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A Case Study of The Performance of A Pile-Supported Bracing Method for Basement Building

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Abstract

Deep excavations in urban areas are highly hazardous due to extensive settling of the surrounding soil, which can lead to the failure of retaining wall systems and the consequent collapse of adjoining properties. The retaining wall and bracing system are important for completing deep excavations for a basement building project. This paper evaluates the performance of an alternative, innovative, low-cost pile-supported bracing system (PSBS) method during excavation for two-level basement construction. Assessed PSBS performance in terms of ground settlement, lateral movement of supporting systems, schedule, and cost comparison. The PSBS excavation method was designed and then implemented to construct a two-level basement using the bottom-up method. The total station was utilized to monitor three-dimensionally, like the adjacent school building, ground surface settlement, and lateral movement of supporting systems. A schedule and cost comparison were performed using internal bracing and the PSBS technique. The recorded filed data was analysed, and it found that the lateral movement of the support system, adjacent building, and ground settlement is within the allowable limit. According to the estimated results, the PSBS method reduces construction time by 272 days compared to the internal bracing system. The PSBS approach is also less expensive than internal bracing for a two-level basement.

Keywords: Bracing system, excavation method, two-level basement, ground settlement, lateral movement.

1. Introduction

Deep excavation for basement construction of a building in the city area is always challenging because there are many types of risks, such as failure of the retaining wall system, excessive settlement of the surrounding structure or soil, and the collapse of adjacent properties. To prevent collapses during excavation for basement construction, various retaining walls, including sheet piles, contiguous bored piles, secant piles, internal or external bracing systems, and diaphragm walls, are required. Numerous investigations [1-4] are conducted to ensure the safety of the support system and surrounding structure during basement excavation using modelling, analytical techniques, and data collected on-site for a different technique. Among the most common excavation techniques are braced excavation, full open cut, island excavation, top-down construction, and anchored excavation.

The open excavation method is a method where no internal or external bracing system is required. It can be divided into slope open cut and cantilever open cut. This method is suitable for shallow excavation if sufficient space is available to maintain the required slope, but no bracing system is required. An internally supported excavation system uses horizontal bracing at the excavation side to resist the earth pressure from the back of the retaining wall. The bracing system includes a waler, strut, end bracing, and king post. The internal bracing system is the most commonly utilized method for deep excavation [5]. A lot of research [6-9] was done on the internal bracing system, but it might be expensive for deep excavations, and this technology slows down the progress because it uses multiple bracing layers with permanent and temporary king posts. A deep tie-back excavation method was developed by Hudson et al. [10] and put into practice, although this approach necessitates additional raker footing, which is a difficult task.

An externally supported or anchored excavation system where the retaining wall is anchored externally. There are three segments of anchor excavation: the fixed section, the free section, and the anchor head. The function of the section is to provide anchoring force, transfer anchoring force to the anchoring head and lock the tendon, and transfer anchoring force to the structure, respectively. The anchoring method of excavation is also well-established, and numerous research had been conducted on it [7, 11]. This strategy, however, is appropriate when skilled workers and necessary machinery are unavailable.

Bottom-up basement construction method where excavation proceeds from ground level to the down until the formation level and casting proceeds from basement level to upward. The retaining wall, king post & bracing system are the basic components to execute the bottom-up method. In contrast, the top-down construction method is where the casting of permanent structures proceeds from ground level to down until the last basement completion. In this method, temporary openings keep facilitating excavation and casting works. The retaining wall & king post are the basic components required for this method [12]. The top-down method can reduce the construction time though the top-down method might cause more deflection of the retaining wall than the bottom-up method [13]. In the semi-top-down method slab at level 1 is used as a temporary working platform where the large opening is kept to carry out excavation. Level 1 slab acts as a frame to prevent lateral movement of the support system [14, 15]. Moreover, the combined top-down and bottom-up method central core zone is normally introduced bottom-up, and the perimeter portion proceeds with the top-down method, which has been implemented by Wang et al. [16].

There are lots of well-established excavation methods for basement construction. However, all the methods use a diaphragm wall, sheet pile, secant pile, or contiguous bored pile as a retaining wall. The internal or external bracing system with a king post was used to prevent movement of the retaining wall and surrounding facilities for a bottom-up method of basement construction. The high expenses and logistical difficulties associated with traditional bracing systems have prompted the investigation of alternative approaches to improve the cost-effectiveness and feasibility of construction projects.

