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# The Behavior of Braced Excavation in Silty Clay Soil under El-Centro Seismic

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**Abstract**: Braced excavation is one of the important systems used to support soil from collapse during excavation. A braced excavation system may be exposed to seismic load and undergoes more forces through the significant vibration of the surrounding soil in addition to the static and lateral loads of soil and nearby structures. The investigation of the braced excavation under the effect of earthquake behavior is still limited or poorly described. Further, this paper presents a numerical study to evaluate the vertical settlement and horizontal displacement of sheet pile wall embedded in silty clay soil in Baqubah city under the influence of the acceleration time history of the 1940 El-Centro earthquake. The study utilized the software PLAXIS 3D. A three-dimensional analysis of the braced system with dimensions of 14m×6m and an excavation depth of 7m was achieved. Three levels of strut and wale layers were used, and five struts for each level. The penetration depth for the sheet pile wall was 9m. The study showed that the El-Centro earthquake laterally moved the braced excavation system as a block mass due to the existence of the excavation system in soft silty clay. The lateral displacement reached approximately 150mm. The differences in lateral earth pressure on sheet pile wall depth a few seconds before and after the earthquake were very small.

# سلوك الحفريات المدعمة في التربة الغرينية الطينية تحت تأثير زلزال اليسنترو

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**الخلاصة**

يعتبر الحفر المدعم أحد الأنظمة المهمة المستخدمة لدعم التربة من الانهيار أثناء الحفر. قد يتعرض نظام الحفر المدعم للحمل الزلزالي ويخضع لمزيد من القوى من خلال الاهتزاز الكبير للتربة المحيطة بالإضافة إلى الأحمال الثابتة للتربة والهياكل المجاورة. لاتزال الدراسات في سلوك الحفريات تحت تأثير الزلازل محدودًا أو غير موصوف جيدًا. علاوة على ذلك، يهدف هذا البحث الى اجراء دراسة عددية لتقييم الاستقرار الرأسي والإزاحة الأفقية لجدار الركيزة اللوحية المغمورة في التربة الغرينية الطينية في بعقوبة تحت تأثير تاريخ التسارع لزلزال El- Centro عام ١٩٤٠. استخدم برنامج PLAXIS 3D في الدراسة. تم إجراء تحليل ثلاثي الأبعاد لنظام الاسناد لأبعاد ١٤ mx6m وعمق حفر ٧ م. استخدمت ثلاث مستويات من طبقات الدعامات والطبقات الحاملة وخمس دعامات لكل مستوى. عمق الاختراق للجدار الصفيحي هو ٩ م. أظهرت الدراسة أن زلزال اليسنترو ((El-Centro جعل نظام الحفر المدعم يتحرك بشكل جانبي ككتلة واحدة بسبب وجود نظام الدعم للحفر في التربة الطينية الناعمة. بلغت الإزاحة الجانبية حوالي ١٥٠ ملم. الاختلافات في ضغط التربة الجانبي على عمق الركائز اللوحية قبل الزلزال وبعده كانت صغيرة جدًا .

