Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-400

A numerical study on the behavior of contiguous pile wall supporting footing adjacent to an excavation

Aradhana Mishra[1], V.A Sawant[2]

Department of Civil Engineering, IIT Roorkee, Uttarakhand, India,247667

ABSTRACT: In this era of urbanization, a contiguous pile wall has emerged as an effective deep excavation solution. The present work focuses on the numerical analysis of contiguous pile walls with the effect of surcharge in unreinforced and reinforced sand bed. The large-scale plane strain model is prepared in PLAXIS 2D, with validated geometrical and geotechnical parameters to neglect boundary confinement. The backfill is maintained at different relative densities from medium to very dense (50 %,75 %, 90 %). The diameter of the pile wall and the location of the surcharge is varied. The static response is further compared numerically with the seismic response of the wall by incorporating k_h and k_v coefficients. It is seen that vertical settlement (Δ_v) of footing, lateral displacement (Δ_h) of the wall, and bending moment (M) are significantly reduced when reinforced with geogrids. The numerical model showed that the contiguous pile wall performed satisfactorily in supporting both reinforced and unreinforced backfill. The wall with geogrid reinforcement beneath the footing can be used as greater excavation support system adjacent to high-rise service buildings.

Keywords: Vertical settlement of footing; bending moment; lateral displacement of the wall; contiguous pile wall (CPW)

1 INTRODUCTION

In metropolitan locations, substantial amounts of excavation have been done near services and structures in recent decades. Buildings with shallow foundations have confined impact zone, but buildings with deeper foundations may need vast excavations that requires support during excavation (Tan and Wei 2012; Ou et al. 2013). Various retention systems were adopted in recent decades to support the excavation like contiguous pile wall (CPW), secant pile wall, diaphragm wall, sheet pile wall, meter panel wall dual row pile wall etc.(Azzam and Elwakil 2016; Khoiri and Ou 2013; Doubrovsky and Meshcheryakov 2015; Sudani et al. 2015). The contiguous pile wall has sparked interest in the research community because of its cost-effective retention method for medium to large excavations. Further, presence of soil (both cohesive and cohessionless soil having lower stiffness) in the gaps between piles (higher stiffness material) makes it a discrete structure with complex interaction mechanism with backfill and surcharge. This requires proper model analysis (inclusive of its discrete behavior) to predeterine the efficiency of CPW in field. Hence, attention needs to be given for understanding the behavior of these walls under static and seismic conditions. Some parametric studies on contiguous pile walls in clay or sandy soil were conducted examining effect of excavation depth, pile embedding depth, wall stiffness, and soil wall friction angle (Ramadan et al.,2018; Ramadan and Meguide, 2020). Guharay and Baidya (2015) used finite-element analysis to study earth pressure on cantilever sheet pile walls during excavation. Some numerical and experimental studies, centrifuge tests are used to determine empirical formulas to ascertain various lateral response parameters including the bending moment, ground settlement, and critical excavation depth of the contiguous pile wall (Viswanadham et al. 2009, Samadhiya 2019; Georgiadis and Anagnostopoulos (1998) Chavda and Solanki 2019, El Sawwaf and Nazir 2012). Singh and Chatterjee 2019 investigated the performance of cantilever sheet pile walls by using seismic pseudo-static analysis. Because of the time and resources required for experimental research, numerical modelling has become an attractive alternative. Various soil constututive models were adopted by previous researchers to study the wall response.The importance of constitutive behaviour is influenced by a wide variety of soil properties (Brinkgreve, 2005). Due to time consumption in pure dynamic analysis, pseudo-static analysis may be used as alternative to assess geotechnical structural stability against earthquake induced forces. Dynamic loading, such as earthquake-induced loading, is represented by equivalent inertial forces, which are approximated as constant body forces with magnitude proportional horizontal vertical accelerations of the dynamic loading (Kramer 1996). The present study involves seismic assessment of the CPW using pseudostatic approach by conservatively determining the optimum depth of excavation.

