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Deep Foundation Pit Excavations Adjacent to Disconnected Piled Rafts: A Review on Risk Control Practice

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Abstract

Foundation pit excavation engineering is an old subject full of decision making. Yet, it still deserves further research due to the associated high failure cost and the complexity of the geological conditions and/or the surrounding existing infrastructure around it. This article overviews the risk control practice of foundation pit excavation projects in close proximity to existing disconnected piled raft. More focus is given to geotechnical aspects. The review begins with achievements to ensure excavation performance requirements, and follows to discuss the complex soil structure interaction involved among the fundamental components: the retaining wall, mat, piles, cushion, and the soil. After bringing consensus points to practicing engineers and decision makers, it then suggests possible future research directions.

Keywords

Deep Foundation Pit Excavation, Disconnected Piled Raft Foundation, Risk Control, Observational Method

1. Introduction

Burgeoning intentions to use basement slabs as a component contributing to the foundation's bearing capacity and settlement requirements have recently spurred an escalated demand for piled-rafts as an economical alternative foundation system. The 828 m tall Burji Khalifa building in Dubai is an example founded on piles beneath the base of thick slab—the raft [1]. Moreover, raft foundations integrated with column type ground improvement (rigid inclusions) have widely been practiced in many parts of the world to utilize marginal urban soft ground [2]. In China, the columns are mainly constructed with cement-fly-ash-gravel (CFG) and the improved ground is termed as CFG pile composite foundation [3] [4] [5]. The 200 m high structure in Dalian City, China, for example, was built on composite foundation where the raft transfers the load from the superstructure to the ground treated by vertical columns [6]. This shows, based on the intended use, piles may be connected or disconnected to the raft. To circumvent localized higher stress and bending moment at the point of connection between the piles' head and the raft during lateral and seismic loads, an interposed layer of sufficient thickness is laid [7] [8]. Previous experimental and numerical analyses indicated that the disconnecting layer plays a significant role in distributing superstructure loads in such an interplay that integrates the piles and the soil in load sharing mechanism [9] [10]. In this case, the piles receive the upper load indirectly and mostly considered as stiffeners of the marginal ground or settlement reducers [11]. Many researches are now being done to understand the complex soil-structure interaction (SSI) phenomena in disconnected piled rafts [12] [13] [14] [15].

On the other hand, in recent years, the use of underground space has evidently become an important attribute to promote sustainable development [16] [17] [18]. In fact, aggressive progress towards underground construction will spate in a complex manner, with stringent performance requirement for deep foundation pit excavation support [19] [20] [21] [22]. The consequences of foundation pit excavation support's failures are significantly dangerous and risky, mandating proper monitoring during construction [23] [24] [25]. For example, the 2004's sudden collapse of Singapore's deep braced excavation of Mass Rapid Transit Circle Line project adjacent to Nicoll Highway was reported to result in a disaster in four fatalities, costing approximately $6.7 billion [26]. The Chinese Hangzhou Metro Line 1 project collapse in 2008 was found to take 17 lives and other four missing, with more than ¥50 million loss [27]. Such catastrophic collapses affect the performance of the surrounding infrastructures; similar to the toppling of the 13-floor building in Minhang District of Shanghai, China causing huge social effects [28]. In 2009, the failure of deep excavation at the Cologne metro station in Germany was anticipated to be due to the increase in hydraulic gradient during the excavation, in turn the historical City Archive Building collapsed [29].

When neighboring structures or public utilities exist, the design and performance requirement of deep excavation project is met on the bases of serviceability rather than failure prevention criteria [20] [30]. The construction method must also be able to confirm practically that the induced ground movement is tolerable, so the subsequent associated risks are controlled. Previous research on the design and construction on deep foundation pit excavation works mainly focused on excavation pit support, related ground and wall movements, design and/or construction risks (see **Table 1**).

Regardless of whether the project is delivered by traditional Design-Bid-Build or Design-build bidding, the construction of deep foundation pit excavation is

Table 1. Selected researches on foundation pit excavation and the interaction with its surrounding.

