State of the Practice of Rigid Inclusions

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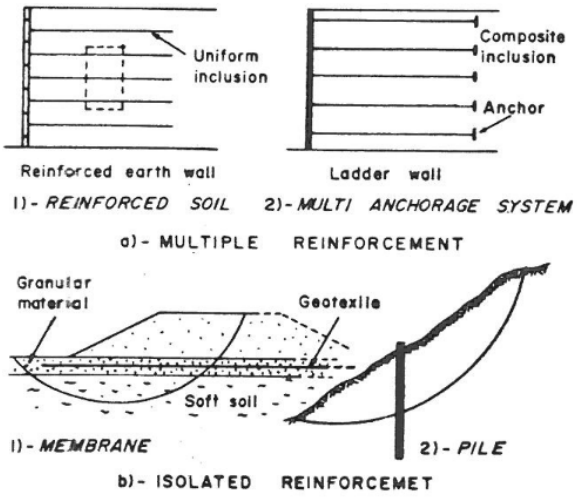
Inclusions for Soil Improvement

"Soil Reinforcement is a special and recent field of soil improvement. It covers a range of techniques which consist of placing **resisting inclusions** in the soil."

Schlosser, F., Juran, I., & Jacobsen, H. M. (1983). Soil Reinforcement: general report: session no. 5. In Proc. of VIII ECSMFE: Helsinki.



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Rigid Inclusions for Soil Improvement

Combarieu, O. 1988. Amélioration des sols par inclusions rigides verticales (**Improvement of soils by vertical rigid inclusions**). Application à l'édification de remblais sur sols médiocres. Revue Française de Géotechnique, 44, 57-79.

Canetta, G. and Nova, R. (1989). "A numerical method for the analysis of ground improved by **columnar inclusions**. " Computers and Geotechnics, 7(1–2), 99-114.

Alamgir, M., Miura, N., Poorooshasb, H.B., Madhav, M.R. (1996). "Deformation analysis of soft ground reinforced by **columnar inclusions**." Computers and Geotechnics, 18(4), 267-290.

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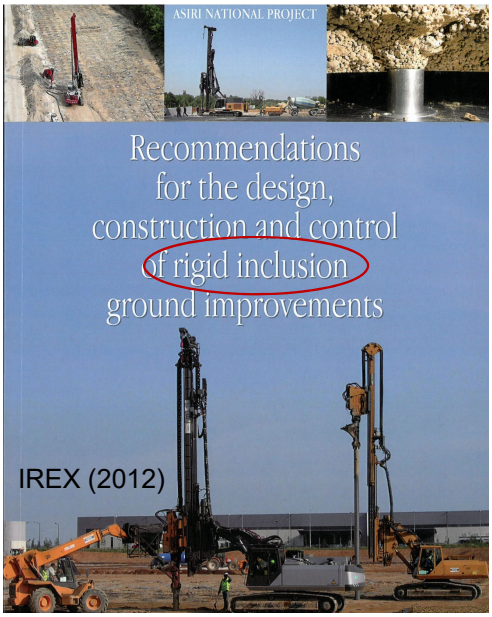
Rigid Inclusions for Soil Improvement

Chu, J., Varaksin, S., Klotz, U. & Mengé, P. (2009). State of the Art Report: Construction Processes. 17th Int. Conf. on SMGE: TC17 meeting ground improvement, Alexandria, Egypt.

- Defined/highlighted rigid inclusions

Other Terminologies

- Composite ground in Japan (1950s)
- Rigid column composite ground (Han & Ye 1991)
- Unconnected, disconnected, or non-connected piled raft (e.g. Wong et al. 2000; Baziar et al. 2018; Ko et al. 2019)



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Definition of Rigid Inclusions

Rigid inclusions are cementitious columns that are significantly stiffer than the surrounding soil and their stability is achieved without any lateral confinement of the surrounding soil . The purpose of the rigid inclusions is to improve the ground performance globally (i.e., increase bearing capacity, reduce settlement, and improve ground stability). A load transfer cushion or platform is typically installed between the top of the rigid inclusions and the bottom of the superstructure, which allows for more load sharing with the surrounding soil.

