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# Assessing Shallow Foundation Responses to Adjacent Excavation in Clay

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**Abstract.** In developing countries like Pakistan, the high population growth rate has caused an increase in urbanization. To accommodate the growing population, there is a dire need for high-rise buildings, especially in the most densely populated cities. Consequently, traffic and parking issues have also increased. To cope with these issues, deep excavations for underground facilities and high-rise buildings in urban areas are often carried out adjacent to existing historic or old buildings founded on shallow foundations. Excavations may cause unfavorable ground deformations that affect neighboring structures, presenting a significant challenge for civil engineers to protect integrity of these historical structures. This research presents 3D coupled consolidation analyses using a clay hypoplastic constitutive model, which accounts for small-strain stiffness, to investigate responses of a shallow foundation to neighboring excavation at different depths and clear distances between footing and diaphragm wall in soft clay. It was revealed that the excavation depth and clear distance between the footing and the diaphragm wall significantly affect induced settlement and lateral movement due to excavation. Moreover, the apparent losses in bearing capacity due to induced settlement of the footings located at 1.0, 1.5, 2.0, 4.0, 6.0, and 8.0 meters from the diaphragm wall are 1.65, 1.73, 1.81, 1.70, 1.53, and 1.30 times the ultimate capacity, respectively.

**Keywords:** Shallow foundation; Excavation; Finite element analysis.

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## 1. Introduction

In developing country, like Pakistan, population growth rate is high that has caused increased in urbanization. To accommodate increased population, there is a dire need of high-rise buildings especially in most densely populated cities of the world. Consequently, traffic and parking issues have also increased. To cope with these issues, deep excavations for underground facilities as well as buildings construction in town areas is carried out adjacent to existing historic or old buildings founded on shallow foundation. Investigations into excavation activities should consider potential negative ground deformations that might impact nearby structures. Hence, a geotechnical engineer must evaluate the risk of severe consequences on foundations caused by neighboring excavations.

The structures constructed prior to 1925, often featuring masonry walls and wooden floors, are typically supported around 12 meters deep in sand, covered by soft Holocene clay and peat deposits (Korff et al, 2016; Chai et al., 2014; Shakeel and Ng. 2017).

Regulate excavation in urban areas to limit ground settlements that may damage low-rise structures, particularly historic masonry buildings, caused by subway or building construction. It is well known fact that excavation in ground certainly results in the ground movements due to induced stress release (Jacobsz et al., 2004; Goh et al., 2003).

Historic buildings with shallow foundation that do not undergo below the influence zone of adjacent excavation are of very great concern. When excavation nearby these buildings is carried out, engineer and designer need to estimate building damages and recommend to minimize or prevent these damages to adjacent building and underground utilities using different types of retaining structure or bracings during foundation construction. To investigate soil-structure interaction, multiple researchers have conducted studies.

A sensitivity analysis was performed to assess the impact of specific structural and geotechnical parameters on the response of masonry buildings to settlements induced by tunnelling. Moreover, the building cracks as well as soil structure interface parameters were also determined (Finno et al., 2014; Ong et al., 2009).

And it was suggested that presented model can be used to improve existing damages design curves. In case of conventional methods of investigating the damages of buildings subjected to free field settlement profile follow ground movement (Leung et al., 2003; Poulos et al., 1997).

Some studies have also show that existing buildings also affect the ground movement profile due to factors such as building weight, relative position, stiffness and other characteristics etc. (Liyanapathirana et al., 2016; Potts et al., 1997).This is because of assuming building as an equivalent elastic Timoshenko beam. While some researcher has modelled building as a bare frame or as masonry facade wall (Franzius et al., 2006; Hsiung et al., 2009)

Previous studies had focused on effects of excavation induced ground movements on high rise building resting on deep foundation (i.e., piles). Despite numerous studies carried out on the investigation of excavation effects on nearby buildings, little attention has been paid on excavation induced ground movement on building founded on shallow foundation. The damaging effects such as cracks on shallow foundation due to excavation are rarely reported.

In most of research, structural components (i.e., columns and beams) were assumed as an elastic material. This research article analyzes the response of building resting on shallow foundation to the excavation induced ground movement which were observed from numerical analysis.