Focus of study	Reference	Methodology	Key research parameter
Prediction of excavation-induced ground and wall movement	[31]	Numerical	Small-strain soil behavior
	[32]	Empirical + numerical	3D distribution of soil movements, small strain behavior of the soil
	[33]	Analytical	Plane strain problem, modes of wall displacement
	[34]	Numerical	Constitutive soil models, displacement of tieback wall
	[35]	Modified mobilizable strength design (MSD) method	Deformation of multipropped excavation, excavation geometries, strength mobilization characteristics of soil
	[36]	Numerical	Sheet pile wall installation, construction sequence and bracing
	[37]	Numerical	Diaphragm wall deflection, ground surface settlement, excavation depths, geological conditions
	[38]	Numerical	Narrow excavations, support stiffness, excavation width-depth ratio
Effect of groundwater (GW) dewatering	[39]	Numerical	Watertightness Assessment Test before excavation, stability of the bottom of the excavation, defects in the enclosure (gaps or open joints)
	[40]	State-of-the-art review	Ground settlement, interactions between the retaining wall-dewatering well, the dewatering-excavation, and dewatering-recharge
	[41]	Field observations	Wall deflection (diaphragm wall/secant-bored pile wall), ground surface settlement, stage of excavation, groundwater drawdown
	[42]	Case study	Dewatering (pumping rate and depth of a cutoff wall), soil properties, building settlement
	[43]	Review on water leak incidents	Water ingress (leak through joints & seepage-prone weak zone), surface settlements and diaphragm wall deflection
Design and support optimization	[44]	Robust geotechnical design (RGD)	Braced excavation, wall deflection, Cost-efficiency (costs of the diaphragm wall, the bracing system, excavation/disposal of the dirt, dewatering, and instrumentation)
	[45]	RGD coupled with first order second moment (FOSM) method	Braced excavation (geometry and depth), wall deflection, uncertainties of soil parameters (noise factors), cost efficiency, robustness and safety
	[46]	Constructing indicator system of optimization of supporting schemes based on TOPSIS	Technical feasibility, effect reliability (such as static and dynamic performances), construction accessibility (complexities during construction), economic rationality
	[47]	Numerical analysis	Bearing capacity, stability design requirements, and environmental requirements during construction, composite support systems, soil arching effect between existing pile foundations (bending moment in the piles)
	[48]	FEM for analysis, BS8081:1989 for ground anchor, BS8002:1994 for toe stability check, BS 5950 and CIRIA Special Publication 95 for strutting elements	Secant pile retaining wall, water-tightness, ability to vary the depth of retaining wall for irregular soil profiles, HS-Small model, grouting techniques, excavation support stability, assessment of surrounding infrastructure's damage

Continued

Construction method	[49]	Numerical inverse analysis	A shift from temporary to permanent support system, over-excavation (design depth increment), stress–strain behavior
	[50]	Divided-pit construction (FEM implemented)	Irregular excavation geometry and depth, displacement of adjacent conserved buildings (relative location from the pit), effects of buildings on excavation process (pit deformation due to buildings)
	[51] [52]	Zoned and staged construction, Channel-type top-down method of excavation	Construction cost and schedule, excavation support deformation, hauling distance, safe operation of adjacent railway (allowable displacement of the rail tracks)
	[53]	Dividing alternate excavation method (strip excavation plus several dividing walls)	Time-space effect and stiffness of tunnel, tunnel deformation, construction period
	[54]	Case histories from bottom-up construction technique	Foundation pit deformation, quick excavation, promptly propping, timely casting of floor slabs, segmented construction, excavation stage
	[55]	Top-down technique and inverse numerical analysis	Displacements of existing buildings, retaining wall deformations, hydraulic uplift failure mechanisms, wall installation effect
	[56]	Both top-down and bottom-up construction method with bipartition walls	Oversized excavation, time-space-effect on both deflection of diaphragm wall and deformation of partition walls
	[57]	Zoned excavation and instrumented observation	Wall deflection, ground settlement, corner effect, construction sequence, performance of adjacent metro line
	[58]	Bottom-up construction method with zoned construction	Lateral wall displacement, adjacent utility tunnel movement, stage and sequence of construction, construction schedule, groundwater dewatering, basal ground treatment
Interaction with the surrounding environment	[59]	Numerical	Excavation zone of influence, building settlement
	[60]	Numerical	Frame action with inclusion of building stiffness, limiting tensile strain
	[61]	Numerical	Stages of construction, deformation of excavation, strains of adjacent buildings
	[62]	Analytical	Excavation induced axial pile deformation, vertical soil displacement, load transfer mechanism
	[63]	Analytical	Tunnel deformation
	[41] [64] [65] [66]	Numerical	Effect of depth of excavation, supporting system stiffness, pile dimensions, pile head condition, working load, soil properties, location from excavation
	[67]	Numerical	Isolation piles and jet-grouted piles, displacement of retaining wall
	[68]	Numerical	Building deformations and settlement due to excavation, distance to excavation, type of building's foundation
	[69]	Numerical	3D structural distortion based on soil-structure interaction, damage due to differential displacement

Continued

Monitoring technology and early safety warning	[70]	Levelling, rod extensometers and torpedo inclinometer	Ground and wall displacements, accuracy of monitoring method (human or environmental errors)
	[71]	Internet-of-Things-(IoT) based safety barrier early warning system	Tracking of workers and "things" to change their risky behaviors, diaphragm wall collapse (elastic potential energy exceeded)
	[72]	Optical fiber sensing technology (fiber Bragg grating-FBG-technology)	Deformation of foundation pi
	[73]	Slope indicator systems, strain gauges, optical fiber and topographic survey	Displacements and strains of a noncontinuous anchored wall, earth pressure influence on lateral displacement (supported by numerical analysis)
	[74]	Displacement monitoring with a precise total station; crack measurements, rainfall observations, groundwater and seepage observations; Stress-monitoring equipment (vibrating string extensometer); Computer aided information management system	Deformation of foundation pit, ground surface settlement, inclination of the surrounding buildings, foundation settlement of adjacent buildings, integrated management of monitoring data (instrumentation, monitoring points, construction progress, the surrounding environment) and 3D visualization
Construction safety risk management	[75]	Numerical	Existing adjacent railway operation, railway subgrade deformation
	[76]	Monitoring based risk disposal	Distance from excavation, additional load due to stock piling materials on the pit edge, groundwater level change
	[77]	Case analysis of safety accidents (accident forecasting and prevention)	Safety behaviors of personnel, technological innovation of safety management, integration of networking and digital technology
	[78]	Support Vector Machine	Excavation deformation, longitudinal slope instability, gushing of water and sand
	[79]	Building Information Modeling (BIM)	Technical risks, Geological risks, Environmental risks
	[80]	Equivalent axial stiffness theory & Monte Carlo simulation technique	Soil parameter uncertainty, tunnel longitudinal stiffness, excavation depth
	[81]	Case study on damage remedial work	Grouting, soil unloading due to excavation, deformation of shield tunnel, groundwater drawdown