2.NUMERICAL MODELING

2.1 Validation

The model validation was done using the experimental findings of El Sawwaf and Nazir (2012) by considering soil relative density, D_r = 75% as in Figure 1. This study validates the experimental model numerically using the Hardening soil (HS) model and Mohr coulomb (MC) model using PLAXIS 2D. Unreinforced and reinforced soil beds were modelled numerically by using geogrids. having peak tensile strength of 13.5 kN/m.

Figure 1 shows that unreinforced wall and footing settlement deviated within a range of 5–7% with findings of El Sawwaf and Nazir (2012). Numerical forecast of wall displacement and footing settlement variation in reinforced example was 2–5% with findings of El Sawwaf and Nazir (2012). PLAXIS 2D plane strain condition with HS model matches confirmed findings and may be utilised in numerical analysis in this research. This validated model was further scaled up 20 times using appropriate scaling laws to represent field behavior of the CPW supporting unreinforced and reinforced backfill under pseudostatic conditions.

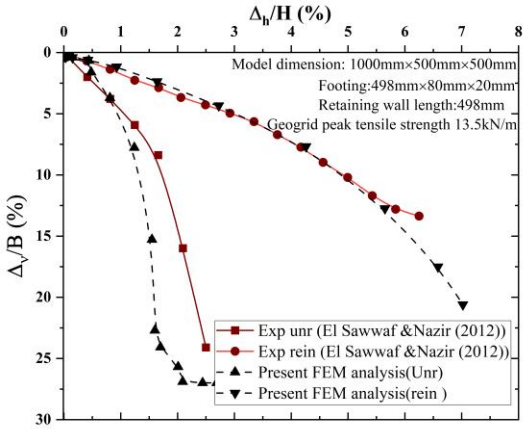


Figure 1. Validation curve

2.2 Prototype study

Contiguous pile wall (CPW) supporting both reinforced and unreinforced backfill with footing load adjacent to it, is analysed using finite element software PLAXIS 2D as in Figure 2. Soil properties with pile characteristic length (T), soil subgrade reaction modulus (η_h) and HS model parameters are presented in Table 1 and Table 2. The details of the model parameters are given in Mishra and Sawant (2023). A 2D plane strain model with dimensions of 40 m (length) ×30 m (depth) with 20 m deep embedded pile wall having diameters 600 mm (for wall type 1) and 1000 mm (for wall type 2) (E_{pile}=28GPa) were used to support a surcharge load of q=50kPa acting over a footing of width *B*= 3.2 m. Dry condition is assumed in this study. Soil was modelled using 15-noded discrete triangular elements. The interface element for the interaction between the soil and piled wall element was employed (R_{inter}=0.7). The HSM uses a hyperbolic stress–strain representation for the soil and three moduli $E_{50}^{ref} = E_{oed}^{ref}$ and E_{ur}^{ref} .Using the empirical relationships presented by Brinkgreve et al. (2010); Ramadan and Meguid (2020), the sand stiffness parameters were determined for a range of relative densities as in Table 2. In PLAXIS 2D plane strain modeling the pile wall was modeled as equivalent plate element. After wall embedment, the backfill surcharge was activated. After this the seismic pseudo static condition was applied.

The model geometry and deformed mesh are shown in Figure 2.The equivalent normal stiffness ($E_pA_{p,eq}$) and bending stiffness ($E_pI_{p,eq}$) of plane strain pile wall (inclusve of discrete nature due to gaps between piles)was calculated as $E_pA_{p,eq} = n(E_pA_p)/L_r$ and $E_pI_{p,eq}=n(E_pI_p)/L_r$, where, n=No of piles in a row., L_r= Out of plan length, (Prakoso and Kulhawy 2001).