Typical rigid inclusions are concrete columns (possibly installed into the ground with a classical piling technique), grout columns, soil mix elements (columns, panels, trenches, blocks, etc.), grouted stone columns, etc.

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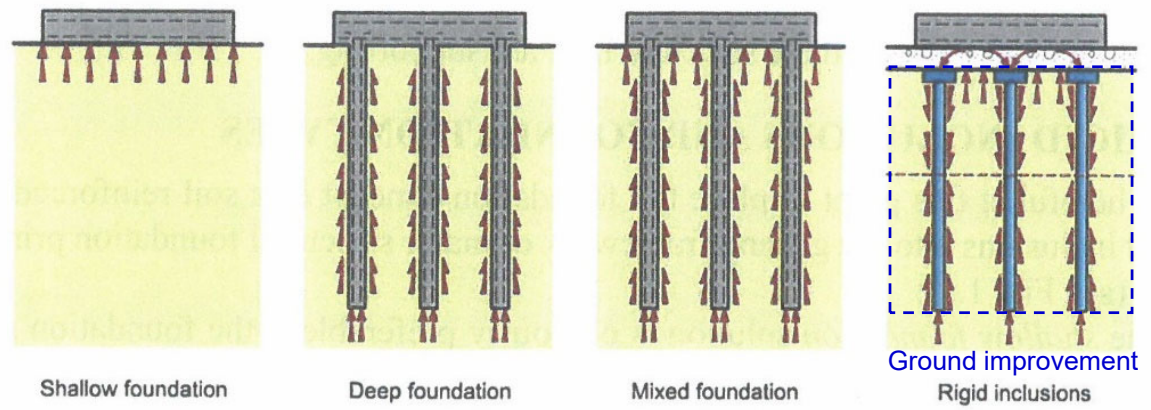
Different Foundation Systems



One important feature of rigid inclusions is that they are not connected with superstructure, often with a cushion (also called load transfer platform).

ASIRI (2012)

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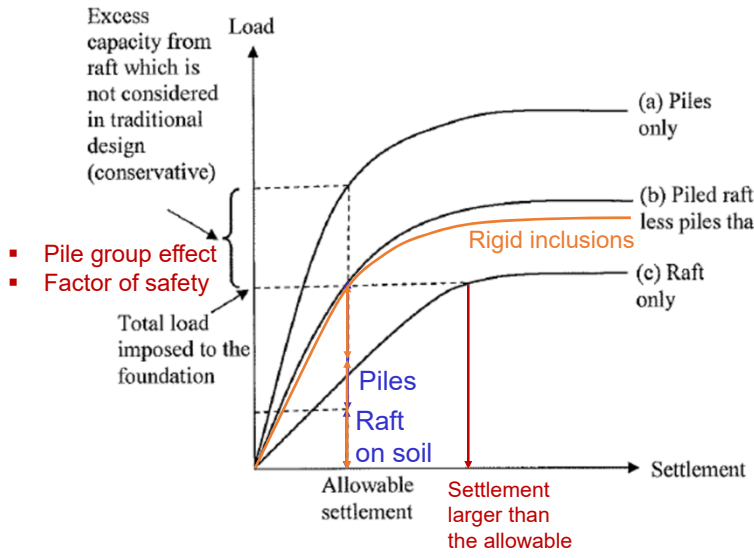
Different Foundation Systems



Modified from Tan and Chow (2004)