Therefore, the specific objectives of the current research are to investigate the bearing capacity of a shallow footing, induced settlement due to excavation, and lateral movement of the footing during excavation. A comprehensive three-dimensional coupled consolidation analysis was performed to understand how shallow foundations respond to nearby excavations in saturated silty clay. The study focused on aspects such as load transfer mechanisms, settlement patterns, and bending moments.

Additionally, an advanced hypoplastic (clay) constitutive model with limited strain stiffness was applied. It is widely recognized that pile foundations support loads by redistributing stresses in their vicinity. In contrast, excavation represents a stress-relieving process that triggers movement in the surrounding ground.

When an excavation is carried out close to a pile foundation, several consequences may arise: (1) Reduction in the load-carrying capacity of the piles (2)

Potential for excessive settlement of the piles (3) Possible appearance of building cracks (4) Risk of structural collapse under extreme conditions.

## 2. Finite Element Analysis

In this paper, 3D finite element analysis is carried out using ABAQUS software, employing an advanced hypoplastic model. To accomplish the objectives of this research, advanced 3D numerical modeling using a hypoplastic model was conducted. A total of eight analyses were carried out, varying the clear distance between the footing and diaphragm wall at 0.5 m, 1.0 m, 1.5 m, 2.0 m, 4.0 m, 6.0 m, 8.0 m, and 10.0 m.

The final excavation depth (He) was set at 12 m. Each simulation focused on the effect of excavation on a 1.2 m × 1.2 m square footing positioned at a depth of 0.75 m. Figure 1 depicts an elevation view of the analysis for a representative case with a clear distance of 2.0 m. Typically, the ratio of wall penetration depth to excavation depth in engineering practice ranges from 0.5 to 2 (Ng et al., 2001), thus a value of 0.67 was selected for this study. The diaphragm wall was 20 meters deep.

The diaphragm wall is supported by the props, which are spaced three meters vertically. The axial rigidity of 81×103 kNm is modeled for the props (Mašín et al., 2005). Ten meters separates the props horizontally. The excavation is 5 meters long. Given the symmetry of the excavation, a half-excavation measuring 4 meters in length was modeled.

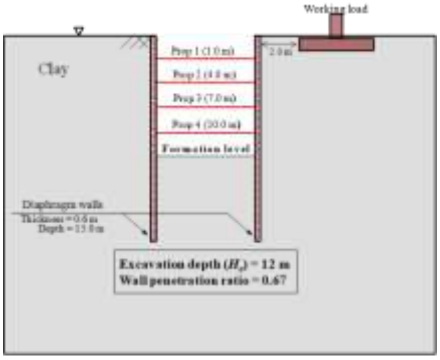


Fig. 1. Elevation view of analysis for case S (a) friction pile (b) end-bearing pile

## 3. Finite Element Mesh and Boundary Conditions

A finite element mesh measuring 50 m × 20 m × 40 m was utilized in the case of S, as shown in Fig. 2. In this three-dimensional parametric study, the diaphragm wall, footing, and soil were all modelled using solid elements with an 8-node trilinear continuum.