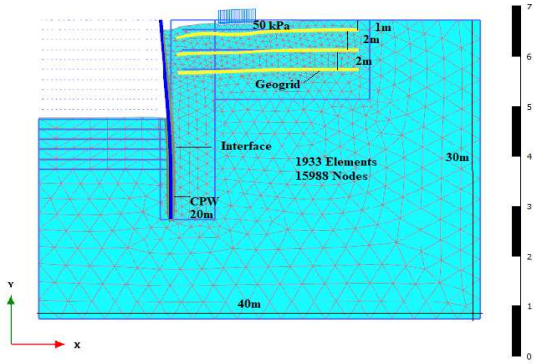


Figure 2. Finite element model with HS model

Table 1. General properties of soil and pile

Soil	D_r (%)	γ_d (kN/m^3)	ϕ	η_h kN/m^3	T(m) (600mm dia)	T(m) (1000mm dia)
Medium	50	17	34	25000	1.48	2.23
Dense	75	18	37	60000	1.24	1.87
Very dense	90	18.6	40	85000	1.16	1.74

Table 2. HS-model parameters for different sands

Property	D_r=50%	D_r=75%	D_r=90%
γ_{unsat}	17	18	18.6
γ_{sat}	19.8	20.2	20.44
E_{50}^{ref}	30000	45000	54000
E_{oed}^{ref}	30000	45000	54000
E_{ur}^{ref}	90000	135000	162000
m	0.54	0.47	0.42
ϕ	34	37	41
ψ	4	7	11
R_f	0.94	0.91	0.89

Table 3. Model input parameters

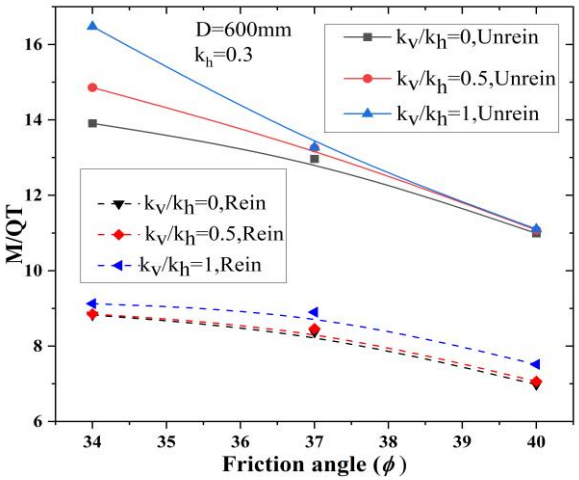
k_h	*0.05g,0.1g,0.15g,0.2g,0.3g,0.4g,0.5g*
k_v	*0k_h,0.5k_h,1k_h*
q	*20kPa,50kPa,100kPa*
a	*0.5B,1B,1.5B,2B,3B,4B,5B*

3. RESULTS AND DISCUSSIONS

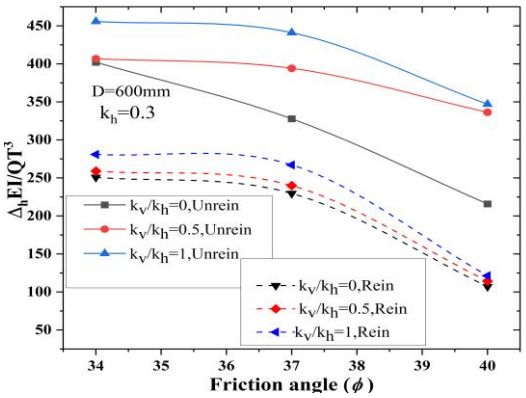
The response of CPW under the action of pseudostatic forces is discussed for both reinforced and unreinforced sand bed. The effect of geogrid reinforcement, soil density, stiffness of wall and surcharge distance on the bending and deformation behavior of the wall are presented. It is worth noticing that the stiffness of the wall contributing towards stability of the structure includes both the stiffness of the piles and soil from the backfill filled between the gaps of the wall. The responses are expressed in normalized terms (bending moment as M/QT, vertical settlement as Δ_v/B and lateral displacement as $EI\Delta_h/QT^3$)

