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EXAMINING FACTORS INFLUENCING PRECISION OF TOP-DOWN STEEL COLUMN CONSTRUCTION AND COUNTERSTRATEGIES FOR DEVIATION

Yee-Chaur Lee[1], Yan-Chyuan Shiau[2,*], Guo-Chin Lee[2] and Pei-Chun Tai[2]

[1]Department of Landscape Architecture
[2]Department of Construction Management
Chung Hua University
No. 707, Wufu Rd., Sec. 2, Hsinchu 30012, Taiwan
joeychuc@yahoo.com.tw; rocklen@ceci.com.tw; E10316016@chu.edu.tw
*Corresponding author: ycshiau@ms22.hinet.net

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Abstract. *As the foundation of steel superstructures, steel columns constructed using top-down approach lead to horizontal decentering or tilting twisted, and generate elevation errors during the construction process, all of which are critical factors in top-down construction methods. Expert brainstorming was used in this study to examine the risk factors affecting construction precision when separately applying top-down-method steel columns in three types of bearing pile, namely full-casing, reverse circulation, and wall piles. Five major dimensions influencing construction precision of the top-down steel columns and 15 primary influential risk factors were compiled in this study to investigate the reasons for these risks and to evaluate the probability and severity of all risk factors. The risk level of the three bearing pile methods was ranked according to the results. Questionnaire survey results were used for risk factor calculation and analysis. Counterstrategies for mitigating relevant risks were proposed as references for relevant business operators, design and construction supervision consultants, and construction firms.*

Keywords: Expert interview, Full-casing pile, Reverse circulation pile, Risk analysis, Top-down construction method, Top-down steel column

1. Introduction.

1.1. **Background.** The top-down construction excavation is one of the important construction methods which are used in digging extra-deep foundation system of underground continuous wall supporting [1]. This method has many advantages, such as forming a complete and stable mechanical structure, reducing construction procedures and the frequency of structure transformation, improving the stability of structure during the construction [2]. The top-down construction process in a column of a pile verticality control requirements is so high that the traditional method does not meet the construction requirements. Li has discussed a new type of hydraulic automatic verticality adjusting method, and verified its superiority and rationality in construction practice [3]. Risk management factors affecting the precision of a top-down construction method for steel columns include various aspects of a construction procedure such as the diameter of bearing piles, drilling of pile bodies, wall verticality, geologic condition, steel cage lifting verticality, structure design, lifting order, length, and lifting crafts of top-down steel columns, use of feigned column or real column coupling, a falsework installation device, concrete grouting, and runaway segment backfill.

A construction site for top-down steels in Taipei City, Taiwan was investigated in this study. The scope of this investigation included different bearing pile bodies, such as foundation piles and wall piles, sequential order of lifting top-down steel columns, types of top-down steel column lifting and fixing, and concrete grouting. Integrated analysis was conducted according to risk factors affecting precision during the construction process to help owners, design and construction supervision consultants, and contractors effectively avoid or reduce the incidence of precision errors when adopting the top-down construction method.

1.2. **Objectives.** The objectives of this study are listed as follows.

A. A literature review and case study were used to examine the current situation and problems encountered during the construction of top-down steel columns in Taiwan.
B. A questionnaire survey regarding the risk factors affecting top-down construction precision was conducted, combined with an inductive analysis of empirical cases, to establish complete evaluation architecture for determining the key risk factors affecting precision.
C. An expert interview method was employed to validate counterstrategies that prevent deviation caused by risk factors affecting the precision of top-down steel column construction. The results can serve as references for owners, design supervisors, and construction firms.

1.3. **Methods.** In this study, counterstrategies for preventing precision deviation were proposed based on a secondary data analysis, case study, and questionnaire survey. These strategies were validated through expert interviews. The research methods in this study are as follows. (1) The secondary data analysis method was adopted to determine the factors affecting the precision of the top-down steel column construction method. (2) A case analysis method was used to analyze the influential factors. (3) Professional engineers with experience in the top-down construction and foundation piles were recruited for the questionnaire survey. The factors influencing precision of the top-down steel column construction method were compiled. (4) An expert interview was conducted to identify risk factors.