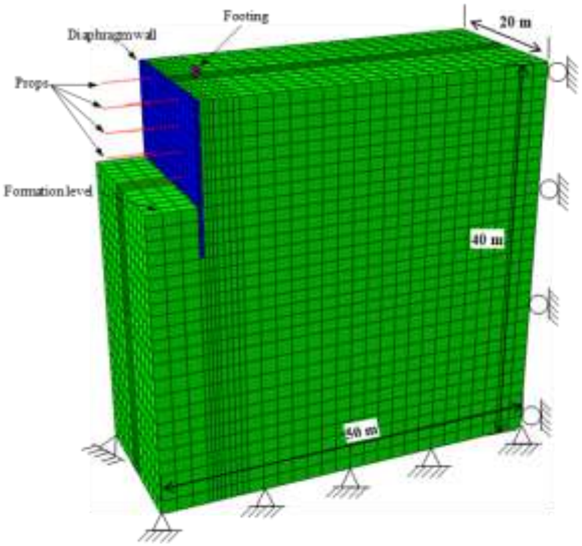


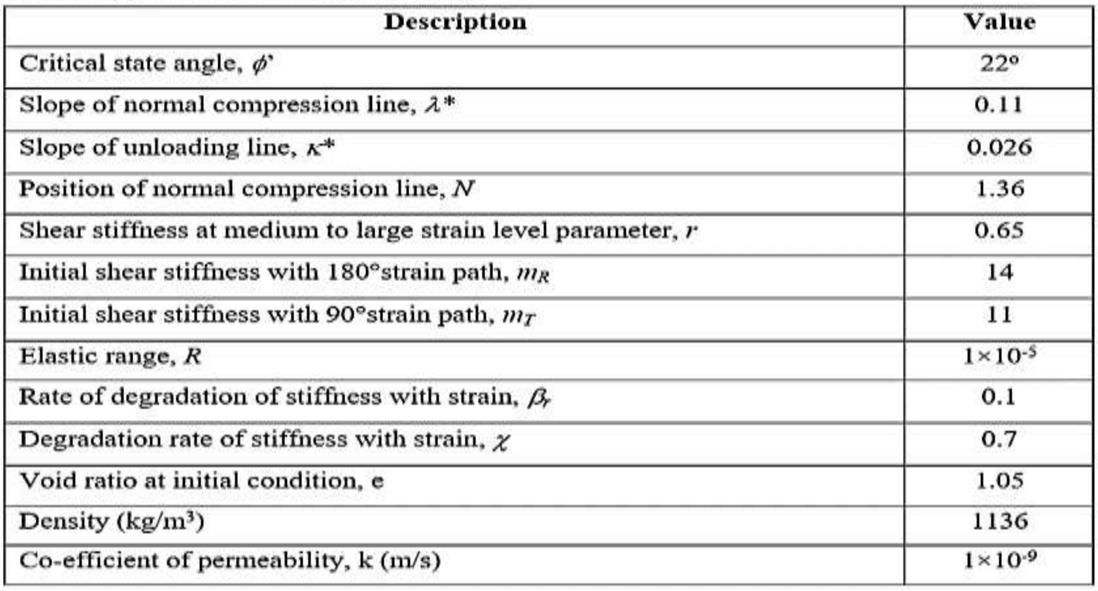
Fig. 2. Finite element mesh and boundary conditions

In this parametric study, the hypoplastic clay model parameters for kaolin powder were taken from the available literature [8] shown in table 1. The horizontal stresses were computed by calculating rest lateral earth pressure coefficient Ko by Jáky's equation.

$$K_0 = (1 - sin\varphi')$$

The concrete footing, diaphragm wall, and props were modelled as elastic materials with the following parameters: Young's Modulus (E) = 35 GPa, Poisson's ratio (v) = 0.3, Density (ρ) = 2400 kg/m³.

**Table 1: Hypoplastic model parameters**



| Description | Value |
|---|---|
| Critical state angle, $\phi'$ | 22° |
| Slope of normal compression line, $\lambda^*$ | 0.11 |
| Slope of unloading line, $\kappa^*$ | 0.026 |
| Position of normal compression line, $N$ | 1.36 |
| Shear stiffness at medium to large strain level parameter, $r$ | 0.65 |
| Initial shear stiffness with 180°strain path, $m_R$ | 14 |
| Initial shear stiffness with 90°strain path, $m_T$ | 11 |
| Elastic range, $R$ | $1\times10^{-5}$ |
| Rate of degradation of stiffness with strain, $\beta_r$ | 0.1 |
| Degradation rate of stiffness with strain, $\chi$ | 0.7 |
| Void ratio at initial condition, e | 1.05 |
| Density (kg/m$^3$) | 1136 |
| Co-efficient of permeability, k (m/s) | $1\times10^{-9}$ |

## 4. Results and Discussion

### 4.1. Ultimate Bearing Capacity of the Footing

This study investigates shallow foundation (subjected to working load) response to adjacent excavations at different horizontal distance from diaphragm wall. A numerical load test was performed for the footing (1.2 m × 1.2 m) to compute its ultimate bearing capacity. The load of 58 kN (with increment of 3 kN) was applied on the footing over period of 24 h.

Fig. 3 shows the relationship between load and settlement the footing. The load curve was obtained through a numerical load test conducted on the footing. In the figure, the estimated "yield" point, which signifies the point when the load-settlement curve begins to deviate from the tangent line, is clearly marked. Additionally, the ultimate load for each footing, calculated using Meyerhof's bearing capacity equation (Liyanapathirana et al., 2016), is shown.