However, this study is presented to evaluate the efficacy of an innovative, low-cost Pile Supported Bracing System (PSBS) in extremely soft and organic soil conditions. The original contribution of the proposed method is as follows: (i) evaluated the performance of PSBS by analysing ground settlement and lateral displacement of supporting systems; (ii) it introduced a low-cost pile-supported bracing system that is unique in the literature; and (iii) a schedule comparison was performed using the PSBS system and traditional bracing. The whole site was divided into four zones, and the excavation of each zone was carried out in three phases. The movement of piles, raker, waler, shore pile, capping beam, and the surrounding structure was monitored three-dimensionally. Moreover, the filed data was compared with the allowable limit of local code.

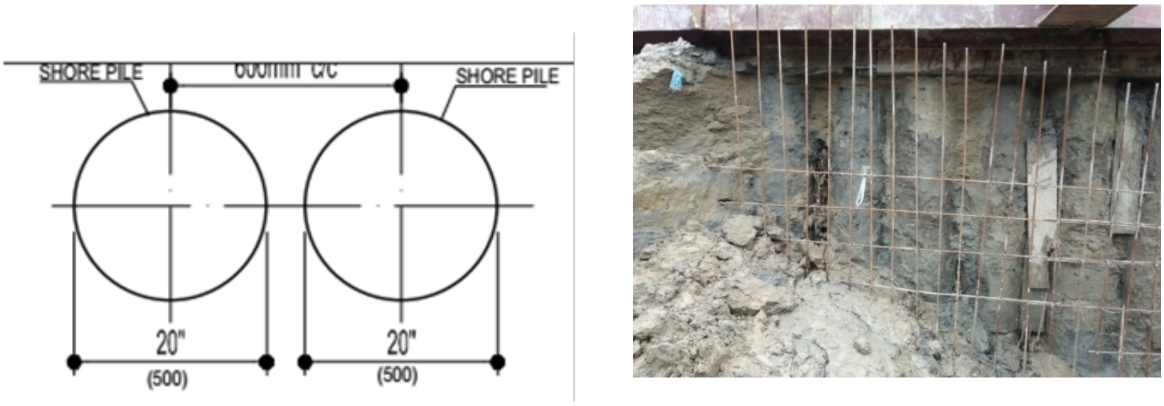
2. Case Study

2.1. Project Description

In this study, a 27-story five-star hotel with two basements is located in the Bangladeshi city of Khulna, with a basement space of 2133.6 m^2 and a ground floor area of roughly 37861.2 m^2. A 27-year-old brick technical school building is located on the project's eastern boundary, while a tin-shade residential building is on the project's northern boundary. The two-layer bracing system is introduced at the top of the basement slab, 5.8 m below the road level. The pump room, treated water tank, raw water tank, firewater tank, and wastewater treatment plant are below the basement level. The bottom of the excavation is 11.275 m from the basement level.

2.2. Supporting system

As a retaining wall system, where a 500 mm x 500 mm capping beam is provided on top of the shore pile to avoid trapping the shore pile, a 500 mm diameter and 15m~18m depth shore pile with a 100 mm gap between two shore piles are used as shown in Fig. 1. Additionally, sheet pile is introduced on the outer side of the shore pile.



(a) (b)

Fig. 1. (a) Setting out of the shored pile, (b) as-built shore pile location.

2.3. Bracing System

Three layers of I-beam with a 600 mm king post have been introduced for excavation. The first brace layer is at -2.2 m, the second is at -4.0 m, and the third is at -7.0 m below zero or road level.

2.4. Problem statement of the original design

The project is in a densely populated urban region, with public roads on the west and south sides. The eastern border of the project features a masonry technical school building constructed 27 years ago. It was found that there was a combination of very soft, soft, and organic soil in the subsurface. However, the project started to excavate according to the original plan without sheet piling. Eventually, water and soil penetrated the 100 mm gap between the shore piles. As a result of the seepage of water and soil movement, the adjacent road, drain, and a portion of the tin-shade building were damaged. It was noticed that some king posts could not resist lateral forces from horizontal bracing [17]. It was almost impossible to excavate by overcoming all the obstacles. However, considering the local perspective, the project used an innovative low-cost excavation method known as the Pile Supported Bracing System (PSBS).