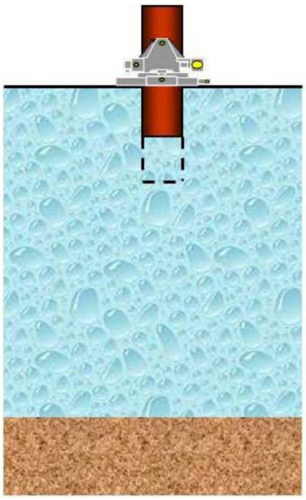
The top-down construction method for steel columns is discussed in Section 2. Construction risk factors are disclosed in Section 3. Brief conclusion is stated in Section 4.

2. Top-Down Construction Method for Steel Columns.

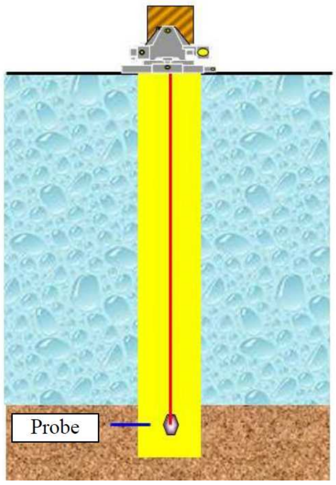
2.1. **Introduction to top-down construction for steel columns.** The top-down construction method involves building retaining walls around a structure before excavating the foundation and installing underground steel or struts to sustain the load. Subsequently, partial excavation is performed, and the slabs of underground structures are used to replace internal struts. From the floor level, the soil is excavated downward at which point construction commences. Concurrently, superstructures can be constructed. Because the top-down steel columns are first completed in the top-down construction method to couple steel superstructures, the construction precision of the top-down steel columns directly affects the coupling of underground structures and steel superstructures [4,5]. The top-down construction method is primarily suitable for any case to be completed within the shortest time and in construction conditions and environments where the bottom-up construction method is not feasible [4]. The conditions and environments are as follows:

A. High-rise buildings and deep-excavation structures;
B. Safety of nearby buildings and roads;
C. Disaster avoidance;
D. Lengthy bottom-up construction, thereby increasing the time cost for owners;
E. Uneconomical bottom-up construction, resulting in high construction costs for owners.

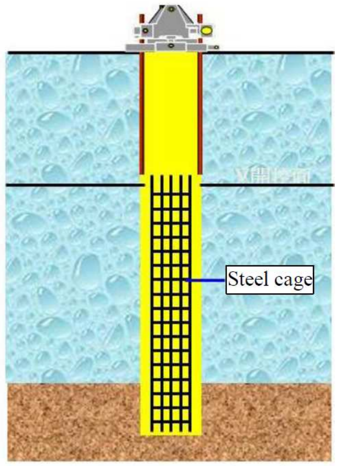
The top-down construction method involves the components of the full-casing pile top-down construction method, including the following nine construction items: (1) staking out and location determination, (2) pile body system, (3) steel cage lifting location, (4) top-down steel column lifting control, (5) top-down steel column lifting, (6) top-down steel column adjustment, (7) termi pipe lifting and sludge pumping control, (8) concrete grouting, and (9) top-down steel column readjustment and runaway segment backfill control (Figure 1).



