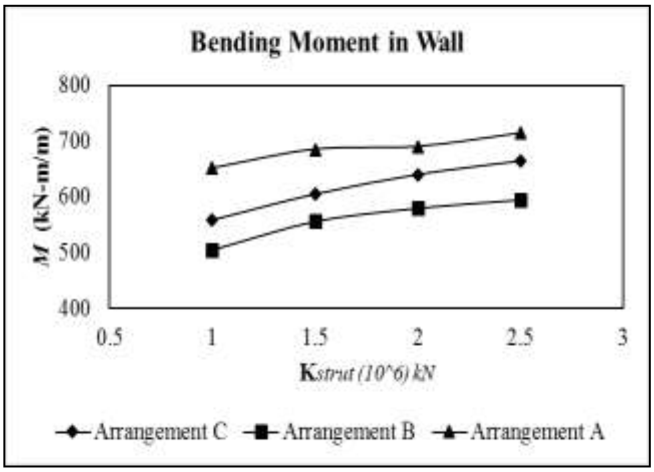


*Figure 5: Variation in Bending moment in diaphragm wall with varying $K_{strut}$*

Table 5: Variation in u, v, V, M and F with different $K_{strut}$ for arrangement B

| Strut's Stiffness K x $10^6$ KN | Strut No. | Horizontal Displacement $10^{-3}$ (m) | Vertical Displacement $10^{-3}$ (m) | Shear Force (kN/m) | Bending Moment (kN-m/m) |
|---|---|---|---|---|---|
| 1.0 | 1B | 1193 | 140.54 | 242 | 505 |
| | 2B | | | | |
| | 3B | | | | |
| | 4B | | | | |
| 1.5 | 1B | 1175 | 133.21 | 256 | 556 |
| | 2B | | | | |
| | 3B | | | | |
| | 4B | | | | |
| 2.0 | 1B | 1163 | 129.06 | 262 | 580 |
| | 2B | | | | |
| | 3B | | | | |
| | 4B | | | | |
| 2.5 | 1B | 1152 | 126.48 | 266 | 595 |
| | 2B | | | | |
| | 3B | | | | |
| | 4B | | | | |



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*Table 6: Variation in u, v, V, M and F with different $K_{strut}$ for arrangement C*

| Strut's Stiffness K x $10^6$ KN | Strut No. | Horizontal Displacement $10^{-3}$ (m) | Vertical Displacement $10^{-3}$ (m) | Shear Force (kN/m) | Bending Moment (kN-m/m) |
|---|---|---|---|---|---|
| 1.0 | 1C | 1190 | 141.03 | 249 | 559 |
| | 2C | | | | |
| | 3C | | | | |
| | 4C | | | | |
| 1.5 | 1C | 1170 | 133.21 | 265 | 605 |
| | 2C | | | | |
| | 3C | | | | |
| | 4C | | | | |
| 2.0 | 1C | 1160 | 129.06 | 273 | 640 |
| | 2C | | | | |
| | 3C | | | | |
| | 4C | | | | |
| 2.5 | 1C | 1150 | 126.48 | 280 | 664 |
| | 2C | | | | |
| | 3C | | | | |
| | 4C | | | | |

Table 7: Variation in Strut's forces with different $K_{strut}$

| | $K_{strut}$ | Sturt No. 01 | Sturt No. 02 | Sturt No. 03 | Sturt No. 04 |
|---|---|---|---|---|---|
| Arrangement A | 1 | 397 | 152.4 | 198.3 | 61.21 |
| | 1.5 | 414 | 150 | 216 | 68 |
| | 2 | 435 | 148 | 207 | 70 |
| | 2.5 | 429 | 146 | 238 | 76 |
| Arrangement B | 1 | 391 | 235 | 119 | 90 |
| | 1.5 | 406 | 247 | 128 | 95 |
| | 2 | 413 | 253 | 137 | 98 |
| | 2.5 | 417 | 257 | 143 | 95 |
| Arrangement C | 1 | 392 | 236 | 117 | 82 |
| | 1.5 | 406 | 247 | 128 | 89 |
| | 2 | 413 | 253 | 137 | 95 |
| | 2.5 | 417 | 257 | 143 | 99 |