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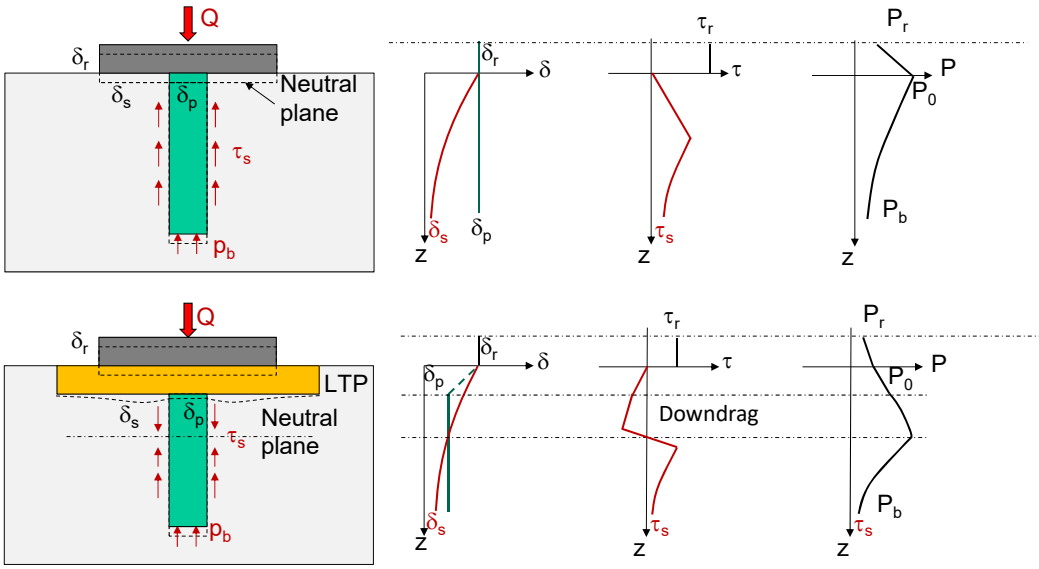
Rigid Inclusions vs. Piled Raft



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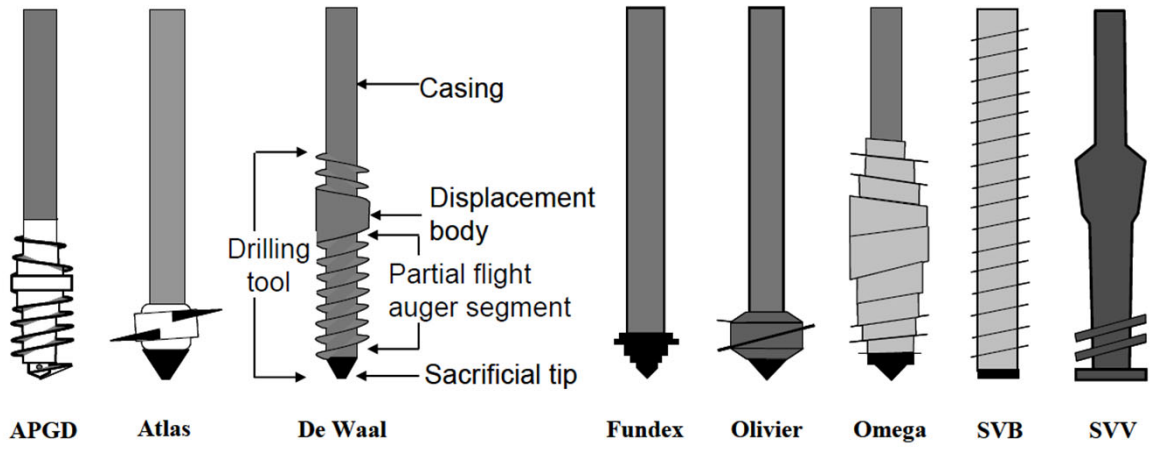
Drilling Tools for Installing Drilled Displacement Rigid Inclusions



Basu et al. (2009)