still fraught with challenges. It requires progressive monitoring of project performance. If deviations from design expectations are encountered during construction, appropriate modifications will be made and the experience gained can be used in a different way in the future [82]. This process usually takes five stages: Information, Analysis, Prediction, Observation and Evaluation [83]. Limited data, as well as the spatial variation of material properties involved in the complex geo-environment and unavailability of soil model to capture all aspects of material's behavior, have forced geotechnical engineers to rely on simplification and engineering judgment to fit analysis and prediction results [5] [34] [84]. This helped to develop presumed designs and safe constructability. Moreover, in the observation process, handling critical data requires more attention than the mechanics and manipulation of the data. Then, during evaluation process, the questions arising from the deviation between observed performance and expected performance will be answered. The results of the analysis will indicate the source of associated risks (hazards) and possible control measures to minimize/alleviate these risks. Therefore, a risk control process that accommodates the daily changes during construction is necessary for the successful completion of deep excavation pit project safely.

With this in mind, it becomes self-evident that the success of deep foundation pit excavation project is reflected on how it links the competence of project management process with risk-informed decision making. Besides, in the context of reasoned geotechnical judgment that systematically combines "data" and "experience", it can succinctly be described that a pressing demand is currently prompted on the role of relevant data which explicitly takes uncertainties into account. Consequently, it is unlikely to possibly reduce taking heed to risks in the near future, especially when novel foundations systems emerge. At this point of departure, this paper enlightens the construction profession regarding geotechnical aspects of risk control and management practice for new foundation pit excavations near the recent widely used on-service disconnected piled rafts.

In what follows, the method for predicting the likelihood and occurrence of unintended events in the deep foundation pit excavation project adjacent to conventional foundation system is introduced first. Then, for space brevity, brief discussion in the context of disconnected piled raft is covertly provided under separate sections allocated to topics on how to confront uncertainties during risk prediction; risk control measures; and risk management process. Ultimately, as there always exists something to explore in any area of study, future research directions, at least to the level of this article, are forwarded for interested scholars. Since several parties are involved to partake decisions at different levels, final decision will be affected by a certain sources of bias among the stakeholders [85]. Geotechnical engineers are responsible to make clear geotechnical bias sources for better decision makings. Accordingly, this paper gives more attention to demonstrate geotechnical aspects; and organizes the challenges arising from direct or indirect risks for deep foundation pit excavations in close proximity to existing structures supported by disconnected piled rafts. The concepts discussed will help practicing engineers to resolve the impact of uncertainties in a well-organized and structured manner.

2. Risk Prediction Methods

Risk and decision are almost interrelated [86]. Many factors exist that cause risk associated with interconnected tasks for a given project. They result in time delay or cost overruns if not properly dealt with in the process of risk management. Risk management mainly includes risk identification, analysis and response. In order to take effective counter measures to deal with the impact of risks, project managers or decision makers should implement strategies. The approach to do so is to measure the expected loss due to risk based on the potential impact and occurrence probability [87] [88] [89] [90]. For projects like deep foundation pit excavation, which is a complex system with many risks, early and effective prediction of possible outcomes can reduce detrimental effect of incidents and accidents. Available risk prediction methods can be grouped into three—1) empirical, 2) numerical and 3) machine learning.

Empirical approaches are qualitative in nature, which limits their application to a certain construction techniques and ground conditions [91]. It is used for predicting settlement and ground loss [92] [93]. Because of the possibilities to simulate excavation sequences numerically, numerical simulation methods are being implemented to analyze safety and cost constraints, incorporating spatial soil variability and pore pressure measurement [94] [95] [96]. However, recently, machine learning methods have been widely applied in risk prediction, and mainly include time series analysis—TSA [97] [98], Bayesian network—BN [99] [100], support vector machine—SVM [101] [102], artificial neural networks—ANN [103] [104], and random forest—RF [105] [106] [107]. Due to algorithmically and computational simplicity than other methods, applicability of supervised learning method, RF, in deep foundation pits has been validated using monitored data [108]. Owing to the complexity of excavation of foundation pits, there is uncertainty in the monitoring data collected from different types and different monitoring points of the same type. Processing of these data implicitly takes uncertainties into account. In view of this, it is prudent to provide relevant practical insights on the ways of handling the reality of "site-challenges" as a result of evolution of uncertainties from different sources, as presented in Sections 3.