3.1 Effect of friction angle

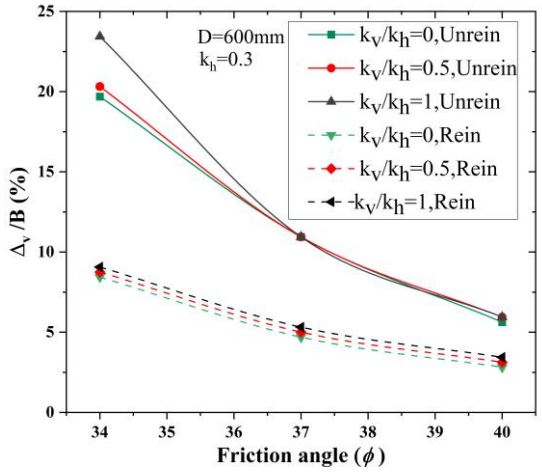
The characteristic of backfill soil is presented in terms of its friction angle (ϕ). Figure 3 shows the variation of bending moment (M/QT), vertical settlement (Δ_v/B) and lateral deformation $EI\Delta_h/QT^3$ with friction angle (ϕ) for D = 600mm and k_h = 0.3. Dense packing of the soil localizes the footing stresses and hence moment observed on the wall decreases (Figure 3-a). In unreinforced case, for a particular value of k_v/k_h = 0.5, a normalized moment of 11.11 is observed for ϕ = 40° which is 25% less than 14.86 observed for ϕ = 34°.



(a)



(b)



(c)

Figure 3. Effect of friction angle on CPW response

The top portion of the wall showed higher bending with M/QT increasing from 14 to 16.48 for k_v/k_h varying from 0 to 1 for ϕ = 34°. Interestingly, the moment reduces by 30 to 45 %, when reinforcements are introduced in the backfill. The trend of bending moment developed over the wall was in accordance with the findings of Nandi and Choudhury (2023). Similarly, for unreinforced case, the normalized lateral displacement increases from 327.8 to 440.9 with increase in seismic ratio k_v/k_h from 0 to 1 for ϕ = 37° (Figure 3-b). Further, 1 – 2 fold reduction in the lateral displacement is noticed when ϕ increases from 34° to 40°. Similar results were obtained by Singh and Chatterjee (2020a) for unreinforced backfill. A significant reduction in the lateral displacement is also observed when backfill is reinforced with geogrids. In terms of normalized vertical settlement, a decrement of 65% - 75% is seen with increase in soil friction angle for both unreinforced and reinforced case (Figure 3-c). However, marginal difference can be observed with variation of k_v/k_h from 0 to 1. It is noteworthy that, for each parameter, the reinforcing effect observed is more pronounced for relatively loose soil.

3.2 Effect of distance of footing

The distance of footing from CPW significantly influences the response of wall especially under seismic conditions. Figure 4 shows various CPW responses with normalised increase in footing distance (*a/B*) for ϕ = 34° and k_h = 0.3.