The load settlement curve initially displays linear behavior but exhibits non-linear characteristics as the load increases, culminating in a distinct "yield" point at 15 kN. Employing the tangent intersection method, the calculated ultimate load is determined to be 25 kN. The ultimate load calculated from Meyerhof's equation the footing was 45 kN, compared to calculated bearing capacity, it is observed that computed bearing capacity is smaller than that of calculated. This is because in analytical solution given by Meyerhof (Liyanapathirana et al., 2016) assumed that soil behave as perfectly plastic. In contrast, the soil behavior modelled in this numerical analysis is assumed as elasto-plastic material with hardening.

The soil will deform due to loading as well as yield progressively because of finite element formulation. Using load settlement curves, the settlement of due to their corresponding calculated ultimate loads were determined as 72 mm, 132 mm and 81 mm, respectively. With factor of safety of 1.5, the working loads were determined as 16.67 kN. Using load settlement curve, the settlement of footing due to their corresponding computed ultimate load was obtained as 4.2 mm (0.34 B%).

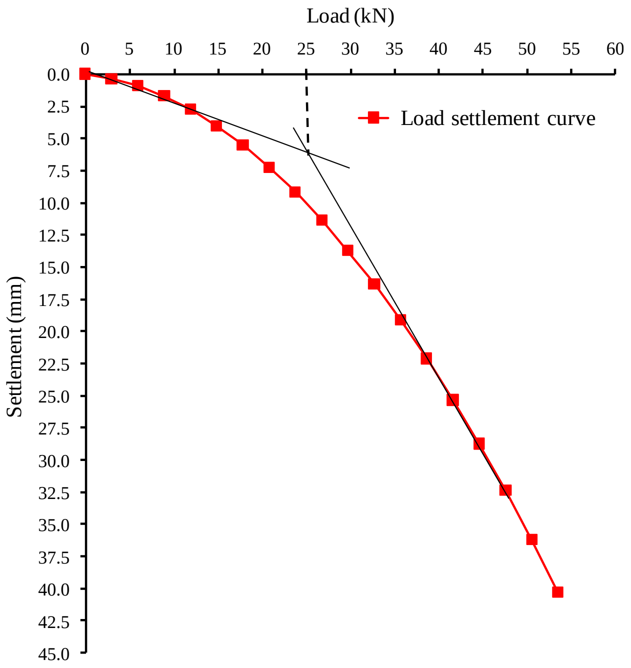


Fig. 3. Load Settlement Curve

## 4.2. Excavation Induced Footing Settlement and Bearing Capacity Loss

Fig. 4 shows normalized incremental settlement of footing (S/B) during different excavation stages for clear distance between footing and diaphragm wall of 0.5 m and 10 m. Excavation stages are indicated by h and are normalized by final excavation depth (i.e., He = 12 m). It can be seen that the non-linear settlement induced during excavation stages for both the cases. The rate of incremental settlement increased as excavation proceeded. The incremental settlement due to final excavation stage (i.e., h/He = 1.0) is the highest as compared to settlement induced due to first three excavation stages (i.e., h/He = 0.25, 0.50 and 0.75).

This is attributed to ground movement due to excavation-induced stress release). Compared to incremental settlement of the footing in case of clear distance = 0.5 m, it is observed that the settlement in case of clear distance = 10 m is smaller at each excavation stage. This is because the footing is farthest and subjected to less stress release and surface settlement is smaller. The final additional amounts of settlement due to excavation are 42 mm (3.45 B%) and 26 mm (2.13 B%) in case of clear distance = 0.5 m and 10 m, respectively.

The settlement of the footing due to the applied working load is 4.2 mm (0.34 B%). Therefore, the footing settles by 46.2 and 30.2 mm (being equivalent to 3.8 B% and 2.47 B%) due to both the applied working load and the excavation in the case of clear distance =0.5 m and 10 m, respectively. Based on data from 95 settling buildings, Zhang & Ng (2005) developed a reliability-based serviceability criterion for settlement (i.e., 56 mm). According to their criterion, the footing in both cases still met the serviceability requirement after excavation. This conclusion might not hold true in situations where the volume loss caused by tunnelling is different from what was used in this study or where the ground conditions are different.

