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

Research progress on the influence of deep foundation pit excavation on adjacent pile foundation

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***Abstract*—The formidable challenge confronted by engineers of this century is designing and construction of sustainable infrastructures that support civilization. Such modern structures in urban dwellings inevitably induces new deep excavations to be built close to existing piled foundations. In order to assess this interaction and to cope the practical challenges faced during construction, thus far there have been numerous researches and advances in experience. The remarkable evolution took place over the decades in the deep excavation technology and other relevant technologies has been well detailed in the literature but needs refinement in considering the complex nonlinear stress-strain response of soils corresponding to different unloading effects (stress-path dependent soil deformation) while analyzing the effect of excavation on the nearby pile foundation. Moreover, it is observed that previous experimental studies performed to simulate the problem did not fully take into account the effect of embedded pile caps, excavation supporting structure installation and superstructure stiffness.**

***Keywords*—deep foundation pit excavation; pile foundation; soil – structure interaction; risk management**

I. Introduction

Underground space development is growing unprecedently in the quest to effective urban land space utilizations for basement and other underground facilities, such as transit and road tunnels. By making design and construction decisions with optimal planning to further consider the underground for future use, the current practice can be refined to approach holistic urban sustainability [1–3]. Among the modern cities' growth-related challenges, being densely populated and urbanization have spurred construction of high-rise buildings in close proximity that are normally supported by pile foundations. If the pile foundations for existing structures were designed without a room, as is in most cases, to how the space beneath or around them could be used in the future, they will significantly be influenced by the deep excavation to be undertaken for the proposed new construction. It will consequently result in huge economic losses, heavy causalities and significant social effect. An example of such incident is the catastrophic collapse of the 13-floor pile supported building toppled in Minhang District of Shanghai, China. The piles were overloaded by the excavation processes as well as the unforeseen soil softening due to subsequent rain event causing huge social effect [4]. Addressing this kind of issue has been a research track direction for many years but failure to achieve the desired result is still apparent as can be witnessed from enormous projects constructed thus far.

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II. Ground movements around excavation

Soil movements behind the supporting wall are unavoidable during deep excavations resulting in stress state change that will have detrimental effect on the performance of existing pile foundation. The direct strains imposed onto the piles as a result this excavation-induced ground movement should be carefully dealt with in design and execution to avoid unexpected behaviour ensuring stability and performance requirements of the project. Over the years, a number of researches have been performed about predicting the magnitude and distribution of ground and wall movements associated with excavations and suggested different empirical and numerical methods [5–16]. If a well propped excavation retaining wall is permitted to deflect inward due to excavation induced stress relief, as shown in Figure 1, usually a concave type ground settlement is found, otherwise, spandrel type appears if the wall deflects as a cantilever [17–19]. These "fee-field" soil movements are imposed on the pile to calculate its response (bending moment and deflection) [20], even though, larger magnitude and wider ground settlement troughs in the green-field are expected [21]. Once the excavation-induced ground displacement is found, its zone of influence (i.e. the primary and secondary influence range) is analysed to obtain the lateral and vertical forces supposed to be acting on the piles.

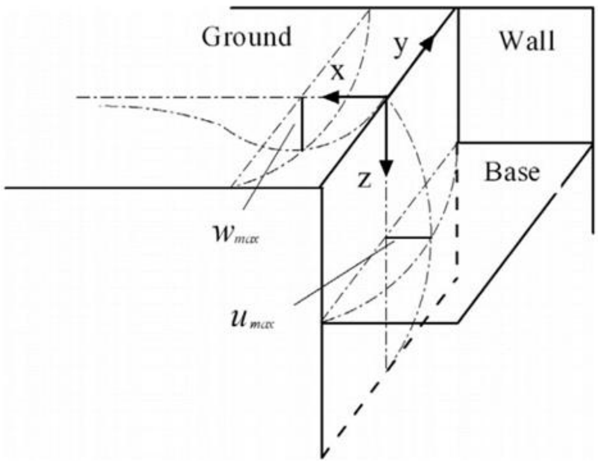

Figure 1. Braced excavation induced wall deformation and concave ground settlement profile [19]

Most proposed expressions were developed either with set of field data collected from projects [6,11,14,22,23] or with a number of FEM analysis of selected hypothetical excavation cases [24,25]. For the latter case, the choice of soil constitutive model to be applied to capture the soil behaviour requires both simplicity and robustness. However, due to the inherent variability coming from the complex nature of geomaterial and subsurface environment, none among the enormous advanced soil non-linear constitutive models has been seen to predict exactly the ground surface settlement that matches field measurement [26–30]. Mu and Huang [19] used on-site testing data to obtain parameters for the HSS model when developing the empirical method to predict 3D displacements of soil induced by braced excavation. It's still self-evident that further researching in this direction is significant.