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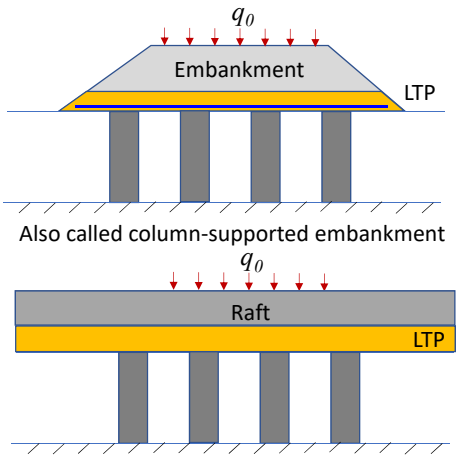
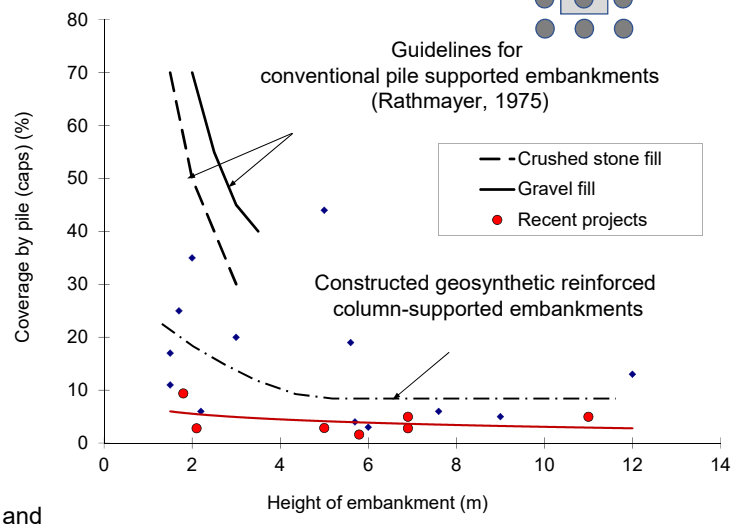
Common Applications





Main applications: (1) embankments,
(2) slabs or raft type structures,
(3) tanks, silos, and heavy storage facilities, and
(4) footings for buildings and wind turbines, etc.

Modified from Han and Gabr (2002)

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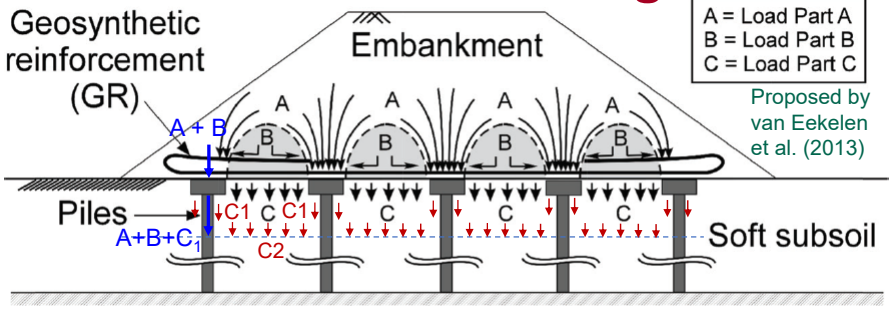
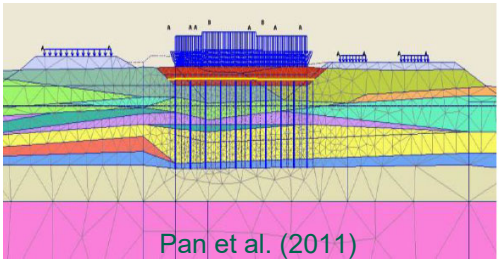
Design



A = Load Part A
B = Load Part B
C = Load Part C

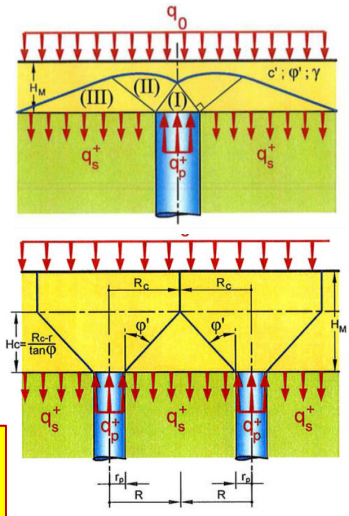
Proposed by van Eekelen et al. (2013)

Modified from Lee et al. (2021)