3. Dealing with Uncertainties and Reliability

Geotechnical engineering practice and research are characterized by the uncertainty of time and space, and often encounter many sources of risk or hazards. As shown in **Figure 1**, uncertainties arise from geotechnical inherent uncertainty (measurement error) and/or transformation uncertainty [109]. Transformation uncertainty appears while using empirical or other correlation models and interactions between the ground and structures, both during and after construction [110] [111]. Consequently, it becomes convenient to acquire reliability index or failure probability for specific circumstances in excavation projects, so

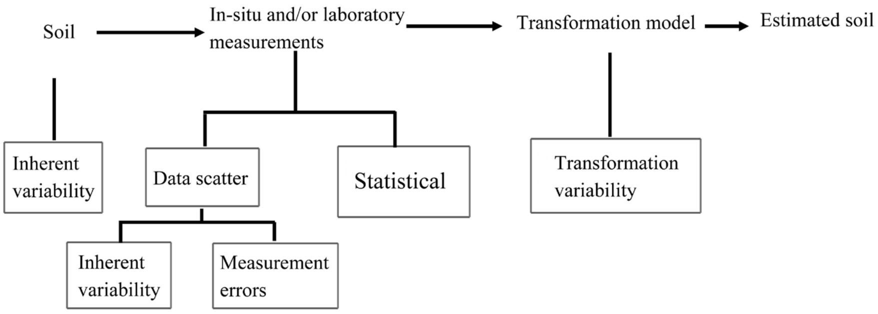

Figure 1. Overview of geotechnical uncertainties [109].

that decisions can be made on the relative contribution of sources of uncertainty [112] [113] [114] [115]. Based on the identified and quantified uncertainties, probability factors are developed to define probability of unacceptable performance, which is very important to identify the leading risk category of concern, especially in the design-build (DB) procurement process [116] [117].

Probabilistic considerations in deep foundation have emerged in applications towards excessive differential settlement; analysis of excavation-induced retaining wall deflection, ground movements, and damage potential to an adjacent building with focus on component reliability assessment of serviceability criterion [27] [118] [119] [120]. Occurrence probabilities of risk events, assessment of consequences, and planning of control strategies require to acknowledge the risk at the very end and provide remedial measures to avoid the risk or recovery methods in the event based on informed decisions [121] [122].

Fenton [123], Fenton *et al.* [114], Fenton and Naghibi [124] have made comparison among existing codes regarding periodic updates and revisions for professional practice harmonization. They indicated that countries have already been shifting the national geotechnical design codes of standards towards reliability-based design concepts where separate "partial" factor of safety is employed unlike that of comprehensive one in the traditional method. In this regard, it is prudent to carefully examine what existing (monitoring) data have to implicate in decision making; especially as data is increasingly being considered as "new oil" to the point whereby data is used to support sensitive decisions apart from project compliance purposes [125] [126]. For instance, if one excavation failure phenomenon among the 15 failure categories seen in china [127] is suspected to possibly occur, then the reliability of the critical event can be checked along with observations made as excavation progresses and remedial measures can be deployed to control it early from happening. Therefore, it is not a trivial thing in deep excavation projects to incorporate new knowledge of site conditions as construction progresses in order to make adjustments on the system performance. Within the framework of observational method, real-time observed data are employed timely to act against uncertainties during construction. This requires understanding of the observational method and appropriate real-time data acquisition system.

3.1. Application of Observational Method (OM)

After Peck [128] formally introduced Terzaghi's "Learn-As-You-Go method", OM has been successfully applied in practice by progressively modifying the design to minimize potential construction risks over the years [129] [130] [131] [132]. If there is enough time to fully implement the revision plan proposed from ab initio or ipso tempore, the overall economy within the safety margin of the project can be achieved. However, some reticence still remains to its wider use [133] [134]. The reluctance of engineers to change design decisions already made has been now ameliorated through monitored-decision process [135]

[136]. Finno [137] used monitoring data to update performance predictions of supported excavations. Young and Ho [138] and Ikuta *et al.* [139] applied OM in design of supported excavation in which excavation sequence is taken into account to revise and confirm initial design assumptions. Corner effects and time-dependent movements in excavation projects have been dealt within OM framework in the context of EUROCODE 7 by Fuentes, Pillai, and Ferreira [140]. Wu, Ching, and Ou [141] adopted probabilistic OM to "update" wall displacements at later stages from earlier stages of excavation, and proposed "stage correlation" based on database of 22 excavation case histories in Taipei.

Implementing OM limits the risk of damage to a satisfactorily low level. Finno and Calvello [142] developed and tested inverse modelling in updating design predictions using inclinometer data obtained from a 12.2 m deep excavation through soft clays in Chicago. Calvello [143] forwarded an approach combining OM and inverse analysis techniques for continuous model recalibration of geotechnical boundary value problem, as shown in **Figure 2**. This time-dependent iterative model calibration using updated new field observations is termed as "observational modelling"; and is found to be effective in predicting associated soil displacements, provided that model uncertainties are dealt with an adequate engineering judgment. Acquiring a high level of good and sound engineering judgment by observing actual performance while the construction proceeds need an ongoing learning and previous experience [144] [145]. Moreover, much computational benefit is gained from computers. [143]