The compressional force in each strut for all types of arrangements are summarized in table 7. The figure 6, figure 7 and figure 8 shows the variation of axial forces in struts with varying strut stiffness for strut arrangement A, arrangement B and arrangement C respectively. It was observed that no significant varriation was occurred in axial force in of strut with increasing the stiffness of strut. So it can be concluded that, the strut's stiffness doesn't affect the axial or compressional forces of strut whereas, the horizontal displacement, shear force and bending moment in diaphragm wall significantly vary with different struct stiffness.

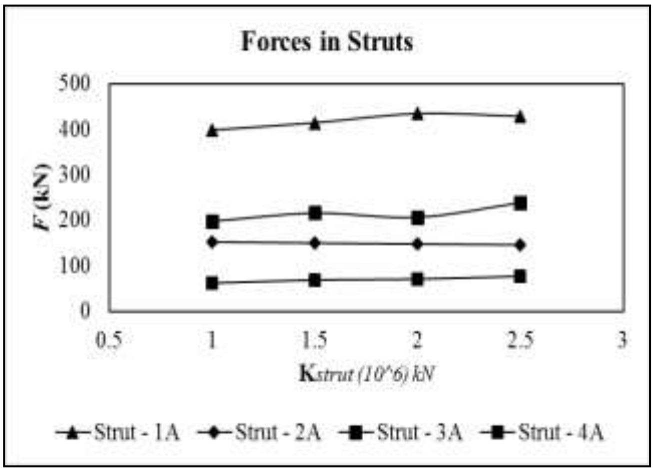


*Figure 6: Forces in Strut for arrangement A*

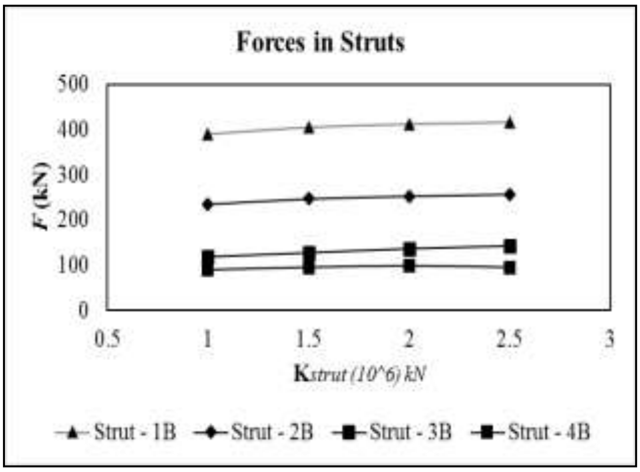


*Figure 7: Forces in Strut for arrangement B*

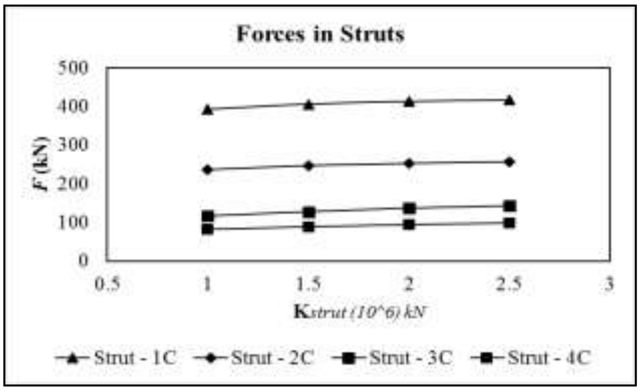


*Figure 8: Forces in Strut for arrangement C*



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# IV. Conclusion

In the present study, an attempt was made in order to estimate the effect of struts location on the deformation of diaphragm wall. Based on the results presented in table 4, it can be concluded that, for a particular wall thickness and strut stiffness, different strut arrangements produced different results for maximum strut force, maximum moment, maximum horizontal wall displacement, and maximum vertical ground surface displacement. Based on these results, an optimum arrangement can be obtained.

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