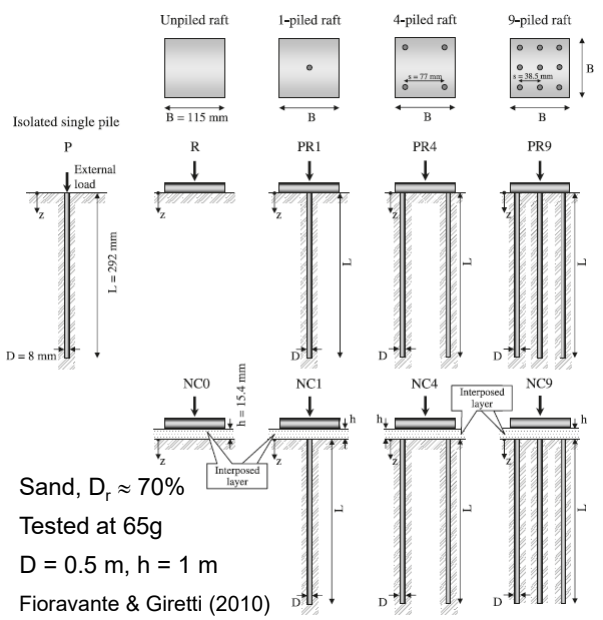
Pan et al. (2011)

Finite element and finite difference methods have been increasingly used to design rigid inclusion -improved systems.



IREX (2012)

Rigid Inclusions vs. Piled Raft

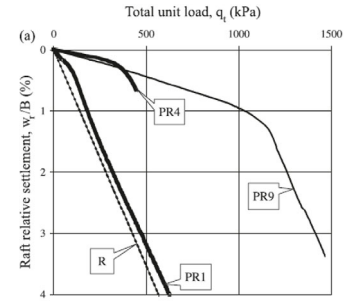


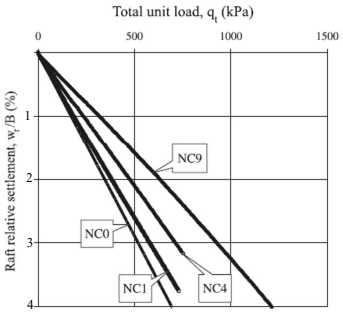
Sand, $D_r \approx 70\%$

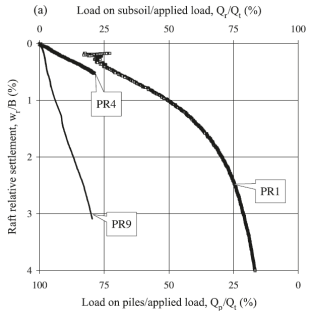
Tested at 65g

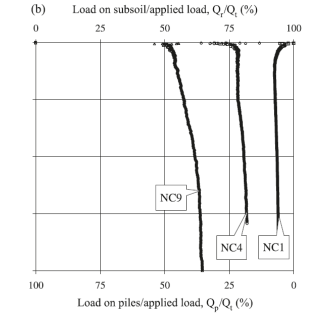
D = 0.5 m, h = 1 m

Fioravante & Giretti (2010)