3.2. Construction Monitoring and Early Warning

As deep excavation pit construction sites generally involve multiple resources in dynamic work task and neighboring structures, the risk warning value needs to be cautiously monitored from the perspective of safety and stability. If the field monitoring result of design performances (be it compression force in the struts

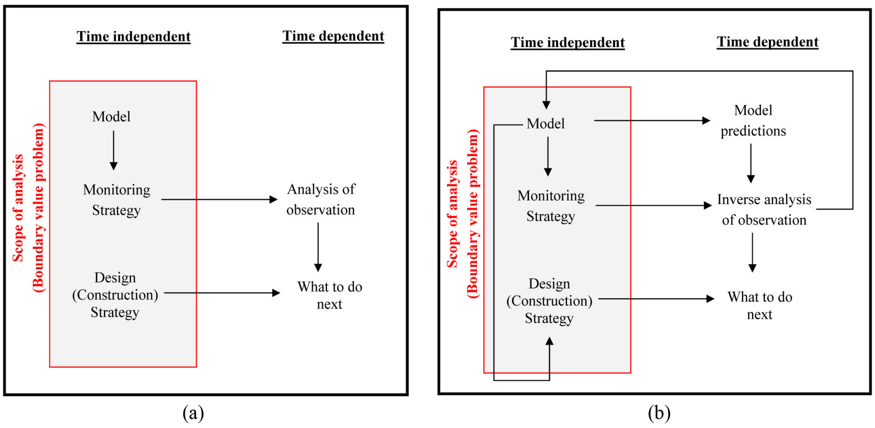

Figure 2. Schematics of: (a) observational method; (b) "observational modelling" approach for updating the design predictions of geotechnical boundary value problems [143].

through strain gauges or load cells; deflection of the wall obtained with inclinometers; ground surface movements via optical surveys, inclinometers and extensometers; and porewater pressures through piezometers) are surpassed, the monitoring personnel sends the forewarning document to overseeing unit to trigger threshold safety alarms [25] [146] [147] [148]. Due to the installation of the instrument, the measurement cost by manual monitoring approach is very high, but emerging safety technology is basically replacing them by the automatic monitoring method. Automatic monitoring mainly works on electromagnetic effects and capacitive effects of sensors [72] [149].

Monitoring performance plays an important role in the construction process. Liu, Ren, and Liu [150] discussed how monitoring-based risk management can be used in risk classification, identification and assessment with early warning in deep excavation engineering. A refined monitoring data can bring good early risk warning. However, as the construction of deep foundation pits continues, the safety risks continue to change, making it difficult to achieve real-time monitoring through traditional safety risk early warning systems [78] [151]. In order to eliminate this drawback, the so called "Building Information Modelling (BIM)" has recently become an inevitable choice owing to its convenience in multi-dimensional visualization and user friendliness [79] [152] [153]. With the advantage to incorporate a time factor in using BIM, an effective safety risk identification and occupational health can be achieved [77] [154] [155]. Qian and Lin [77] also detailed the progress of Chinese real-time online safety risk management.

A safety barrier early warning system using the Internet of Things (IoT) has been implemented in underground construction sites to improve safety management by gathering monitoring data of workers and "things" [71] [148]. The system uses a hazard control alternative, in which the sensing unit, wearable device and monitoring apparatus interact with each other to reduce the contact between hazard energy (danger/risk source) and target (workers, the environment, or physical assets); and recovery enforcement necessary to step away from any potential hazards. An increasing research interest on sensors is putting Information technology (IT)-based construction management into practice [156] [157] [158] [159]. IT-based construction management addresses the following aspects: 1) fast and accurate tracking of construction resources, 2) assuring effectiveness of proximity detection and alerting technology, 3) efforts to replace human operations with robots, and 4) combination of BIM and GIS technologies; in addition, it improves the accuracy and processing time of data, forecasting capability and information feedback.

4. Risk Control Measures

Construction safety risks can be addressed by identifying the consequences of critical risk factors (causes) and evaluating their occurrence probability to select preventive and protective strategies [160] [161]. The notable construction risk factors according to Tinghua, Siping, and Jingru [160] include design and construction scheme; edge protection; side-wall supporting; drainage measure; loads close to pit side; up-down passage; earth excavation; deformation monitoring; and working environment. These factors contributed to main risk events such as pit collapse, collapse of pit bracing structure, high-fall accident and other causalities. In order to control these risk events, a detailed process is needed that ensures providing satisfactory safety factor during the design process, combined with an inclusive quality control program and monitoring system applicable to the source of risk during the construction process, and applying appropriate contingency plans that fit-for-purpose [162].

As envisioned by the need for economic foundation system in marginal soils and the growing practice of overlaying high-rise structures on piled rafts, it is now inevitable to find new foundation pit excavations adjacent to them. As previously shown in **Table 1**, the performance of foundation pit excavation work has gained much attention. The focus was mainly concentrated to adjacent structure's settlement and more specifically the challenges to neighboring piled foundations. Many studies have attempted to respond by investigating the response of piles, which involves consideration of pile-soil interactions [62] [163] [164]. The ultimate lateral resistance of a pile in a group under passive loading is affected by the pile-soil interaction [165]. Likewise, assessment has to be done for the stability and integrity of piled rafts under the influence of adjacent deep foundation pit excavations. However, when it comes to disconnected piled rafts, the soil-structure interaction mechanism gets even more complex due to the coordinating effect among the raft, cushion, pile and ground. Partly because of this complexity, straightforward solution has not yet been issued and its associated risk has been given little attention. For such a project with intricate boundary conditions, investigating the response of existing foundation would essentially require knowing its current condition and implementing observational method with proper data-interpretation methodology. Due to this distinctive sophistication, an independent peer review (4-eye-principle) on technical matters made by independent experts is highly sought [166] [167].