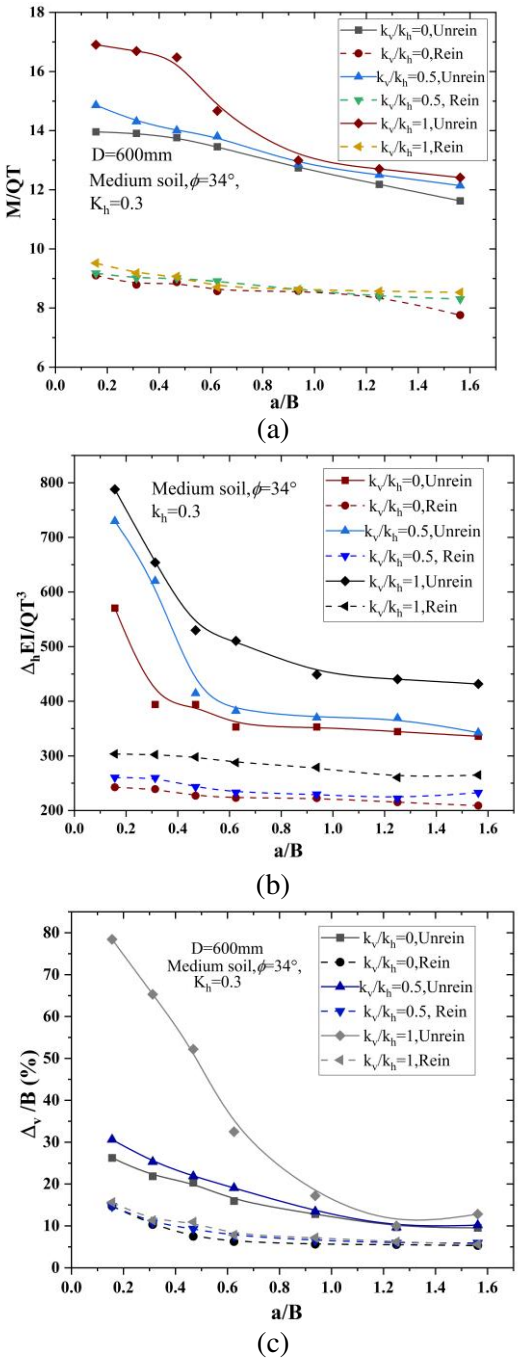


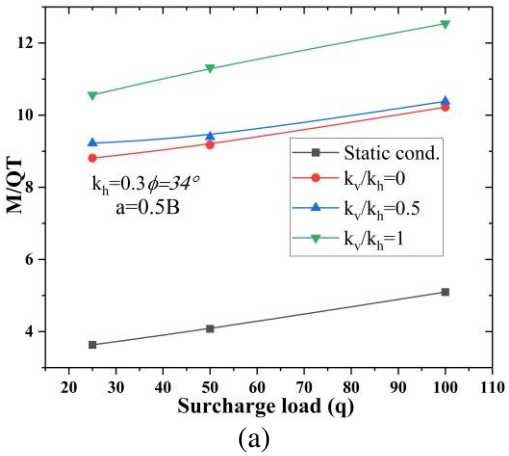
Figure 4. Effect of footing distance on CPW response

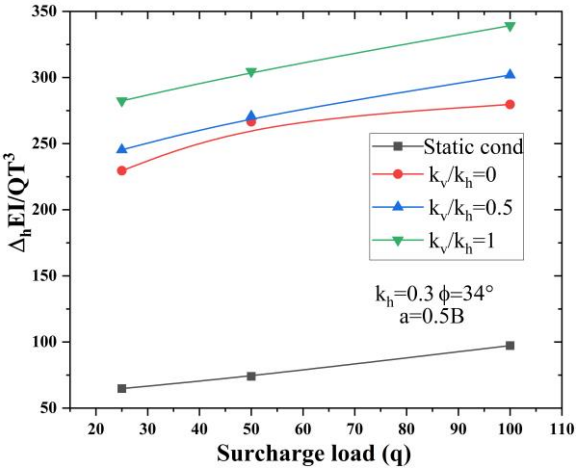
Highest *M/QT* response is observed for maximum excitation case of k_v/k_h = 1 for unreinforced case which decreases from 16.98 to 13 with increase in *a/B* from 0 to 1.6 (Figure 4-a). Similarly, maximum values of 800 and 80 are obtained for $\Delta_h EI/QT^3$ and Δ_v/B respectively for excitation value k_v/k_h = 1. However, the value of each parameter decreases with increase in footing distance. This is in accordance to the behavior observed by Singh and Chatterjee (2020b). It is worth noticing that the rate of decrease becomes negligible for *a/B* > 1. The footing distance has no further effect on the seismic response of the wall. Additionally, for each parameter, a significant reduction in the values are observed for the reinforced case for any distance of the footing. However, for closer distances (*a/B* < 0.6), the amount of reduction varied between 50% – 80% which reduced to 20% - 35% for *a/B* > 1.