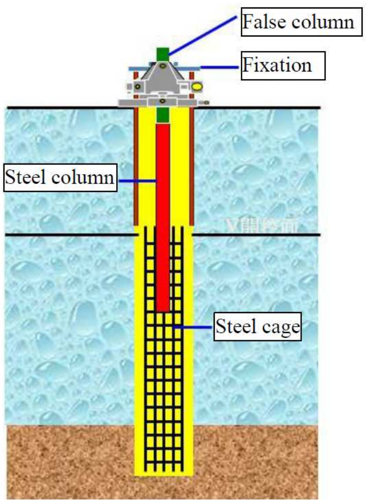
(a) Sleeve positioning and boring



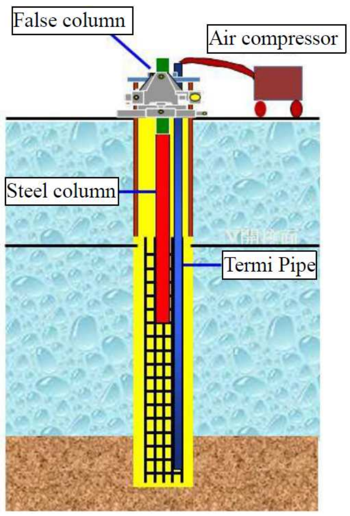
(b) Ultrasound detection



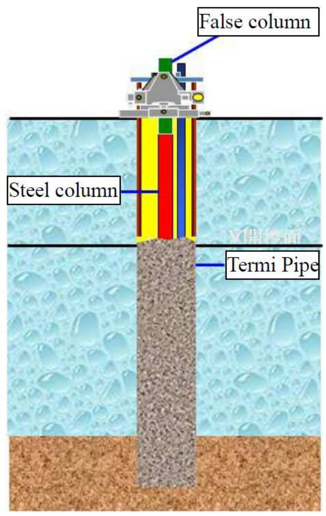
(c) Dipping steel cage



(d) Dipping and positioning steel column



(e) Dipping termi pipe and extracting silt



(f) Pour concrete

FIGURE 1. Construction flowchart of steel column for full casting pile foundation

2.2. **Risk identification of top-down construction method for steel columns.** In the present case study, the top-down steel column is constructed using bearing piles. Thus, the foundation pile drilling method must be used for construction. Various construction items possibly affect the process of identifying risks associated with the precision of the top-down steel columns, including full-casing, reverse circulation, and wall pile construction methods [6]. The risk factors generated within are approximately similar, and their effects on the construction precision vary. The uniqueness and uncertainty of construction risks of the top-down steel columns differ from those of conventional construction. Thus, counterstrategies for the problems encountered in the top-down construction method must be determined according to different construction environments and conditions. The process of risk identification in this study involved expert consultation, secondary data analysis, brainstorming, and check sheet methods to identify the sources of risks in top-down construction methods, the possible outcomes, and possible effects on the target, and determine how risks can be managed.

2.3. **Case of top-down steel column construction.** This study focused on a construction case in which the top-down-method steel columns were used as the real columns in the Taipei Metro Area. The basic introduction to the cases is detailed in Table 1 [7-11]. To investigate the differing precision levels of top-down steel columns caused by different pile construction methods, identical construction conditions were used and included identical design requirements, steel column type, steel column length, geologic condition, pile diameter and depth, and construction management and supervision. Thus, different precision deviation results were observed. Historic data documenting the entire process of constructing top-down steel columns to earth excavation were collected and used to analyze factors influencing the precision deviation of top-down steel column. The results can serve as references in the risk management of top-down construction methods for steel columns. The results of the historic data analysis showed that the precision deviation of top-down steel columns after earth excavation included high elevation, column core position, column face twist, verticality, and inclination. Although the precision deviation patterns of the four cases were identical, different pile construction conditions were observed.

Table 1. Case description

Case	Region	Pile type	Pile depth	Pile diameter /wall pile thickness	Length of the top-down steel column
A	Xinyi District, Taipei City	Full-casing pile Reverse circulation pile	60-99 M 60-99 M	150 cm 200 cm	18-20 M 18-20 M
B	Songshan District, Taipei City	Reverse circulation pile	47 M	150 cm	16 M
C	Xinyi District, Taipei City	Reverse circulation pile	43 M	100 cm	14-16 M
D	Nangang District, Taipei City	Full-casing pile Full-casing pile Wall pile	45 M 45 M 38 M	200 cm 250 cm 150 cm	16-20 M 16-20 M 16-20 M

Source: [7-11] and compiled by this study

3. Construction Risk Factors.

3.1. **Identification of construction risk factors.** To establish risk factors for risk analysis, a questionnaire survey was conducted with 65 management and engineering experts from construction agencies, architecture firms, and construction firms with more than 5 years of experience in foundation pile construction and top-down construction. A total of 15 risk factor items affecting the precision of the top-down steel column construction were determined. All of the risk factors were analyzed, compared, and categorized. The risk levels of the established risk items and the results can be employed to adjust the required costs and period of construction based on considerations for precision. The construction procedures and their associated risk contents, risk causes, and counterstrategies are summarized in Table 2.

Table 2. Risk factors, causes, and counterstrategies for ensuring the precision of top-down construction methods for steel column