2.5. Sub Soil Conditions

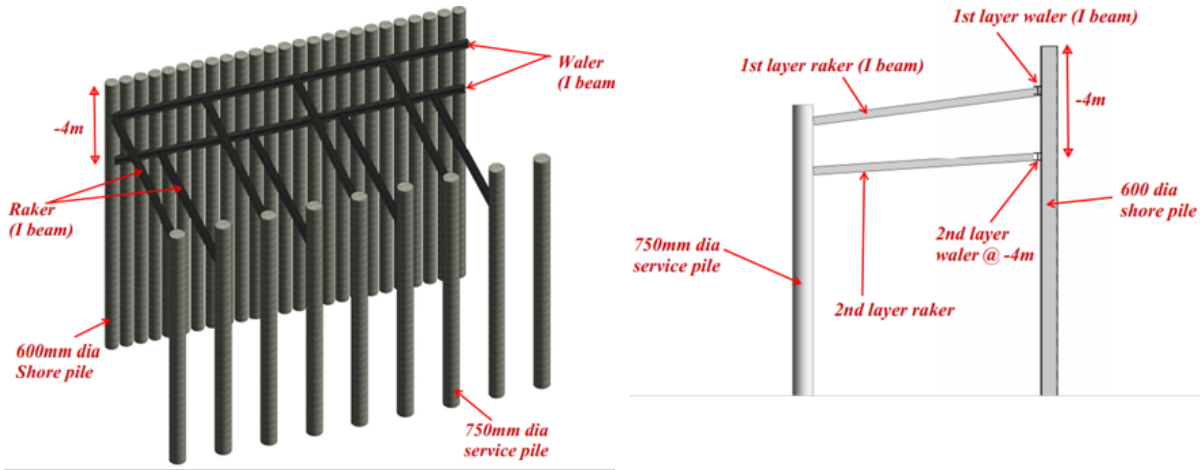
This is the first instance in Khulna City, Bangladesh, to complete a double basement structure on soft soil. According to Table 1, the soil consists mainly of silt and clay, with just a tiny amount of fine sand present.

Table 1. Soil profile in terms of depth of the project location

Depth from EGL (m)	Soil type
0-6	Fine Sand
6-9	Very soft silty clay
9-12	Black organics
12-13.5	Clayey silt
15.5-26	Very soft to medium clayey SILT
26-29	Black decomposed
29-35	Medium stiff to clayey SILT
35-39.5	Gray medium-stiff to stiff silty CLAY
39.5-42.5	Gray medium-stiff clayey SILT
42.5-45.5	Gray stiff to very stiff silty CLAY
45.5-48.5	Brown very stiff silty CLAY
48.5-50	Brown stiff clayey SILT
50-60	Very dense silty SAND

3. Pile Supported Bracing Systems

An alternative pile-supported bracing systems (PSBS) was implemented to address the shortcomings of the initial construction project design. The PSBS method (Fig. 2) involves connecting (raker) steel I-beams to existing working/service piles to maintain the retaining wall structure during excavation. The PSBS approach is implemented by dividing the site into four phases, as indicated in Fig. 3.



(a) (b)