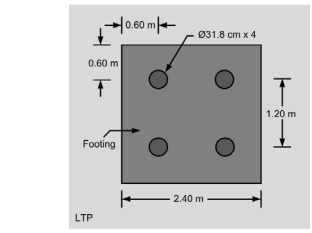


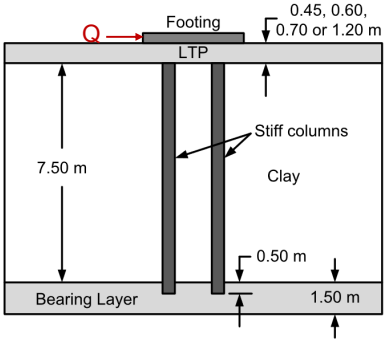


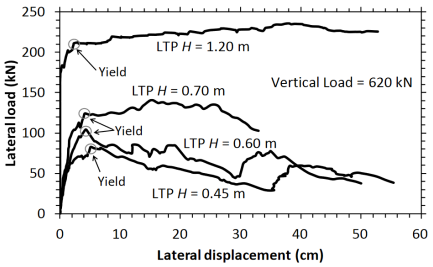


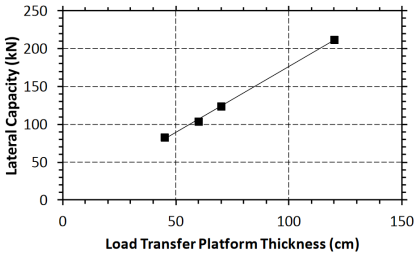


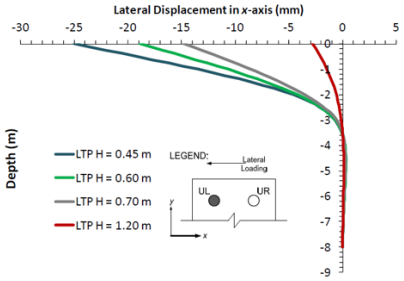
Lateral Load Behavior

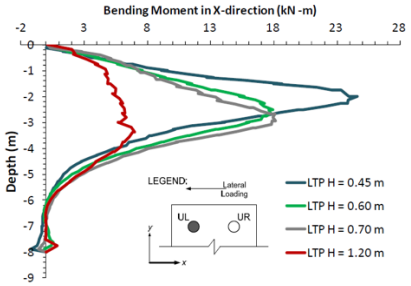






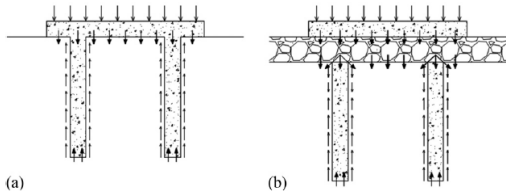


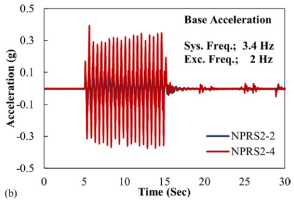


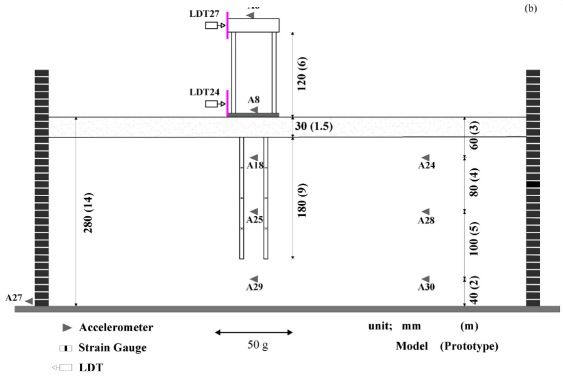


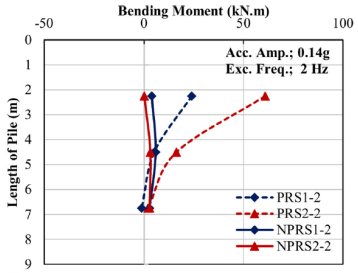
Rivera Rojas (2019)

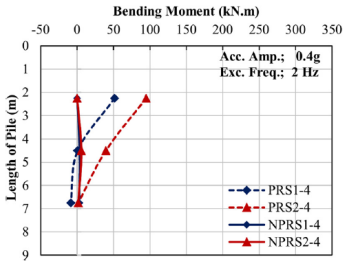
Seismic Behavior











Baziar et al. (2018)

Liquefaction Mitigation

Possible benefits by rigid inclusions:

1. **Densification**: installation of rigid inclusions (e.g., lateral displacement and vibration) may densify surrounding soil, which should be verified by in situ tests between inclusions.