**الكلمات الدالة:** قطع، هزة ارضية، حفر، موديل عددي، حمل هزة ارضية.

## 1.INTRODUCTION

Many projects required ground excavations, such as a basement for high buildings and pipelines. The vertical excavation faces should be supported by a tentative bracing system to avoid failure that might occur during construction. A study by Ref. [1] used the finite element technique (FEM) with reduced shear strength to analyze the failure mechanisms of excavations. They discovered that when an elastoplastic support system was in place, the yielding of the struts and walls first caused a sharp increase in the soil heave and wall deflection before the excavations failed. On the other hand, when an elastic support system was used, the collapse of the excavations was brought on by a significant amount of soil plastic heave at the bottom of the excavation. The study of Ref. [2] determined the impact of various design factors, including excavation depth, acceleration amplitude, and wall stiffness. Braced excavation in dry sand was examined under seismic conditions. Additionally, FLAC 2D numerical studies that considered one level of bracing were carried out. The study demonstrated that when other factors were constant in a post-seismic condition, excavation depth and base acceleration amplitude enhanced lateral displacement, bending moment, strut forces, and maximum ground surface displacement. A study by Ref. [3] investigated the settlement of sheet pile walls under surcharge loading utilizing a pseudo-static technique and the finite difference tool FLAC 2D. The authors found that sheet pile walls' bending moment and settlement increased with the horizontal seismic acceleration coefficient. Additionally, it was found that both settlement and deflection decreased as the distance of the surcharge from the top of the wall increased. The work by Ref. [4] studied the soil-structure analysis of the deep excavation supported by a contiguous pile wall using a two-dimensional finite element method in PLAXIS 2d and the Mohr-Coulomb soil constitutive model. It was found that the maximum lateral wall deflection occurred with lower values of pile stiffness. While the bending moment grew as the support stiffness increased. The maximum lateral wall deflection calculated using the MC model for horizontal anchor spacing was roughly 40.4%. A study by Ref. [5] carried out a parametric study to provide practical approach/guidelines to design excavations by analyzing and comparing calculated data by monitoring general trends and comparative study of the obtained data using Finite Element integrated PLAXIS 2d software. The study found that a Piled-raft or Mat foundation with a 10m Diaphragm wall length and 0.39m thickness with strut stiffness of $10 \times 10^5$ kN/m² was the most optimized design for braced excavation in terms of cost-effectivity and practical implementation. Several numerical and experimental studies dealt with braced excavation under a static condition, i.e., [6-14]. A few studies deal with the excavation when it is subjected to seismic loading. A study by Ref. [15] showed that the displacement and bending moment during seismic depended on the intensity of the earthquake in addition to the acceleration time change. The work by Ref. [16] stated that the lateral earth pressure was affected by the excavation depth and a peak value of the earthquake acceleration but did not largely alter with sheet pile wall stiffness. A study by Ref. [17] confirmed the prominence of dependency on the structure behavior of soil material, particularly in the parsing of the interaction system exposed to an earthquake excitation transmitted through the soil media. Some projects need long periods, i.e., 3 to 6 years, to complete construction, such as metro construction projects; therefore, the probability of earthquake occurrence is high during construction, especially in the seismic active zone. The behavior of braced excavation during seismic should be investigated to avoid the risk of failure and influence on the workers' safety. The analysis was conducted to estimate the behavior of braced excavation during the El-Centro earthquake in X and Y directions.

## 2.NUMERICAL MODELING

The soil properties in the study, structure element, and construction stage were utilized in the software program Plaxis 3D. Also, the displacements and stresses after implementation were considered a case study problem. Two principal modes were used in Plaxis 3D: soil and structure geometry. After completing structure mode, mesh generation processes can generate 3D solid models. The construction stages include activating and deactivating soil volumes and structure parts, such as strut, wale, and sheet pile walls.

### *2.1.Case Study Problem*

The case study consists of a braced excavation system with dimensions 6mx 14m and an excavation depth of 7m below the ground surface. The selected dimensions of the problem were 80m×50m and a total soil layers depth of 30m. The embedment depth of the sheet pile wall was 9m. Three levels of struts and wales layers were used in this study. The horizontal and vertical spacing between struts was 3m and 2.5m, respectively. The first level of struts and wales was 1m below the ground surface. The whole shape of the problem is illustrated in Fig. 1.

### *2.2.Soil Modeling*

The problem chosen is in Baqubah city, consisting of three layers: soft silty clay depth of 12m, Medium silty clay depth of 8m, and dense sand depth of 10m. The water level is 1m below the ground surface. The Mohr-Coulomb was used to simulate these soil layers to simplify the studied problem. The values of soil parameters are listed in Table 1.

### 2.3.Sheet Pile Wall, Strut, and Wale Modeling

The sheet pile wall was (PS-31) type with 9m-depth and 12.7mm-thickness. Strut is a compressive beam element with a hollow circular section of 300mm. Wale is a longitudinal beam that connects the sheet pile wall and strut. The cross-section used for wale was HE 300A 300mm×280mm. The properties of the sheet pile wall, strut, and wale are shown in Tables 2 and 3.

### *2.4.Boundary Conditions and Seismic Loading*

At the bedrock level of the model, the seismic motion of the El-Centro earthquake was defined as a dynamic surface (Prescribed displacement multiplier). The acceleration time history for the El-Centro earthquake was adopted, which was applied in two cases: (1) Along the X-direction at the bottom boundary, as shown in Fig. 2, and (2) Along the Y-direction at the bottom boundary. In reality, seismic waves propagate indefinitely through the soil. To avoid the sudden reflection of these waves on the model boundaries inside the soil body, absorbent boundaries were generated by selecting the standard absorbent boundaries (viscous boundary) in the Plaxis program. The absorbent boundaries are applied at the lateral sides and the bottom boundary in this model. The amplitude of the El-Centro earthquake used in this study is demonstrated in Fig. 3.