Given that settlement criteria are frequently used to interpret footing capacity, it is possible to link excavation-induced footing settlement to an apparent loss of bearing capacity. According to this study, each case's footing settling as a result of the applied working load (prior to excavation) is 0.34 B%, or 4.2 mm. The induced settlement of the footing in the clear distance = 0.5 m case was 42 mm as a result of the subsequent excavation. Based on the load settlement curve in the fig. 4, the footing acts as though it were loaded with an additional 55 kN load on top of this additional settlement. The additional load is equivalent to 1.5 times the footing's ultimate capacity, as established by the tangent intersection method.

Put another way, in the case of clear distance = 0.5 m, the excavation resulted in an apparent loss of footing capacity (ALFC) that was 1.5 times greater than the ultimate capacity. In a similar vein, it is easy to compute that in the case of a clear distance of 10 m, the ALFC was 1.2 times that of the ultimate capacity.

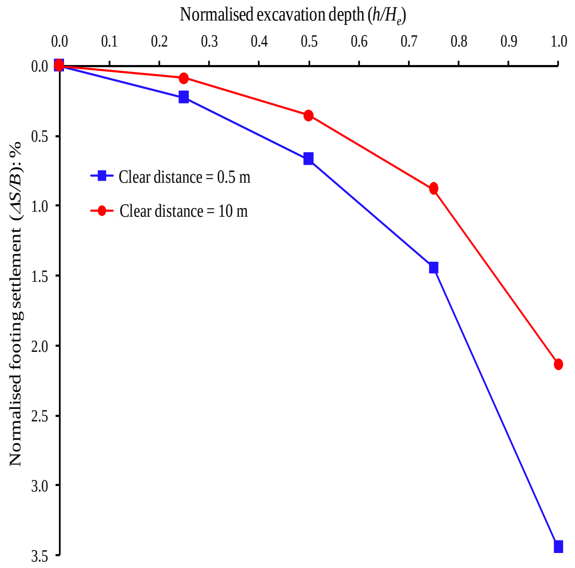


Fig. 4. Normalized footing settlement due to different excavation stages

### 4.3. Effect of Footing Locations on Induced Settlement

Fig. 5 shows the induced footing settlement after excavation at different horizontal distance from diaphragm wall (i.e., 0.5, 1.0, 1.5, 2.0, 4.0, 6.0, 8.0 and 10.0 m). The incremental settlement (S) and clear distance between footing and diaphragm wall (x) is normalized by footing width (B). The induced settlement decreases exponentially with distance away from diaphragm wall. Firstly, the excavation induced settlement increases as clear distance increases with maximum settlement at clear distance = 2 m. However, as clear distance increases the induced settlement decreases. This can be because of ground surface settlement. The maximum ground surface settlement is found at 2.0 m distance from diaphragm wall. This reason can be ascribed to stress release due to excavation.

The stress release decreases with distance away from diaphragm wall and no shear strain is induced away from the diaphragm wall. Consequently, the induced settlement of footing decreases. The incremental settlements of 44.5, 47, 48, 46.5, 38.5 and 30.0 mm were induced in footing located at 1.0, 1.5, 2.0, 4.0, 6.0, 8.0 m from diaphragm wall, respectively after completion of excavation. The apparent loss in bearing capacity of the footing located at 0.5 and 10.0 m due to excavation-induced settlement is discussed in pervious section. Similarly, the apparent losses in bearing capacity due to induced settlement of the footings located at 1.0, 1.5, 2.0, 4.0, 6.0, 8.0 m from the diaphragm wall are 1.65, 1.73, 1.81, 1.70, 1.53 and 1.30 times of ultimate capacity, respectively.