Dimension	Risk factor	Risk cause	Counterstrategy
Bearing pile excavation	Decentering the pile body	Improper location	Location confirmation
	Inclined verticality of the pile body	Geologic variation or improper machine operation	Enhance personnel skills and geologic investigation
	Collapse of the pile body	Poor quality of stabilizing solution or geologic variation	Improve the quality of stabilizing solution
Steel cage lifting and releasing	Steel cage elevation error	Unsteady hoisting or human error	Steady overlapping and hoisting
	Crane fall	Improper hoisting	Enhance personnel skill training
Top-down steel column hoisting	Support structure sinking	Geologic variation or improper operation of instruments	Enhance machine operation training
	Calculation error of feigned column length	Human error	Recheck the length calculation of top-down steel columns
	Incorrect number of top-down steel columns	Human error	Recheck the number of top-down steel columns
	Incorrect orientation of top-down steel column	Human error	Recheck the orientation of top-down steel columns
Adjustment and correction of top-down steel column	Jack malfunction	Improper machine operation	Jack device maintenance
	Leveling instrument malfunction	Improper machine operation	Leveling instrument maintenance
	Transit instrument malfunction	Improper machine operation	Transit instrument maintenance
	Supportive observation facility malfunction	Improper machine operation or human error	Supportive observation device maintenance
	Human errors in instrumental measurement	Improper machine operation or human error	Recalculate instrumental measurement errors
Concrete pouring	Pouring concrete too quickly	Pouring concrete too quickly	Adjust speed of pouring

3.2. **Risk priority number of risk factors.** The risk probability multiplied by severity was used to obtain the risk priority number (RPN; risk value = frequency P $\times$ severity I) [11]. The risk probability (frequency) values of 1, 3, 5, 7, and 9 indicates extremely low, low, medium, high, and extremely high frequencies, respectively. Severity values of 1, 3, 5, 7, and 9 represent not severe, mildly severe, moderately severe, severe, and extremely severe, respectively. The RPN of each risk factor was examined. Table 3 shows the 15 risk factors included in the questionnaire survey and the RPN of full-casing pile, reverse circulation pile, and wall pile construction methods.

3.3. **Validation by expert interview.** In this study, counterstrategies based on the risk factors were proposed and validated through expert interviews. A total of 11 experts with more than 10 years of experience in the field of top-down construction methods were recruited for the interview (three from planning design sectors, four from on-site

Table 3. RPN of the three top-down construction methods

Risk factor	Full-casing pile		Reverse circulation pile		Wall pile	
	Mean	Order	Mean	Order	Mean	Order
1. Decentering the pile body	8.6	9	18.1	5	9.6	10
2. Inclined verticality of the pile body	10.2	7	21.3	2	9.1	11
3. Collapse of the pile body	6.4	13	20.3	4	13.6	6
4. Steel cage elevation error	6.6	11	11.6	11	4.5	15
5. Crane fall	9.3	8	16.6	6	10.8	8
6. Support structure sinking	6.4	12	26.8	1	6.8	14
7. Calculation error of feigned column length	20.2	3	14.2	9	23.1	3
8. Incorrect number of top-down steel columns	11.2	6	12.6	10	14.5	4
9. Incorrect orientation of top-down steel column	13.3	5	11.3	13	10.4	9
10. Jack malfunction	7.5	10	11.4	12	11.7	7
11. Leveling instrument malfunction	5.3	14	8.6	14	7.6	13
12. Transit instrument malfunction	3.9	15	8.6	15	8.9	12
13. Supportive observation device malfunction	22.5	1	14.9	8	14.2	5
14. Human errors in instrumental measurement	17.0	4	20.9	3	27.0	2
15. Overly fast concrete pouring speed	19.1	2	16.4	7	31.3	1

supervision sectors, and four from construction firms). Subsequently, a risk factor of support structure skew was added and inductive correction for each risk counterstrategy was made, as shown in Table 4.

4. **Conclusion.** The conclusion of this study is as follows.

A. Through a literature review, empirical case construction analysis, and preliminary expert interviews regarding the precision of top-down steel column construction, the 15 primary influential factors were obtained. The survey results indicated consistency. The influential risk factors of different methods are shown as follows:
   a. The three items in ascending order of priority in the full-casing pile method were "13. Supportive observation device malfunction," "15. Overly fast concrete pouring speed" and "7. Calculation error of feigned column length."
   b. The three items in ascending order of priority in the reverse circulation pile method were "6. Support structure sinking," "2. Inclined verticality of the pile body," and "14. Human errors in instrumental measurement."
   c. The three items in ascending order of priority in the wall pile method were "15. Overly fast concrete pouring speed," "14. Human errors in instrumental measurement" and "7. Calculation error of feigned column length."

B. Considering the precision of the top-down steel column construction method combined with full-casing pile, reverse pile, and wall pile methods, this study investigated different influential precision factors by using various construction cases and expert interviews. The results can serve as references for construction firms to consider the required construction conditions and resources that ensure precision and be aware of and correct the factors during construction.