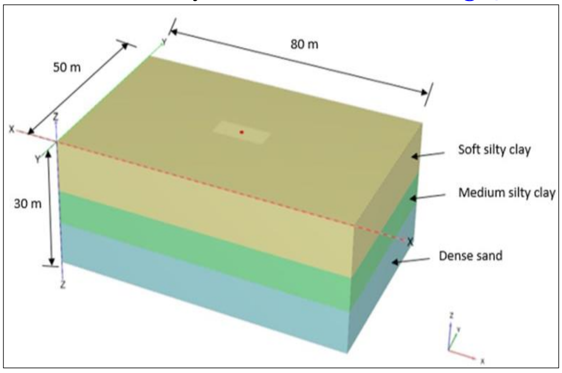


**Fig.1** Soil Layers and Location of Excavation Area of the Case Study.

**Table 1** Properties of Soil Layers Used in the Study [18].

| Property | Soft Silty Clay | Medium Silty Clay | Dense Sand |
|---|---|---|---|
| Elastic Modulus, E(kPa) | 10000 | 50000 | 90000 |
| Poisson's Ratio, υ | 0.4 | 0.4 | 0.3 |
| Unsaturated Unit Weight, $\gamma_{unsat}$ (kN/m³) | 15 | 16 | 17 |
| Saturated Unit Weight, $\gamma_{sat}$ (kN/m³) | 19.4 | 19.6 | 20 |
| Cohesion, c (kPa) | 40 | 82 | - |
| Friction Angle,(φ) | - | - | 35 |
| Elastic Modulus, E(kPa) | Rigid | Rigid | Rigid |
| Poisson's Ratio, υ | 0.01 | 0.01 | 0.005 |

**Table 2** Properties of Sheet Pile Wall [19].

| Property | Value |
|---|---|
| Elastic Modulus, E (MPa) | 200000 |
| Poisson's Ratio, υ | 0.3 |
| Unit Weight (kN/m³) | 78 |
| Thickness(m) | 0.0127 |

**Table 3** Properties of Strut and Wale [19].

| Property | Strut | Wale |
|---|---|---|
| Elastic Modulus, E (MPa) | 200000 | 200000 |
| Area(cm²) | 96.2 | 112.5 |
| Unit Weight (kN/m³) | 78 | 78 |
| Moment of inertia $I_2$ (cm⁴) | 7023 | 18260 |
| Moment of inertia $I_3$ (cm⁴) | 7023 | 6310 |

### *2.5.Mesh Generation, Stage Construction, and Calculations*

The mesh element type used in the mode was medium mesh to improve the accuracy of the results. A medium mesh was selected to avoid lengthy time calculations with fine or very fine mesh, as shown in Fig. 4. The calculation process was classified into five phases: (a) The initial phase (Initial Stress Generation used $K_o$ procedure), (b) The second phase was an activated sheet pile wall to a depth of 9m, (c) The third phase activated the first level of struts and wales and deactivated soil in excavation to a depth of 1.20m, (d) Forth phase activated the second level of struts and wales and deactivated soil in excavation to a depth of 4m, and (e) Fifth phase activated the third level of struts and wales and deactivated soil in excavation to a depth of 7m. Finally, the phase for the dynamic calculations was chosen after creating prescribed displacement multipliers in the X direction for the first case and the Y direction for the second case. The dynamic time interval was 35 seconds. After the analysis achieved for the braced excavation system, the settlement variations and sheet pile wall displacement were investigated.