Fig. 2. (a) 3D view of PSBS method, (b) Typical section of PSBS

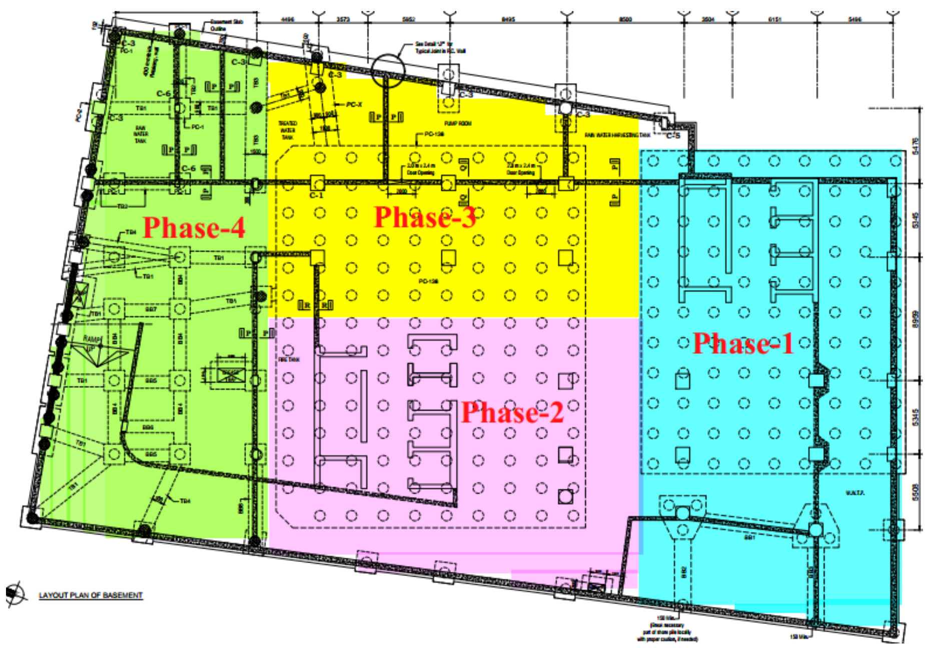


Fig. 3. Phases of basement construction

3.1. Sequences of Basement Construction

Step 1: Excavate -1m from the top of the capping beam.
Step 2: Install waler beam onshore piles and pack the gap between waler and shore pile to transfer uniform load.
Step 3: Install the raker (I-beam) with the first layer of waler (I-beam) that is installed on onshore piles (Fig. 2).
Step 4: Further excavate up to 1.0m, and a 100mm thick skin wall (Fig. 4) is cast at the inner side of the shore pile on the same day to prevent water and soil slurry ingress.

Step 5: Repeat steps 2 to 4 until - 4.0m of excavation.
Step 6: Install the 2nd layer of the waler beam at 4.0 m levels (Fig. 2 and Fig. 4).
Step 7: Install the raker (I-beam) with the 2nd layer of waler (Figs. 2 and 4).
Step 8: Repeat steps 2 to 4 until the formation level of the basement slab.
Step 9: Cast Phase-1 of the basement slab at 2–2.5 m from the shore pile.
Step 10: Cast the first lift retaining wall 2 m high from the basement slab.
Step 11: Remove the 2nd layer of waler and raker, followed by backfilling behind the shore piles.
Step 12: Excavate for Phase-2 of the basement raft and followed by casting.
Step 13: Transfer the raker from the working pile to the Phase-2 raft.
Step 14: Excavate for Phase-3 of the raft.
Step 15: Cast vertical elements from the basement to the semi-basement.
Step 16: Cast semi-basement beam and slab
Step 17: Cast vertical elements from the semi-basement to level-1
Step 18: Cast level-1 beam and slab.
Step 19: Completion of basement construction.

(a) (b)

Fig. 4. (a) Reinforced concrete wall, (b) Application of the PSBS method.

4. Instrumentation

To reduce the risk of excavation, a total 20 prisms were installed on the cap of beam and adjacent school building to monitor 3-dimensional movement, with readings taken using a total station. Fig. 5(a) depicts the arrangement of the installed prism distributed in Phase-2 (T-01 to T-03), Phase-3 (T-04 to T-08) and Phase-4 (T-09 to T-12). The prism was also installed in the adjacent school building (B-01 to B-08). Figs. 5(b) and 5(c) show the installed prism on the school building and the cap of beam.