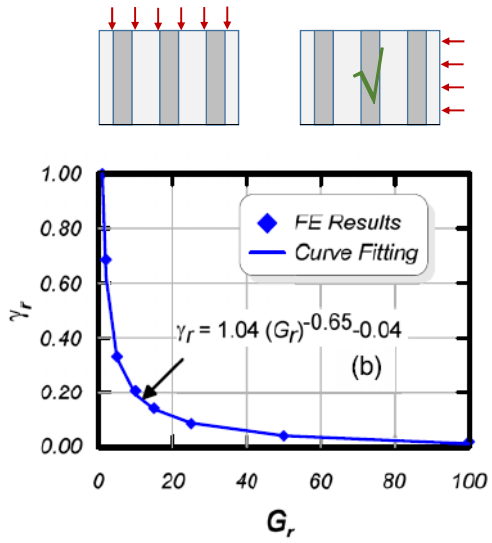
2. Shear stress reduction:

Shear stress ratio $\mathrm{CSR_{RC}} = \mathrm{CSR} \cdot \mathrm{K_G}$

Stiffness effect

$$\mathrm{K_G} = \frac{1}{\mathrm{G_r}\left[\mathrm{a_s}\gamma_\mathrm{r} + \left(1-\mathrm{a_s}\right)/\mathrm{G_r}\right]} \approx \frac{1}{1-\mathrm{a_s}} \approx 1$$

G_r = modulus ratio of rigid inclusions to soil



Rayamajhi et al. (2014)

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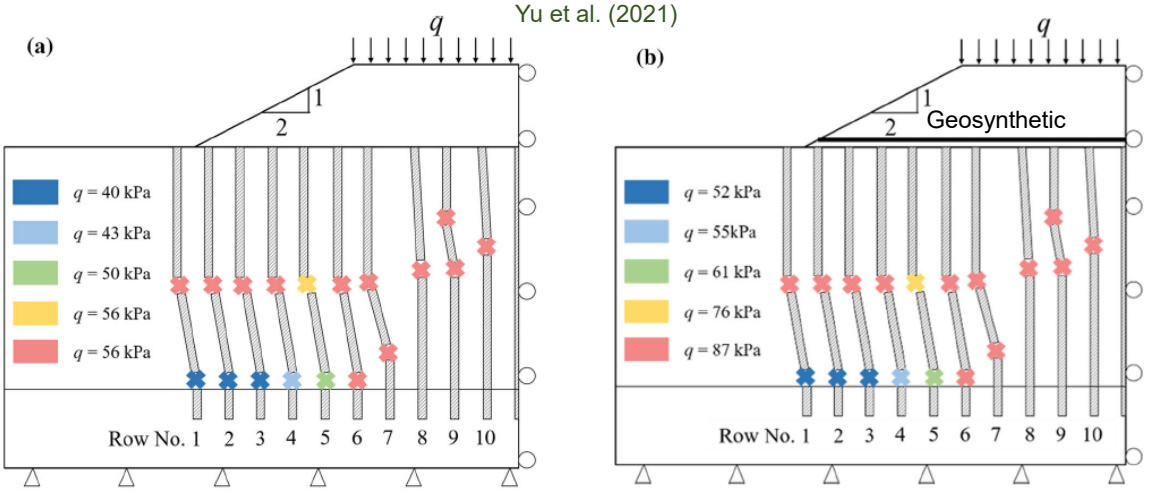
Progressive Failure of Rigid Inclusions

Yu et al. (2021)



Geosynthetic reinforcement did not change the sequence of column progressive failure but increased load capacity.

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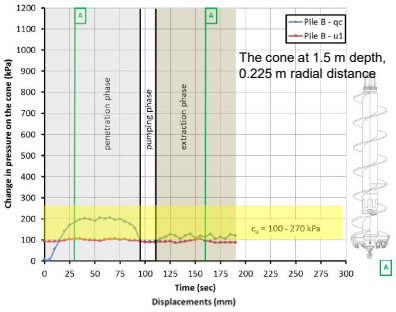
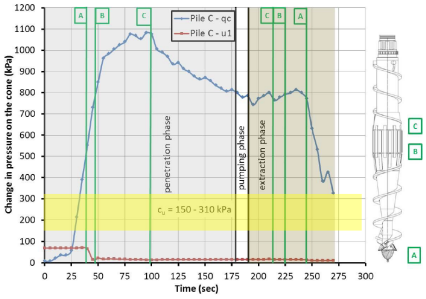
Installation Effect of Rigid Inclusions