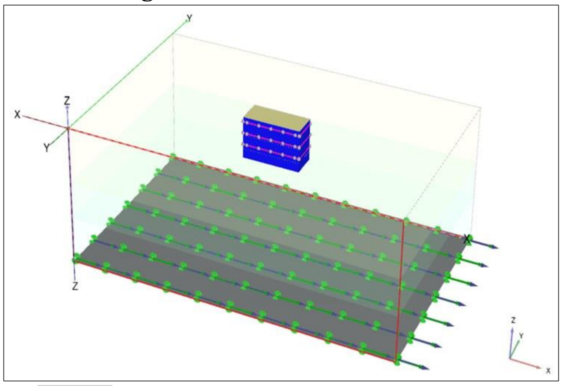

**Fig. 2** Applied Seismic at the Base of the Model in the X-Direction.

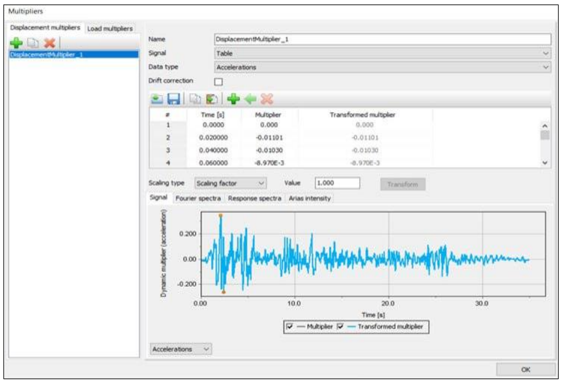


**Fig. 3** The El-Centro Seismic Amplitude Used in this Study.

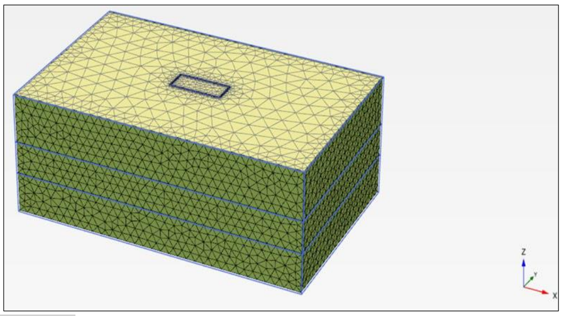

**Fig. 4** Mesh Generation of the Model Problem.

## 3.RESULTS AND DISCUSSION

To investigate the settlement and lateral displacement generated during the El-Centro earthquake, four points; A, B, C, and D; were selected. These points were located at the top and center of four sides of the sheet pile wall, as shown in Fig. 5. Also, four sections, 1-1, 2-2, 3-3, and 4-4, were chosen to determine the variation of horizontal effective stress with the sheet pile wall depth after the seismic end, as shown in Fig. 6.

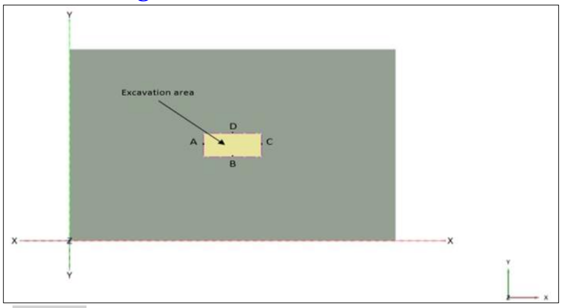


**Fig. 5** Selected Points of the Model Problem.

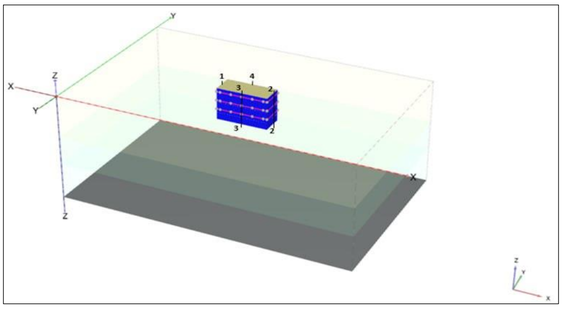

**Fig. 6** Selected Sections of the Model Problem.

### *3.1.Variation of the Horizontal and Vertical Displacements during the Period of Seismic*

It is noticed from Fig. 7 that the lateral displacement was identical for all points, which increased sharply with seismic time until it reached a maximum value of 150mm at 35 seconds. This behavior occurs when the direction of an earthquake is in the X-direction (perpendicular to the long direction of braced excavation). On the other hand, the contrary behavior of the lateral displacement of selected points when seismic happened in the Y-direction. The lateral displacements of all points were oscillated and unidentical, as shown in Fig. 8. The lateral displacement for the excavation system in case of earthquake happened in the Y direction was slightly more than in the X direction because the surface area of the excavation braced system was sparsely in the Y direction compared to the X direction. Regarding the vertical displacement (settlement), it is clear from Figs. 9 and 10 that the settlement happened from seismic in the X and Y direction was very small for all points. In general, the braced excavation system horizontally moved in the direction of the earthquake occurring. The oscillation of the acceleration time history of the El-Centro earthquake moved the wending and backing of the excavation system and soil mass around the system. In this type of analysis, two types of strains come up from earthquakes, namely the El-Centro: 1-Strains or translation experienced by the soil structure itself. So, the overall stability of it will be this work's concern, 2-Strains that will eventually occur in the soil body nearby or surrounding the soil structure. Here, the stability of any geotechnical installation or engineering facility will be within the interest of the study. If an engineering rigid installation is to pass through the zone next to the braced excavation, then whether it can sustain or not this sagging must be investigated. Considering the other direction of the excavation, there was a lateral movement of 153mm, which was relatively close to the shorter direction value. Also, the horizontal sagging ratio was (13/20000). The vertical settlement in this type of earthquake was almost negligible, i.e., about one millimeter, considered nothing.