Compared with research concentration on understanding the load sharing mechanism of disconnected piled rafts [8] [168] [169] [170] [171] [172] and on excavations either on infinite soil or adjacent pile foundations (**Table 1**), little is done on understanding the influence of excavation on nearby piled raft foundations with interposed layer. Zhu *et al.* [173] experimentally evaluated the horizontal bearing characteristics of disconnected piled rafts. They found that the frictional resistance at the interface of mat and cushion layer provides the horizontal resistance to the applied lateral load. However, their load was not passively applied on the piles. Azizkandi *et al.* [174] and Sharma *et al.* [14], for example, have discussed the efficiency of unconnected piled rafts under seismic loading. Recently, focus is placed on the behavior of pile-soil system under lateral soil spreading due to liquefaction [165]. Nevertheless, liquefaction-induced flow imparts negligible load on the pile due to sudden loss of soil stiffness, which is not experienced by the pile-soil system subjected to excavation induced soil displacement [175] [176].

Wang and Yang [177] performed experimental study on the interaction of new excavation with adjacent high-rise building founded on CFG piled raft. The results of their model test indicated that as the adjacent excavation work was proceeded, the adjustment of the load shared by the CFG piles continued in a complex manner of joint interaction among the pit retaining structure (piles), composite ground and strip of soil column between pit supporting piles and CFG pile composite ground. The centrifuge experimental test performed by Li, Huang, and Han [178] also confirmed the same and revealed the presence of CFG piles reduces the active earth pressure compared to the conventional Rankine theory. Yan-qing Wei [179] also performed indoor model test. The results showed that as the retaining wall was moved, the sliding surface in the retained soil was different from the conventional slip surface because of the piles (see **Figure 3**). Furthermore, the same study pointed out that that with the gradual movement of the wall, the load transmitted to the piles' head increased and consequently, the load shared by the soil decreased, see **Figure 4**. The numerical analysis of Ren and Qiao [180] showed that with an increase in excavation depth, the lateral displacement of the CFG piles increases.

On the other hand, according to some research results, because the axial working load has little effect on the lateral response of pile, once the serviceability limit is exceeded, it may cause sudden damage and collapse of the pile without any signal [64] [181]. Moving on, the lateral response behavior of front piles is highly affected by excavation induced extra passive loading than the rear ones [66] [182] [183]. Therefore, it may be necessary to check whether the structural and geotechnical capacity of the pile is sufficient to withstand the passive load applied due to ground movement caused by excavation. In order to eliminate such and other risks (see **Table 2**), engineering experience and judgment play a significant role. In the risk management process, engineering experience and

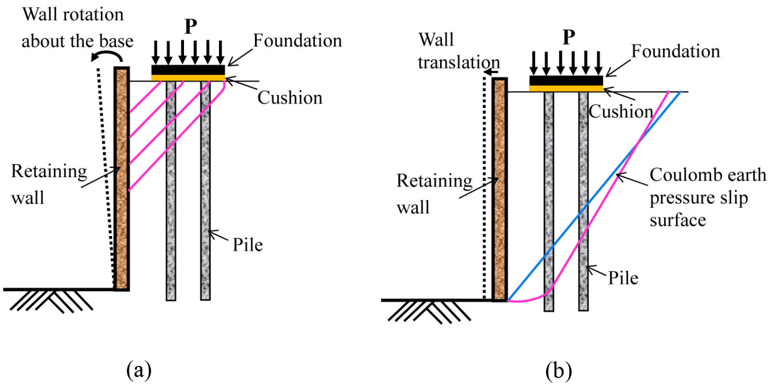

Figure 3. Potential failure surface in the soil behind a retaining wall under (a) rotation about its base; (b) translational mode [179].

Table 2. Selected potential risks with countermeasure suggestion and/or comments.