3.3 Effect of different surcharge loading

Surcharge load may cause foundation pits to distort excessively or possibly collapse, however this impact has only been examined in a small number of studies. Loading was decided according to Ye & He (2022). The effect of various surcharge loading (*q*=25, 50 and 100 kPa) on CPW by considering the seismic condition was examined. Analysis has been done for *D*=600 mm diameter CPW with k_h=0.3, D_r=50% and *a*= 0.5B. The normalized bending moment (*M/QT*) and lateral displacement ($EI\Delta_h/QT^3$) of wall was analysed as in Figures 5(a) and (b). The static and seismic response of CPW was analysed and compared. With increasing surcharge load, a greater increase in bending moment was observed. At 25 kPa there is increase of 50%-58% of bending moment when k_v/k_h varied from 0 to 1. Similarly, for 50 kPa and 100 kPa increment of bending moment was around 51%-66% from static bending moment as in Figure 5(a).

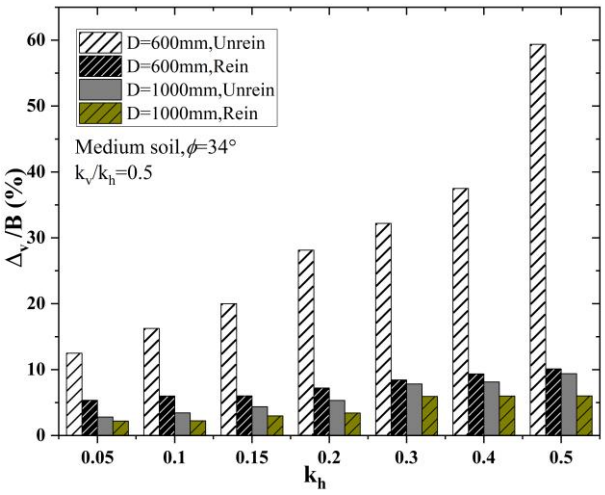
Similar trend was observed in case lateral displacement for static and seismic response. A huge variation of 71%-78% of increment in lateral displacement in CPW was observed with increase in k_v along with increase in surcharge magnitude as in Figure 5(b). However, the moment and lateral displacement obtained in reinforced cases or cases with larger pile diameter (mentioned in section 3.1, 3.2 and 3.4) were significantly lower.





(b)

Figure 5. Effect of surcharge on CPW response

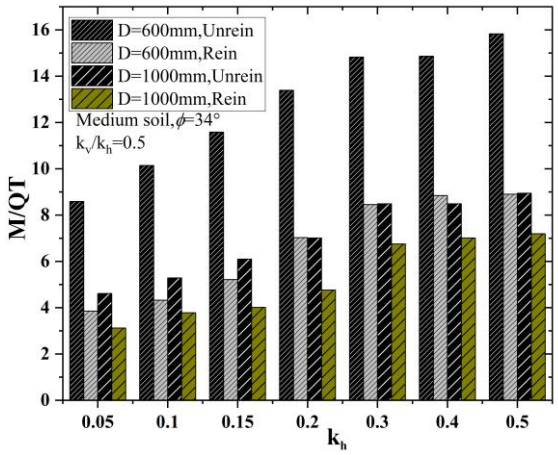


(c)