III. Modelling and prediction approaches

Avoiding the adverse effect of excessive ground movement on the adjacent piles starts from careful design and construction of the excavation. Deep excavation pit is a serviceability problem that should answer the questions: how can the excavation induced movements be kept within the allowable values? And if these permissible movements are surpassed, then what possible mitigation measures can be provided during and after construction to eliminate unsatisfactory performance? As the theories and technologies to address this are still behind perfection, design and analysis for a deep excavation is becoming more challenging. But it has so far been approached through the earth pressure method [the limit equilibrium and subgrade reaction method], the numerical method, and the robust geotechnical design [RGD] method [29,31–34]. The construction technology on the other hand is developing to accommodate time-space-effect with either bottom-up or top-down construction method [35–40]. For oversized excavation pits, it has been reported that zoned and staged construction successfully reduces time dependent pit deformations [41–43]. Thus, modelling and prediction approaches of the interaction between new deep excavation pits and adjacent piled supported structures comprises a complex soil-structure interaction problem, see Figure 2.

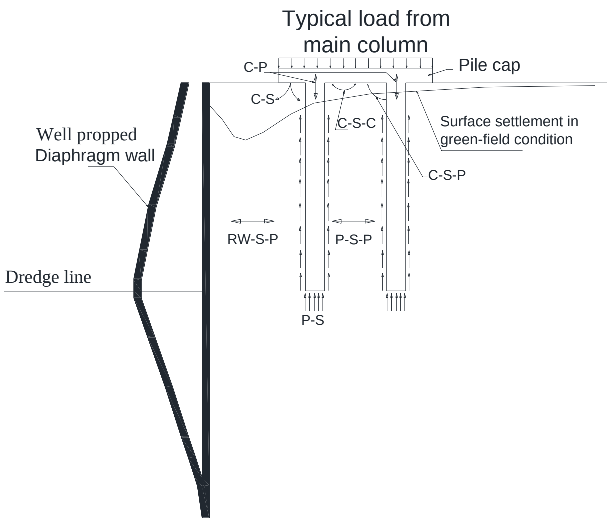

Figure 2. Typical interactions between soil and structural members [RW = excavation support structure; P = pile; S = soil; C = Pile cap)

When the excavation support is to be constructed in close proximity, the concern to accurately estimate the maximum excavation pit supporting wall movement and the surface settlement gets higher. Moreover, the ability to properly model the excavation pit has a significant influence in capturing the actions involved in the analysis since the spatial variation in terms of geomaterial and loading effects the stress distribution behind the wall [7,44,45].

With proper instrumentation, the excavation-induced wall and ground movements can be monitored during construction but observations along the length of existing pile is practically difficult except measuring movement at the top of the pile cap. As a result, instead of full-scale field instrumentation of existing pile foundations prior to excavation, researchers tried to use plane strain FE analysis to assess pile deformations along with other monitored construction activities [46–48]. Assuming the soil behind the walls responds to an unloading process close to plane strain condition due to the relatively long wall in out of plane direction, excavations have generally been analyzed with 2D as plane strain problems. However, comparison between 2D – 3D analysis shows the 3D analysis reasonably matches with field data [49–51].

Knowing the initial stress state in the ground is altered because of excavation triggering ground movements and being able to reasonably predict them at a given location, then the adequacy of the pile capacity is estimated implementing a pile-soil interaction program to estimate the forces and moments brought onto the piles [52, 53]. It is found that pile distance from retaining wall, its head condition, formation level of the excavation, and the embedment depth of the wall highly influence the magnitude of the extra bending moment and lateral deflection of the pile [54]. In a group pile, the front piles decrease the adverse of effect of excavation-induced soil movement on those at the back [48, 55]. Some scholars used advantage of this perception to place a row of isolation piles behind the wall as a protective measure to control soil movements [56–58]. Since lateral loads on the piles vary during the soil displacement, the relative movement between the pile and the soil governs the reaction force mobilizing on the pile that depends on the relative stiffness of the pile to the soil.