Objective	Target	Risk/event source	Methodology	Remedies/comment
Deep excavation assuring protected environment	1) Controlling foundation pit deformation; 2) Limiting ground movement (sudden ground loss or subsidence)	Geotechnical conditions	Spatial geo-material variation & uncertainties (different site conditions)	Inverse analysis based on observations during excavation to confirm actual & design assumption; Enhance soil strength by grouting; Turn to appropriate construction method to suit unanticipated condition
			Leakage & hydraulic failures	End-plate method connection for diaphragm wall joints; With relief wells release confined aquifer pressure; Waterproof curtain by mixed-in-place technology; Prevent uplifting by hybrid of jet grouting & deep soil mixing
			Global and/or localized soil and excavation support structure failure	Zoned construction method (quick excavation, prompt propping, casting rigid floor slab timely); Provide sufficient wall embedment & adequate passive resistance (including stiffness of retaining wall-strut system, soil/anchor length with soil voids filled by grout); Increase unlading moduli of basal stratum with ground improvements
			Selection of proper constitutive model (model simplification and omissions)	Consider optimum compromise to account for path- and state-dependent soil properties; Insufficient level of detailing and design accuracy
		Surrounding existing condition	Structural and geotechnical failure of existing piles	Construction of isolation/barrier piles to reduce imposed external passive loading (bending moment and forces) on piles
			Abrupt loss of foundation bearing capacity	Avoid over-excavation to prevent toppling; Compensation grouting
			Tensile strains induced in a building	Component and system fragility assessment for limiting tensile strain (reliability analysis approach)
			Differential foundation settlement; movement and rotation at pile head	Renovation, backfilling and underpinning to limit distortions in the sagging and hogging zones
		Project-delivery system	Uncertainties in performance measurements as required by the contract	Risk transfer through negotiated exception clauses included in the bid or through claims
			Amount of risk willingly taken by the owner	The traditional design-bid-build is ineffective in minimizing adversarial relationships
			Poor on-site management & communication	Continues performance & productivity monitoring with 4-eye principle; Turn to Design-Build or Construction-Management at work mode of project delivery
			Political and financial related	Change of related-low and regulations; Price escalations, payment delays, etc.

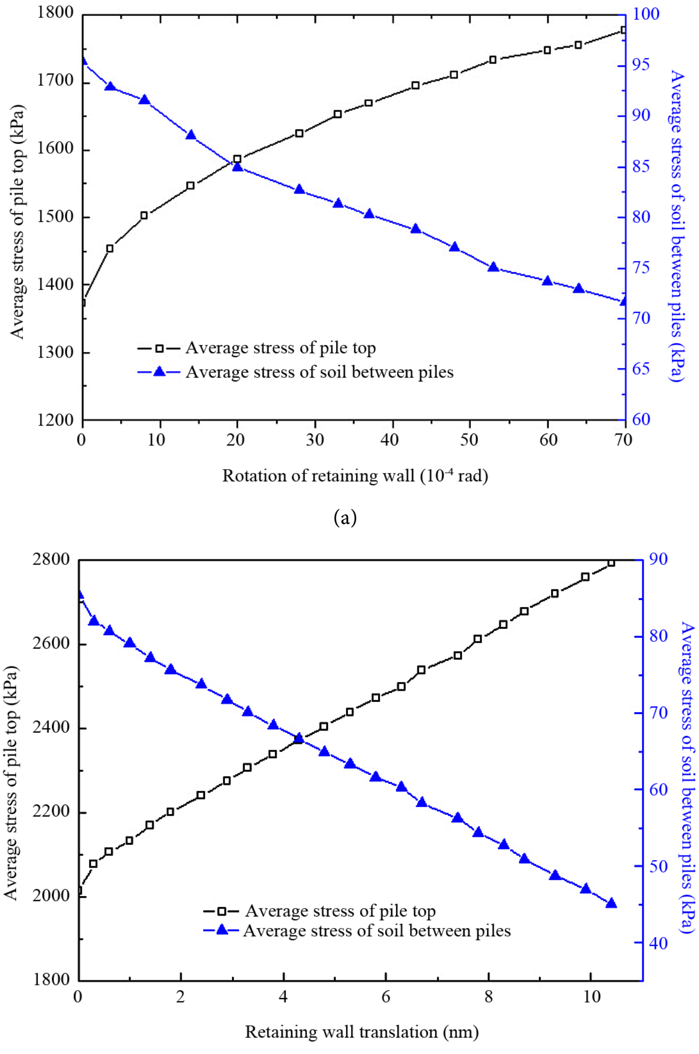

Figure 4. Influence of retaining wall movement on the average stress of soil between piles and pile head of composite foundation under a working vertical load of 88 kPa (a) rotation about the base; and (b) under translation mode [179].

judgment will normalize the decisions regarding Contractor's means and methods, choosing appropriate and mature technology, and dealing with uncertainties in design and construction phases [116] [184] [185] [186].

5. Risk Management Process

It is not enough to understand the probability and consequences of each risk event. There is a need for a systematic method called a risk management process that responds to minimize adverse risk by transferring, avoiding, mitigating or accepting specific risk elements among risk owners and action parties, as illustrated in **Figure 5** [76] [87] [187] [188] [189]. There is also a need for a system that delivers information appropriately at the right time to ensure that the identified risks and their treatment plans are well communicated [188]. For example,