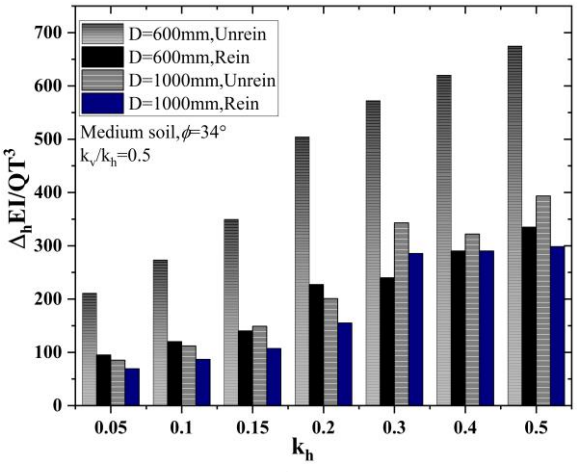
Figure 6. Improvement in CPW response

3.4 Effect of k_h and improvement in CPW response

For a designer, typically two alternatives are available for improving the performance of CPW, either increase the pile diameter or reinforce the backfill using geogrids. Figure 6 describes the improvement in the performance of CPW upon seismic excitation for $k_v/k_h = 0.5$ and $\phi = 34°$.



(a)



(b)

It can be seen from Figure 5(a) that decrement in *M/QT* lies in the range of 50%-60%, 40%-50% and 60%-70% when pile wall with *D*=600 mm is reinforced on the backfill side, diameter increased from *D*=600 mm to *D*=800 mm keeping the backfill unreinforced and reinforcing the backfill with increased diameter, respectively. Similar range of decrement are also observed for $\Delta_h EI/QT^3$ values with increase in k_h from 0.05 to 0.5 (Figure 6(b)). However, considerably large decrement is observed for Δ_v/B in the range 60% for k_h = 0.05 to around 90% for k_h = 0.5 (Figure 6(c)). It is worth noticing that for most of the cases, improvement by increasing the pile diameter has better effects than improvement by reinforcing the backfill. Nevertheless, best results are obtained when both the measures are adopted simultaneously.

4 CONCLUSIONS

In this study, the behavior of CPW retaining unreinforced and reinforced sand bed under seismic conditions has been numerically investigated by varying soil density, wall stiffness, footing distance, surcharge magnitude and seismic conditions. Further, the improvement in the performance of CPW in terms of bending and deformation capacity has been proposed by two techniques as either increase the pile diameter or reinforce the backfill soil. The major takeaways from this study are:

1. Increasing the density of the backfill (ϕ > 35°) can significantly reduce the vertical and lateral deformations observed in the structure by 40% - 60%.
2. The effect of seismic excitation (k_v/k_h) on the response of wall and footing becomes constant when footing is placed at larger distances (a/B > 1) from the CPW. However, for closely placed footing, vertical deformation of footing and lateral displacement and bending moment of wall are amplified.

3. The CPW constructed using larger diameter piles (D = 1000 mm) have high bending capacity and reduces the induced vertical and lateral deformations by 60% as compared to walls with smaller diameter piles (D = 600 mm).
4. The pile wall with higher diameter (D =1000 mm) or reinforced backfill pile wall configuration can effectively reduce the incumbent effects of high load intensity (till 100 kPa).
5. CPW retaining superstructures constructed on reinforced bed suffers 40% lesser deformations than unreinforced case. However, the stiffness of the reinforcements contributes primarily towards this stability and hence smaller diameter piles (D = 600mm) may be opted in conjugation with the reinforced case.

5 ACKNOWLEDGEMENTS

The authors acknowledge the following contributions: Mishra A: conceptualization, investigation, software, validation, writing - original draft and, Sawant, V.A: conceptualization, methodology, supervision, writing – review & editing references

6 REFERENCES

Azzam, W. R., and Elwakil, A. Z. 2017. Performance of axially loaded piled retaining wall: Experimental and numerical analysis, *International Journal of Geomechanics*, *17*(2), 04016049.

Brinkgreve, R.B., 2005. Selection of soil models and parameters for geotechnical engineering application. In *Soil constitutive models: Evaluation, selection, and calibration* (pp. 69-98).

Brinkgreve, R.B.J., Engin, E. and Engin, H.K., 2010. Validation of empirical formulas to derive model parameters for sands. *Numerical methods in geotechnical engineering*, *137*, p.142.

Chavda, J.T., Solanki, C.H. and Desai, A.K., 2019. Lateral response of contiguous pile wall subjected to staged excavation: physical and numerical investigations. *Indian Geotechnical Journal*, *49*, pp.90-99.