While assessing the behaviour of a pile within a pile group under excavation induced soil movement, due consideration needs to be given to the pile-soil pile interaction as well as direct pile-pile interaction through the connecting pile cap or tie beam. Load-deformation characteristics of laterally loaded piles has been theoretically approached through the subgrade reaction method, the p-y method, the elastic continuum method, and the FE approach. The complexity associated with FE approach to capture soil nonlinearity, soil continuity, and pile-soil interfacial behaviour, the interaction factor according to boundary element method was developed and is still being researched [48,59–64]. Moreover, as a measure to eliminate differential settlement of piled rafts, dissimilar piles and cushion layers have been widely used as a composite foundation by many engineers even though the theory falls behind the practice, which is the special nature of geotechnical engineering [65–68]. The research on the interaction behaviour of such foundation system under lateral loading, especially under passive loading induced by excavation is very sparse.

IV. Experimental studies

As piles adjacent to excavations suffer from passive loading due to lateral movement of soils, considering experimental studies on passively loaded piles is of interest to assess the interaction between the moving soil and the pile shaft [69–71]. The effectiveness of the experimental results to be obtained from model tests depends on (1) the model soil preparation, (2) model pile selection, (3) the ability to simulate excavation process, and (4) capability to reflect actual loading scenario with appropriate loading method. Centrifuge test is the common experimental method used in high scale laboratory testing of interaction between new foundation pit excavation and adjacent existing pile foundations.

Many more previous laboratory model tests on the response of piles to lateral soil movements has recently be detailed in the state-of-the-art review reported by Li and Zhao [72]. They have discussed that many researchers chose model piles made of aluminium ally and simulation of excavation process in centrifuge test is performed with (1) stop and start method, (2) removing heavy liquid [or gas] method, or (3) auto-excavation device method depending on the research objective. In excavations and tunnelling model testing, loading can be applied with different methods such as Jack loading method, dead load method, air (water) bag loading method, motor loading method or air cylinder loading method. In most of the current studies made with model tests, little attention is paid to the influence of embedded pile caps as previously foundations with elevated pile caps were researched and the stiffness of the superstructure has not been given much attention.

Furthermore, excavation-induced pile settlement and variation of pile shaft resistance has been investigated by Ng et al. [73] using centrifuge simulation. Al-abboodi and Sabbagh [69] investigated the influence of progressively moving soil on the lateral behaviour of piled raft using large scale shear box. Al-Salih et al., and Toma Sabbagh et al. [74,75] studied the response of batter pile groups under lateral soil movement using a specially designed laboratory model testing box. Lianxiang et al. [66] used centrifuge test to experimentally investigate excavation behaviour adjacent to existing composite pile foundation. Wang and Yang [67] used a steel framed model box and silty clay as a model soil with a model piles made up of cement and medium sand to investigate the effect of cantilever soldier pile foundation excavation closing to an existing composite foundation. More recently, Ambooken et al. [76] has conducted a model test to investigate a combined effect of ground movement due to excavation and tunnelling on pile.

Cheng et al. [77] carried out a model test to investigate the progressive collapse due to sudden failure of certain retaining piles. Considering a construction activity may induce an abrupt or progressive failure (Puzrin et al. [78]) possibility of the retaining wall itself, which will change the soil movement pattern, Shukla [79] used a wooden shutter in his model test to simulate an abrupt collapse of a retaining wall so that the response of single model piles or pile groups could be determined. As this study was made by varying embedment ratio by changing pile length, various parametric studies including settlement of the pile groups and the effect of dissimilarity among the piles can further be studied.