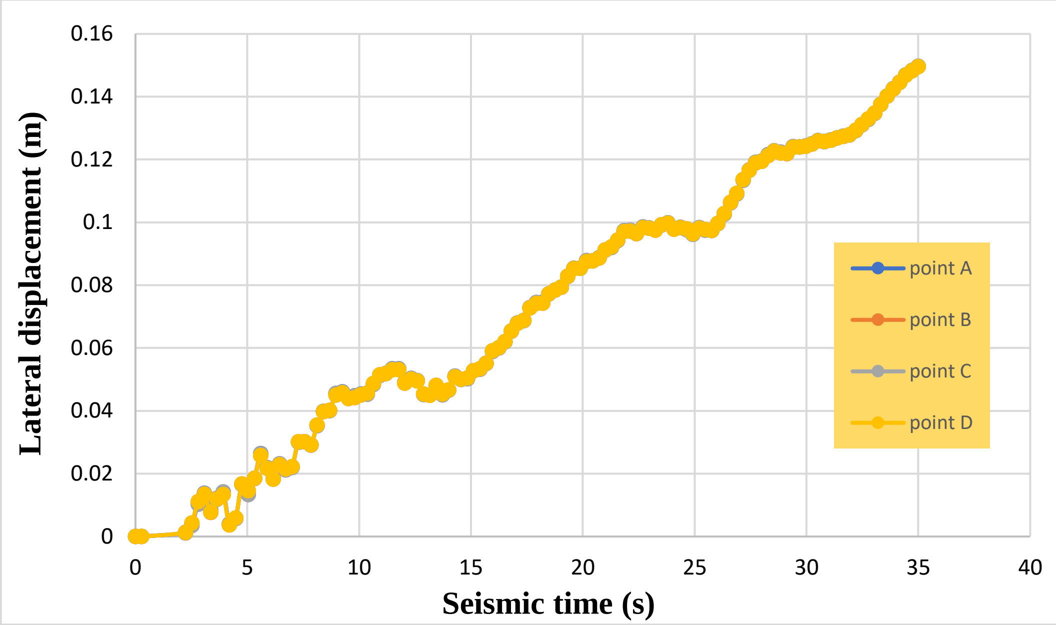


**Fig. 7** Variations of Lateral Displacement for Selected Points with Dynamic Time When Seismic in the X-Direction.

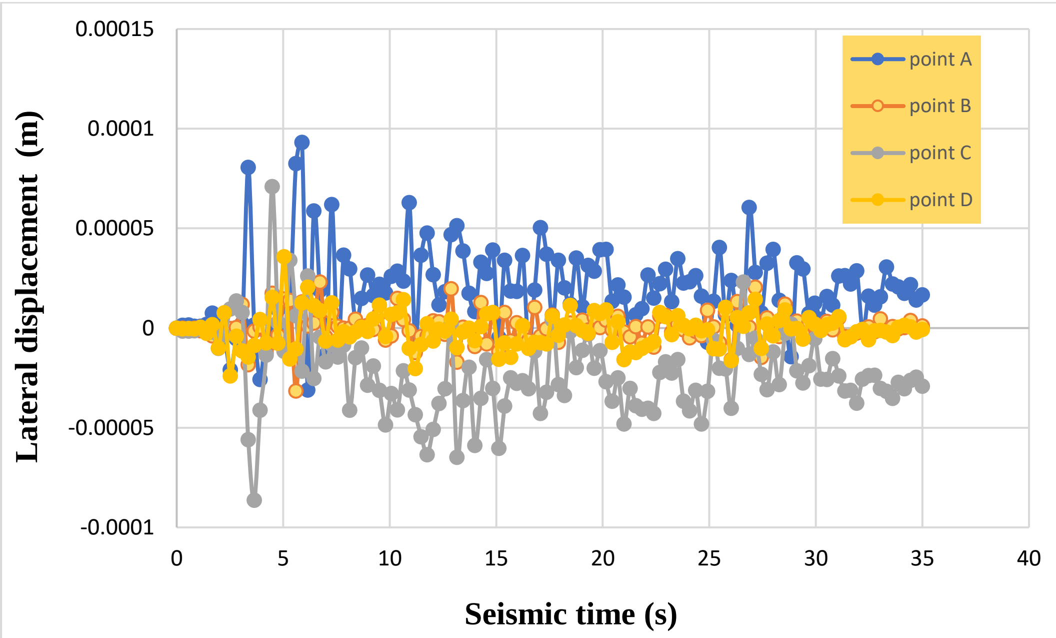


**Fig. 8** Variations of Lateral Displacement for Selected Points with Dynamic Time When Seismic in the Y-Direction.

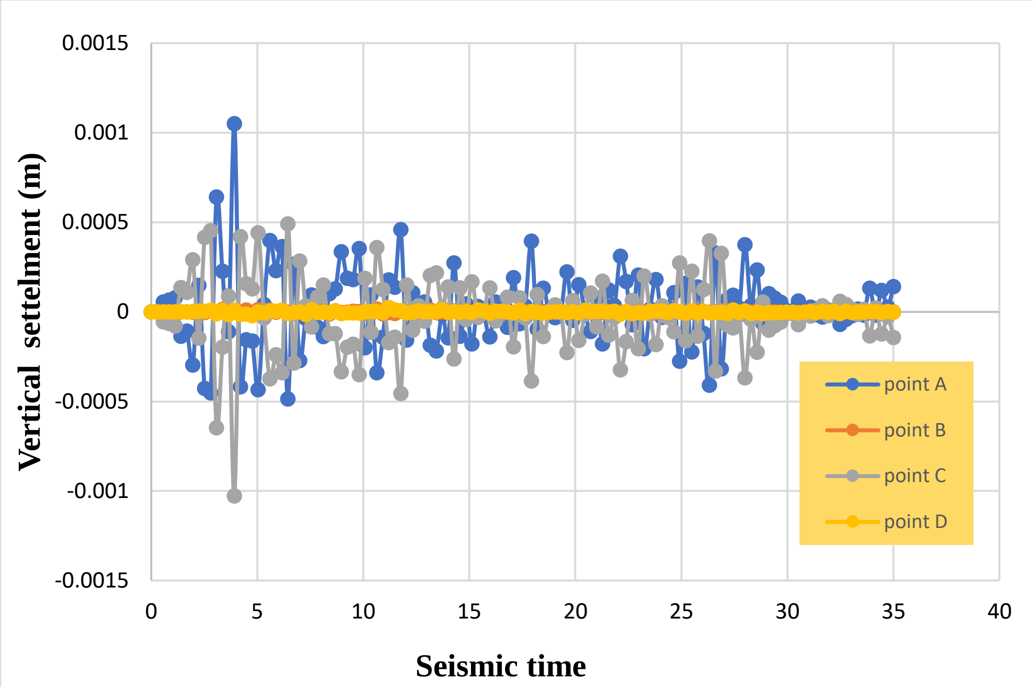


**Fig. 9** Variations of Vertical Displacement for Selected Points with Dynamic Time When Seismic in the X-Direction.

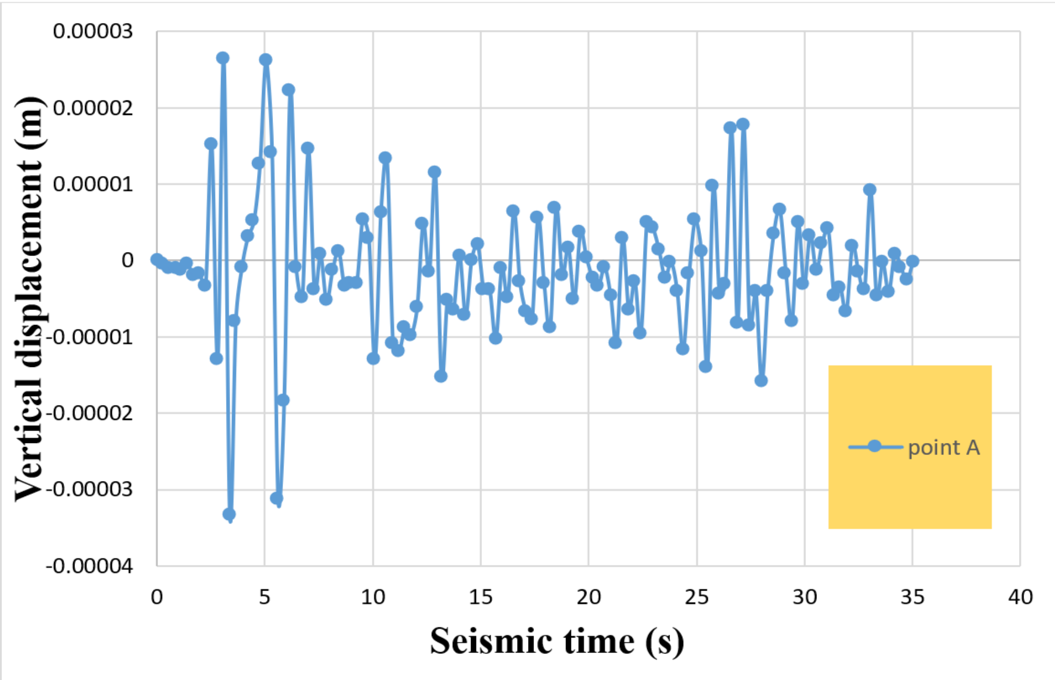


**Fig. 10** Variations of Vertical Displacement for Selected Points with Dynamic Time When Seismic in the Y-Direction.