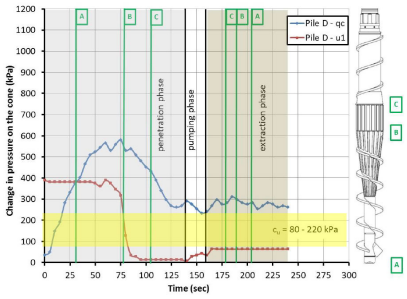
Continuous Flight Auger

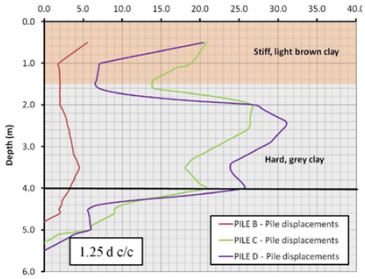


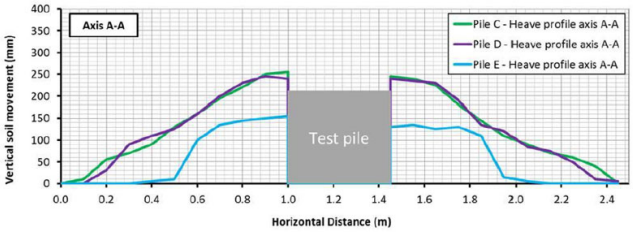
Progressive Displacement Auger



Rapid Displacement Auger





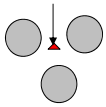


Limited soil property changes before and after installation

Larisch (2014) 17

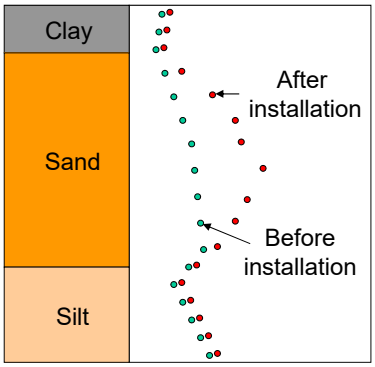
Performance Evaluation

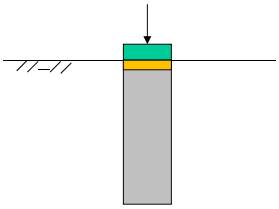
Test point



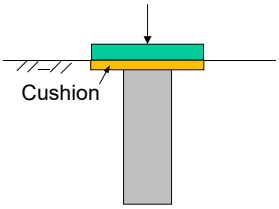
Sampling, SPT, CPT, etc.

SPT N value

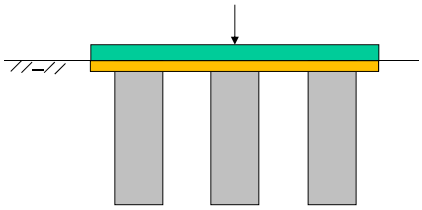




Individual column



Individual column composite ground



Multiple column composite ground

Masse et al. (2020)

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Concluding Remarks

- The concept of rigid inclusions has been used in different countries for many years (e.g., composite ground, unconnected piled raft, and column-supported embankment) but become popular in the US with different applications in recent years.
- The advancements of installation equipment and method (especially for drilled displacement columns) and theories have promoted the use of rigid inclusions.
- Rigid inclusions are stiffening elements in composite ground improving global performance (increasing bearing capacity and stability, reducing settlement) instead of piles in pile foundations.
- Load transfer platform is important for distributing superstructure load to soils, minimizing stress concentration on superstructures, and minimizing lateral load and bending moment on rigid inclusions.

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Concluding Remarks

- Soil arching, tensioned membrane (if geosynthetic is used), stress concentration, and downdrag are main load transfer mechanisms in the system.
- Numerical methods have been increasingly used to design the complex system.
- Rigid inclusions may have progressive bending failure close to slope of embankment.
- Rigid inclusions may mitigate soil liquefaction by soil densification but stiffness effect is limited.
- Different installation methods may cause different levels of disturbances to surrounding soils and pre-installed inclusions.
- Performance verification is needed for surrounding soils, rigid inclusions, and composite ground.

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