Although excavation unloading results in an in-situ soil stress changes, investigations on the soil stresses surrounding the pile using field tests are comparatively uncommon due to practical inability to instrument existing piles. However, Finno et al. [46] tried to observe movements of the pile caps towards the excavation in order to analyse the existing foundation condition. Besides that, to carry out full scale study, Goh et al. [47] installed an in-pile inclinometer to investigate pile behaviour during nearby excavation process. Ong et al. [80] monitored cast-in-place concrete piles by in-soil and in-pile inclinometers to evaluate pile group responses under lateral soil movement. Recently, Li et al. [81] conducted an actual full-scale pre- and post- excavation Cone Penetration Tests (CPTs) close to the test piles installed prior to the excavation to assess the piles' responses and proposed a prediction method based on p-y curves from CPT data. Similar study has been reported by Li et al. [82,83] on the soil stress variation and lateral pile response but further research can be done for comprehensive understanding in large-scale.

On the scaled model test by Guo and Ghee [84] on the behaviour of axially loaded piles under lateral ground movement showed the axial load on the pile cap decreases the induced bending moment, pile lateral deformation and soil reaction.

V. Case studies

Improvement in the current design and construction method is a result of the lessons gained from the past construction experiences that are practically proved to be effective and/or publicised cases of failures necessitating areas of enhancement for use in the current practice as well as future projects. Moreover, performance predictions made using FE analysis are usually compared with observed performances taking a specified project – case study. Despite disinclination of peoples to document failure reasons, continuous record of experiences about risks and responses, and storing it in databases and/or repositories refines the current practice with a learning-based approach to reuse previously gained risk-related knowledge. Chang - Yu [85] states no matter successful or not the case history of nearby excavation, it helps the design and the choice of the convenient construction method. Lessons learnt from earlier stages of the same project [86] and previous experiences from other projects [87] can be reutilized to support risk management decisions.

Boscardin and Cording [88] presented case studies of building performance near excavations. (Hung and Phienwej [89] considered more than 50 projects of deep excavations in Vietnam. Tan et al. [90] compared well-documented field data from four bottom-up excavations in Shanghai having similar pit geometry and supporting system but varying procedure for soil removal. Zeng et al. [91] reported the performance of adjacent foundation pits concurrently excavated in Shanghai soft clay. Chen et al. [92] have reported collapse of excavation in very sensitive organic soft clay. Lu and Tan [93] mentioned how it is still tough to accurately predict excavation performance in advance based on excavation failure cases in different Chinese cities. They have also shown that 65% excavation projects in China experienced different kind of problems resulting failure modes among the 15 categories they mentioned. Dalgic et al. [94] carried out a review on the limiting tensile strain method which is still used for damage classification in assessing building response to excavations. Cases have also been reported about the effect of excavation dewatering on the performance of the excavation [95–97] as it might bring collapse like the failure of Germany's Cologne deep excavation for metro station [98].

Hosny and Mohamed [99] has reported a case history of diaphragm wall pit excavations adjacent to piled deep foundation extending deeper than the depth of excavation resulting a total pile settlement of 0.12% of the excavation depth. Korff [100] showed piled foundations near deep excavations suffer from serious settlements due to negative skin friction resulting from groundwater table lowering based on a reported case histories from Hong Kong [excavation for mass transit railway situated around timber pilled Courts of Justice building, Mandarin hotel and Prince's Building founded on driven piles], Singapore (multi-propped excavation near a 12 story building with H-Piles), and Rotterdam (excavation near the 11 story pile founded "Witte Huis" building). Extending the same, Korff [101] found that 60% of failures in 50 underground deep excavation projects analysed in the Netherlands happened due to not applying existing knowledge that shows regular learning is not entirely taking place from project to project. Significant failures are believed to be happened because of flaws in accessing and utilizing existing information and knowledge instead of a consequence of unexpected events [87,102,103].

Kok et al. [104] reported a case of pile failure due to excavation induced bending moment in Malaysia. Thorley and Forth, [105] reported actual settlement of piled foundation adjacent to diaphragm walling in Hong Kong and revealed the substantial contribution of pre-excavation construction activities such as ground treatment, drilling, and preboring for wall panels. Rahardjo [106] found higher calculated movements than the measured in most excavations in soft soils of Jakarta by installing in-pile inclinometers during pile casting to measure the soldier pile's behaviour, and also reported failure of pile resulting tilting of the office and hotel building with excessive pile movement (about 1.0m) which only 20cm would have been sufficient to achieve its ultimate moment capacity when analysed by software.