Doubrovsky, M.P. and Meshcheryakov, G.N., 2015. Physical modeling of sheet piles behavior to improve their numerical modeling and design. *Soils and Foundations*, *55*(4), pp.691-702.

El Sawwaf, M. and Nazir, A.K., 2012. The effect of deep excavation-induced lateral soil movements on the behavior of strip footing supported on reinforced sand. *Journal of Advanced Research*, *3*(4), pp.337-344.

Georgiadis, M. and Anagnostopoulos, C., 1998. Lateral pressure on sheet pile walls due to strip load. *Journal of geotechnical and geoenvironmental engineering*, *124*(1), pp.95-98.

GuhaRay, A. and Baidya, D.K., 2015. Reliability-based analysis of cantilever sheet pile walls backfilled with different soil types using the finite-element approach. *International Journal of Geomechanics*, *15*(6), p.06015001.

Khoiri, M. and Ou, C.Y., 2013. Evaluation of deformation parameter for deep excavation in sand through case histories. *Computers and Geotechnics*, *47*, pp.57-67.

Kramer, S.L. 1996. *Geotechnical earthquake engineering*, Hoboken, NJ: Prentice-Hall.

Mishra, A. and Sawant, V.A., 2023. A Detailed Investigation on Contiguous Pile Wall with Homogeneous Backfill. *Geotechnical and Geological Engineering*, pp.1-25.

Nandi, R. and Choudhury, D., 2023. Analytical method for determining displacement and bending moment of embedded cantilever retaining walls subjected to pseudo-static earthquake accelerations. *Soil Dynamics and Earthquake Engineering*, *164*, p.107642.

Ou, C.Y., Hsieh, P.G. and Lin, Y.L., 2013. A parametric study of wall deflections in deep excavations with the installation of cross walls. *Computers and Geotechnics*, *50*, pp.55-65.

Plaxis 2D v21 Plaxis material models. *Plaxis reference manuals*. The Netherlands.

Prakoso, W.A. and Kulhawy, F.H., 2001. Contribution to piled raft foundation design. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(1), pp.17-24.

Ramadan, M.I., Ramadan, E.H. and Khashila, M.M., 2018. Cantilever contiguous pile wall for supporting excavation in clay. *Geotechnical and Geological Engineering*, *36*, pp.1545-1558.

Ramadan, M.I. and Meguid, M., 2020. Behavior of cantilever secant pile wall supporting excavation in sandy soil considering pile-pile interaction. *Arabian Journal of Geosciences*, *13*(12), p.466.

Samadhiya, N.K., 2019. Evaluation of model sheet pile wall adjacent to a strip footing–an experimental investigation. *International Journal of Geotechnical Engineering*.

Singh, A.P. and Chatterjee, K., 2020. Ground settlement and deflection response of cantilever sheet pile wall subjected to surcharge loading. *Indian Geotechnical Journal*, *50*, pp.540-549.

Singh, A.P. and Chatterjee, K., 2020. A simplified method for seismic design of cantilever sheet pile walls under infinite uniform surcharge load. *International Journal of Geomechanics*, *20*(9), p.04020139.

Sudani, G.A., Brake, N. and Jao, M., 2015. Stability of footings adjacent to pile walls. *International Journal of Geomechanics*, *15*(6), p.04015006.

Tan, Y. and Wei, B., 2012. Performance of an overexcavated metro station and facilities nearby. *Journal of Performance of Constructed Facilities*, *26*(3), pp.241-254.

Viswanadham, B., Madabhushi, S., Babu, K. and Chandrasekaran, V., 2009. Modelling the failure of a cantilever sheet pile wall. *International Journal of Geotechnical Engineering*, *3*(2), pp.215-231.

Ye, J. and He, X., 2022. Response of dual-row retaining pile walls under surcharge load. *Mechanics of Advanced Materials and Structures*, *29*(11), pp.1614-1625.