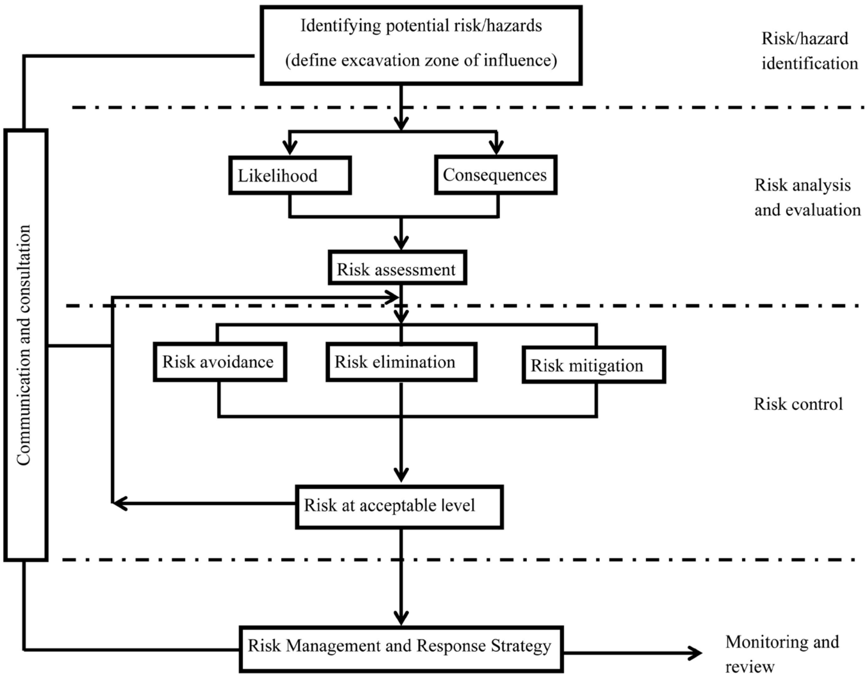

Figure 5. Risk management process for construction projects [187] [188] [189].

the case studies of 50 Dutch underground deep excavation projects in the Netherlands conducted by M. Korff [82] indicated that evaluating and documenting risks during the project by itself is not sufficient to prevent failures but also the lesson systematically gained for the next stage or project needs to be incorporated. In the same report, it was shown that the knowledge to prevent 60% failures existed outside the project, indicating clearly that it is not common to learn regularly between projects. O'Neil [190] also argues to involve all project personnel to search for opportunities in order to enhance margins with constant anticipation and conscientious efficiency in all areas. Similarly, the study on safety risk management for Chinese large scale subway and underground construction projects pointed out that weak risk management mechanism is the leading cause of economic losses and casualties [191].

In general, the approach for risk management and response strategy can either be applied through risk control (by avoiding, loss reduction, risk prevention, and risk transfer) or financing the losses that may occur [189]. While applying observational modelling, the lesson learnt from the earlier stage of the same project is used to reduce the size of the initial risk. Progressive application of such dynamic risk management is termed as Multiphase Risk Management Method [192] [193]. Furthermore, the cushion layer compressibility and the interaction effects among each pile while the soil moves around the piles would require 3D finite element analysis. It is worth noting that when implementing risk response strategies, back analysis with pit and ground deformation control criteria as well as monitoring based risk tracking by considering risk interdependences play an important role. Needless to say, achieving project objectives and successful delivery largely depends on how the risk management and response strategy is practically structured and properly implemented among concerned parties.

6. Future Research

Despite project managers are fully cognizant and give much attention to high-risk projects, the following issues are worthy of further study:

- Holistic geotechnical risk management plan from the perspective of stakeholders. Often statistical results were reported on previous studies, thus, further study is suggested on the risk diagnostics to refine the bias sources and risk decision theory.
- Issues related to risk and knowledge management at the company and site level. Is there any structured knowledge sharing platform to capture, encode and transfer lessons gained from organization's practice and experience in deep foundation pit excavation?
- More parametric numerical studies on the load transfer mechanism and excavation-induced settlement characteristics. Since disconnecting the pile from the raft is a novel practice, more and more researches are needed to fully understand the complex soil-structure interaction due to the presence of the deformable cushion layer.
- Advanced technologies to capture the soil-structure interaction experimentally. In fact, the current experimental setup lags behind perfection to take into consideration factors such as superstructure stiffness, retaining wall installation, and embedded basement slabs (mats).
- Back analysis during OM highly depends on the model parameters. Thus, further study may be necessary to understand the non-linear soil stress-strain response under different loading/loading states due to excavation.

7. Conclusions

This paper dissects the risk management approach from the perspective of geotechnical engineering and enlightens the need to account for risk interdependences and proper communication of lesson learned from other projects and/or ongoing ones. To this aim, based on risk triggering conditions, risk/event sources can be categorized broadly into 1) geotechnical conditions, 2) surrounding environment, and 3) project delivery system. For deep foundation pit excavations in congested urban dwellings, the risk control practice is essentially concentrated on limiting foundation pit deformation and associated ground displacements to an allowable amount that ensures serviceability limit state requirements are met.

Supplemented with sound engineering judgment, a well-posed observational modelling allows to better understand the load and deformation behaviors of the foundation pit and adjacent on-service foundations. If the expected performance cannot be achieved during the observation period, rigorous and timely research on the uncertain parameters and predicting their potential impact will provide reliable elements for risk-based decision-making. Currently, numerical simulations are widely used to assess the effect of ground movement on piles.

Each deep foundation pit excavation has its own challenges to take lessons from it due to the very nature of pertinence and strong locality. Although it is not necessarily copied and pasted, the essential information systematically explored out of the "dark data" of the completed project and/or the ongoing monitoring data can avoid failures. Therefore, proper communication of such information is germane to the competency of decision makers along the risk management process. It eliminates predictable risk events. Yet, comprehensive future study is needed to fully understand the behavior of disconnected piled rafts subjected to excavation-induced soil movements.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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