Pile top movement has been showed to have significant influence on the pile [20,107]. To assure pile capacity in the influence zone of the excavation and assess the allowable tilt arising from pile head movements and rotations in high rise buildings, Fok et al. [52] suggested a refined dusk-study to incorporate the structural condition (whether it can sustain or not potential effects of adjoining excavation in its current condition, like the condition survey in [17]). From the cases, thus, further need apparently exists to incorporating the effect of pre-excavation activities, accounting for the green filed displacement modification due to the presence of pile, and considering the past proven tracks or failed cases to learn and stablish risk prevention strategy using knowledge outside of the project. As part of risk management, the stringent performance requirement is bringing a high level and detailedness of monitoring scheme in each and every foundation pit project so that, in the near future, it will be possible to obtain a worldwide refined database for the effect of excavations on adjacent piled structures.

VI. Control measures for undesirable conditions.

Prior detailed design which is able to incorporate possible mitigation methods for undesirable conditions popping out during construction and proper selection of excavation technique shall be compatible with the full range of anticipated uncertainties. Engineering experience and judgment plays an important role in dealing with uncertainties in design and/or making further construction monitoring based decisions [108–110]. Many researchers have forwarded their control measure strategies to improve the level of sound engineering judgment through observation of actual performance and updating initial design assumption as the construction progresses [14,111,112]. Calvello, [113] proposed a time-dependent iterative model calibration [inverse modelling] called "observational modelling" to control excavation induced soil displacements. Such activities to deal with uncertainties may require to go beyond the code requirement [114,115]. This needs to be supported by continuous monitoring [116–119]. Though probabilistic considerations have been emerged in application [120–122], handling all uncertainties involved to achieve structural system reliability remains to be one of the important research directions.

Basically, to preserve buildings from the effect of adjacent deep excavations, protective measures can be made through plans before-excavation, monitoring based actions during excavation or compensation and fracture grouting after damage (caused by design mistakes or construction flaws) happened [85]. The effectiveness of these approaches depends on the resulting excavation-induced ground movement, the proximity to the excavation and sensitivity of the adjacent structure [123]. As the study about the complex mechanism of settlement-induced damage is on progress and intricacies involved with never ending challenges and excitement, monitoring of performance during excavation still continues to be a concern among scholars.

Zoned and staged construction to consider time-space effect (TSE) in retaining wall deformation control [35,43], implementing observational method [14,113,114,124], use of isolation piles, micro piles or jet-grouting columns interposed between the piled foundation and the excavation [56–58,125], reducing the unsupported length and increasing the stiffness of the retaining wall-strut system during excavation, underpinning, embedded barriers such as compaction and compensation grouting [85,126] are the most common methods being applied to prevent excavation-induced settlements.

It is well known that, as a beacon modern solution is given when successful collaboration is met among the risk owners and action parties involved from the design to construction stages, the geotechnical engineer ideally makes sure that the team is aware of geotechnical risks and opportunities involved [127–129].

VII. Conclusion

Deep foundation pit excavation has attracted broad attention due to its inherent complexity and the associated high risk. To understand the response of existing piled founded structure to the new deep excavation induced stress releases and ground movements, enormous researches have thus far been done and forwarded most promising findings focusing on the inevitable ground movements as well as modern design approaches, construction technologies and risk management process to improve the performance of the excavation. Based on the review made, for refining the current theoretical and practical experiences, further inclination towards the following are recommended:

- As the deformation of soils under excavation is stress path dependent and affects the soil stresses around the pile due to unloading, its impact on the lateral pile response necessitates to consider the state of a stress corresponding to different unloading effects. Thus, the current assumption that the horizontal stress does not change during excavation needs further investigation.
- The complexity involved with the nonlinear stress-strain response of soils subjected to different stress path needs to be further understood.
- The future improvement in the model test result is expected to incorporate the effect of embedded pile caps, i.e. the complex interaction of pile-soil-cap, foundation pit excavation supporting structure installation, and superstructure stiffness which are among the factors ignored in the current practice of simulating excavation process in laboratories.

Acknowledgment

The authors gratefully acknowledge the support of Zhengzhou University's Presidential Scholarship Program for sponsoring the research area “Foundation Treatment and Foundation Pit Support Engineering”.

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