C. The obtained counterstrategies for preventing precision deviation in the top-down construction of steel columns can serve as references for owners, design and supervision units, and construction firms to control the precision of steel columns during top-down constructions.

Some topics, such as steel columns patterns, excavation styles and steel column layout, are suggested as future related researches.

Table 4. Counterstrategies integrated with expert suggestions

Risk description	Risk cause	Counterstrategy
1. Decentering the pile body	Improper location	• Relocation • Remove obstacles • Backfill excavated segments before relocation for excavation.
2. Inclined verticality of the pile body	Geologic variation or improper operation of instruments	• If inclined verticality of the pile body occurs in shallow excavation, resume excavation after backfill. • Reduce excavation speed for deep excavation segments. • Regarding improper deployment of machines, relocate and replace machines with appropriate ones before relocation for excavation.
3. Collapse of the pile body	Poor quality of stabilizing solution or geologic variation	• If inclined verticality of the pile body occurs in shallow excavation, resume excavation after backfill. • Reduce excavation speed for deep excavation segments to reduce disturbance on the wall. • Use fresh stabilizing solution to enhance protection on the wall.
4. Steel cage elevation error	Unsteady hoisting or human error	• Recalculate the height to which the first and second sections of the steel cage should be lifted before hoisting. • Reinforce the second sections or higher of the steel cage depending on the error type. • Punish individuals involved in incorrect hoisting.
5. Crane fall	Improper hoisting	• When inclination is observed, release the hoisted object immediately. • For severe fall of the crane, immediately rescue the crane and deploy another one; dismantle the fallen crane, main machine, and steel cage. • Backfill excavated segments before relocation for excavation.
6. Support structure sinking	Geologic variation or improper operation of instruments	• Add support structure skew as a new risk factor. • Update new risks causes, geologic variation, and overload. • Before hoisting, relocate the support structure and reinforce the pedestal. • When mud is formed because of rain, reinstall the support structure when rain stops. • When the steel cage or column is already lifted, adjust the jack. If manual adjustment is not possible, reinforce the jack afterward.
7. Calculation error of feigned column length	Human error	• Carefully measure the sizes of feigned columns to ensure sufficient overlapping length. • Adjust support structure to correct difference in feigned column lengths. • When calculation error is discovered only after completion, make corrections and reinforcement according to the error status.
8. Incorrect number of top-down steel columns	Human error	• Before the top-down-method steel column is lifted, the number of the columns should be verified meticulously. • When the column listing is completed, correction and reinforcement are made according to the error status. • Material control is enhanced and on-site sheets are completed meticulously. • For any incorrect number of the top-down-method steel columns caused by human error, relevant staff will be punished strictly.
9. Incorrect orientation of top-down steel column	Human error	• Before concrete pouring, use a jack for correction. • After the column lifting is completed, make corrections and reinforcement according to the error status. • For any incorrect orientation of the top-down steel column caused by human error, punish those involved.
10. Jack malfunction	Improper machine operation	• Relocate machines.
11. Leveling instrument malfunction	Improper machine operation	• If inclined verticality of the pile body occurs in shallow excavation, resume excavation after backfill.
12. Transit instrument malfunction	Improper machine operation	• If inclined verticality of the pile body occurs in shallow excavation, resume excavation after backfill. • Reduce excavation speed for deep excavation segments to reduce disturbance on the wall. • Use fresh stabilizing solution to enhance protection on the wall.
13. Supportive observation device malfunction	Improper machine operation or human error	• Recalculate the height to which the first and second sections of the steel cage should be lifted before hoisting. • Reinforce the second section or higher of the steel cage depending on the error type. • Punish individuals involved in incorrect hoisting.
14. Human errors in instrumental measurement	Improper machine operation or human error	• When inclination is observed, release the hoisted object immediately. • For severe fall of the crane, rescue the fallen crane and deploy another crane; dismantle the fallen crane, main machine, and steel cage. • Backfill excavated segments before relocation for excavation.
15. Overly fast concrete pouring speed	Overly fast concrete pouring speed	None
16. Support structure skew	Geologic variation and overload	• Before hoisting, relocate the support structure and reinforce the pedestal. • When mud is formed because of rain, reinstall the support structure when the rain stops. • When the steel cage or column is already lifted, adjust the jack is adjusted. If manual adjustment is not possible, reinforce the jack afterward.

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