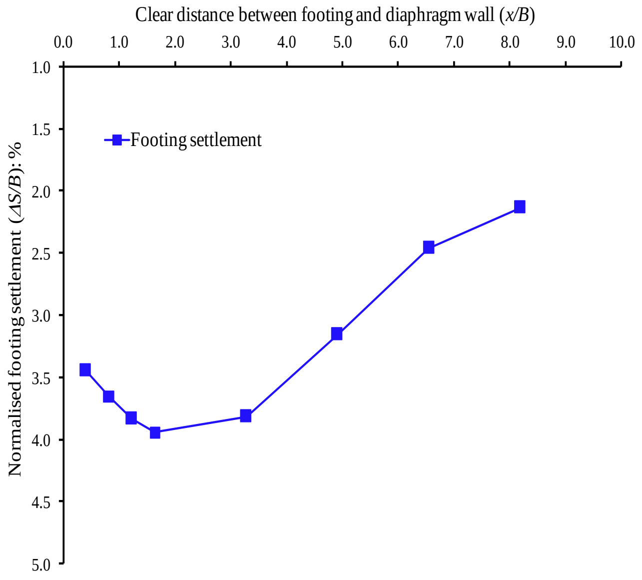


Fig. 5. Effect of location of footing from diaphragm wall on induced settlement

### 4.4. Effect of Footing Locations on Induced Lateral Movement

Figure 6 illustrates the lateral movement of the footing caused by excavation at various horizontal distances from the diaphragm wall (i.e., 0.5, 1.0, 1.5, 2.0, 4.0, 6.0, 8.0, and 10.0 m). The clear distance (x) between the footing and diaphragm wall is normalized by the footing width (B). It is evident that the lateral movement diminishes exponentially as the distance from the diaphragm wall increases.

Initially, the lateral movement resulting from excavation increases as the clear distance grows, reaching its peak settlement at a clear distance of 2 m. However, as the clear distance continues to increase, the induced settlement decreases. This reduction may be attributed to ground surface settlement, which is most significant at a distance of 2.0 m from the diaphragm wall. This phenomenon is likely caused by stress release due to excavation, with stress release diminishing as the distance from the diaphragm wall increases, resulting in no shear strain being induced away from the diaphragm wall and leading to a decrease in induced lateral movement of the footing. After the completion of excavation, the lateral movement induced at distances of 0.5, 1.0, 1.5, 2.0, 4.0, 6.0, 8.0, and 10.0 m from the diaphragm wall amounted to 0.22, 1.7, 3.0, 4.0, 5.0, 4.5, 4.0, and 3.22 mm, respectively.

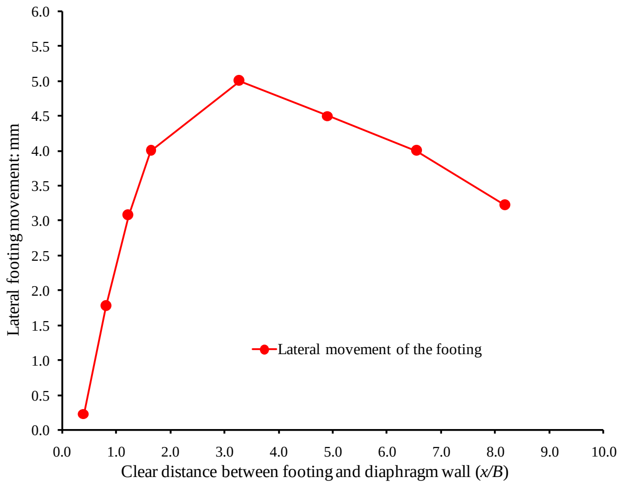


Fig. 6. of location of footing from diaphragm wall on induced lateral movement of the footing

## 5. Conclusions

The following are the conclusions:

- The induced settlement decreases exponentially with distance away from the diaphragm wall. The incremental settlements of 44.5, 47, 48, 46.5, 38.5 and 30.0 mm were induced in footing located at 1.0, 1.5, 2.0, 4.0, 6.0, 8.0 m from the diaphragm wall, respectively after completion of excavation.
- Considering footing capacity is often interpreted using settlement criteria, excavation induced footing settlement may be correlated to an apparent loss of bearing capacity. The apparent losses in bearing capacity due to induced settlement of the footings located at 1.0, 1.5, 2.0, 4.0, 6.0, 8.0 m from the diaphragm wall are 1.65, 1.73, 1.81, 1.70, 1.53 and 1.30 times of ultimate capacity, respectively.
- The excavation depth and the space between the footing and the diaphragm wall both have a significant impact on the induced lateral movement of the footing.

## 6. Recommendations

Based on the computed results of excavation effects on square footings in soft clay, following are the recommendations for future work:

- Excavation effect on different footing shape and size.
- Excavation effect on different types of shallow foundations such as raft and strip footing.
- Excavation effect on shallow foundations subjected to lateral loading.

*DECLARATION OF COMPETING INTEREST*: I declare that I have no competing interest as a reviewer.

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