### 3.2.Variation of Horizontal Effective Stress at the End of Seismic

It is clear from Figs. 11 and 12 that the effective horizontal stresses in the X-direction earthquake that happened for sections 1-1and 2-2 were identical and convergent for static and dynamics loads, as shown in Fig. 11. Also, the effective horizontal stresses values for section 3-3 were lower than section 4-4 at the end of earthquake because of soil's state at the earthquake end. In the case of an earthquake in the Y direction, the differences between static and dynamic load were slightly small, as shown in Figs. 13 and 14 because the soil mass movement around the excavation braced system in soft silty soil without low resistance from soil led to a horizontal slide. The previous results were after the earthquake when the soil became relaxed.

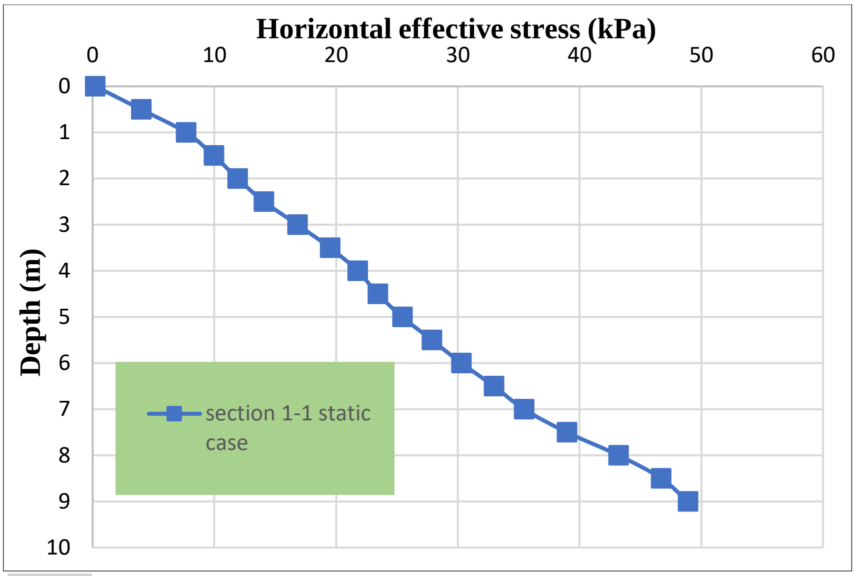


**Fig. 11** Variations of Horizontal Effective Stress for Selected Sections 1-1 and 2-2 under Static and Seismic Loads during the Earthquake in the X-Direction.

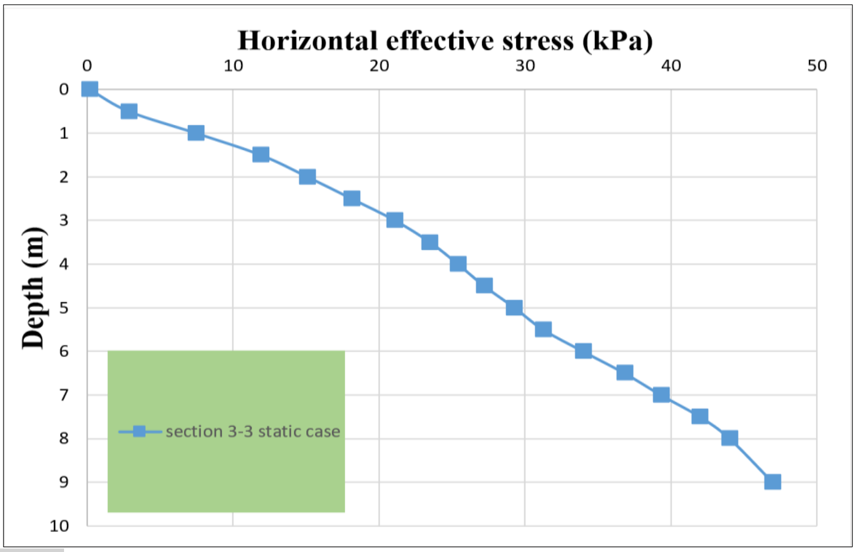


**Fig. 12** Variations of Horizontal Effective Stress for Selected Sections 3-3 and 4-4 under Static and Seismic Loads During the Earthquake in the X-Direction.

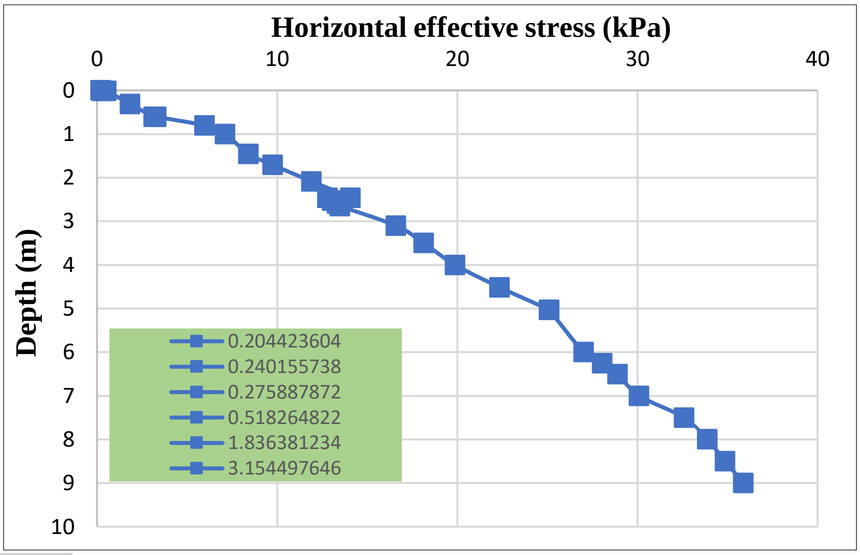


**Fig. 13** Variations of Horizontal Effective Stress for Selected Sections 1-1 and 2-2 under Static and Seismic Loads During the Earthquake in the Y-Direction.

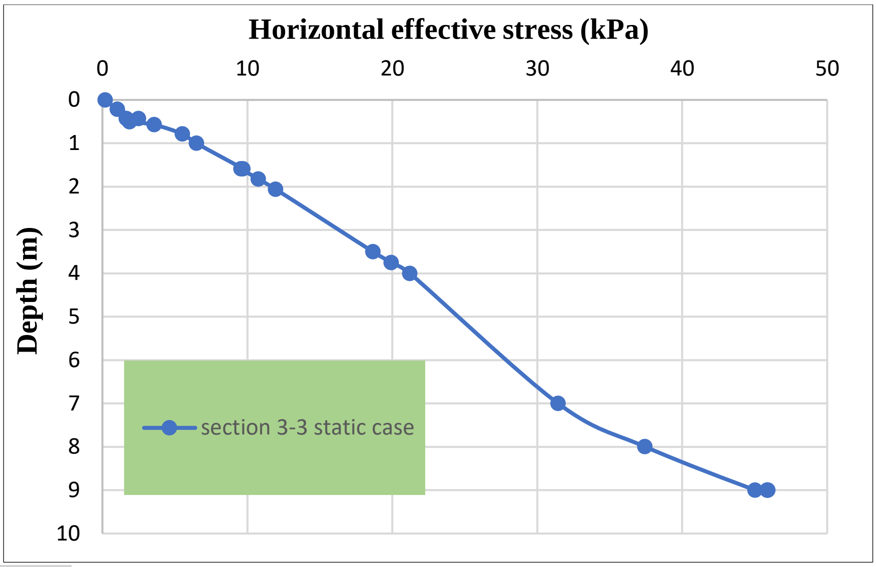


**Fig. 14** Variations of Horizontal Effective Stress for Selected Sections 3-3 and 4-4 under Static and Seismic Loads During the Earthquake in the Y-Direction.

## 4.CONCLUSIONS

The braced excavation system was laterally moved as a block system approximately (150-156) mm in the direction of the El-Centro earthquake. The lateral movements experienced perpendicular to the braced excavation short and long sides were 150mm and 156 mm, respectively. These values are considered rather large. The settlement of the braced excavation system subjected to the El-Centro earthquake was very small. The change in horizontal earth pressure on the sheet pile wall between static and seismic loads was slightly small. Since, in general, the earthquake can produce deflections in both directions, i.e., vertical and horizontal, care and caution should be paid for any engineering installation or facility that can exist under and next to the braced excavation, especially if it is of-rigid type.

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