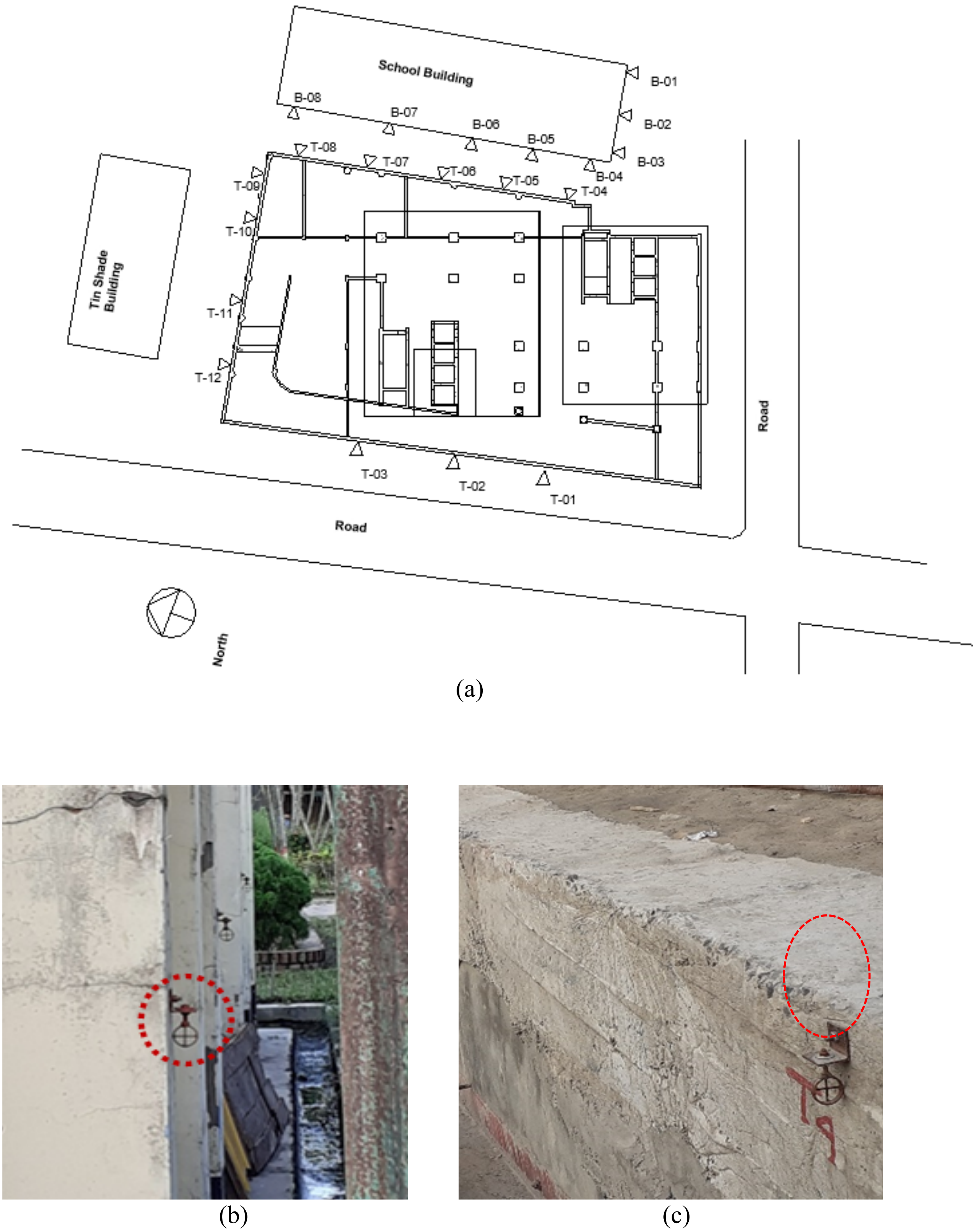
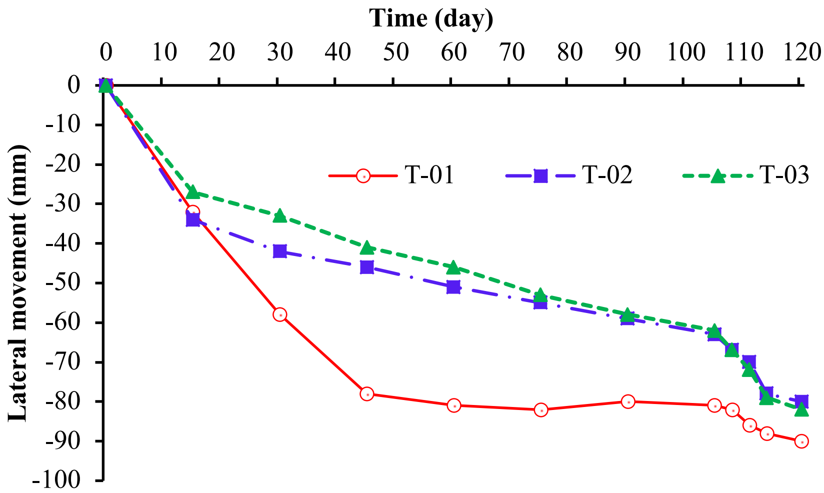


Fig. 5. (a) Prism layout plan, (b) Prism installed on the adjacent school building and (c) Prism installed on the capping beam

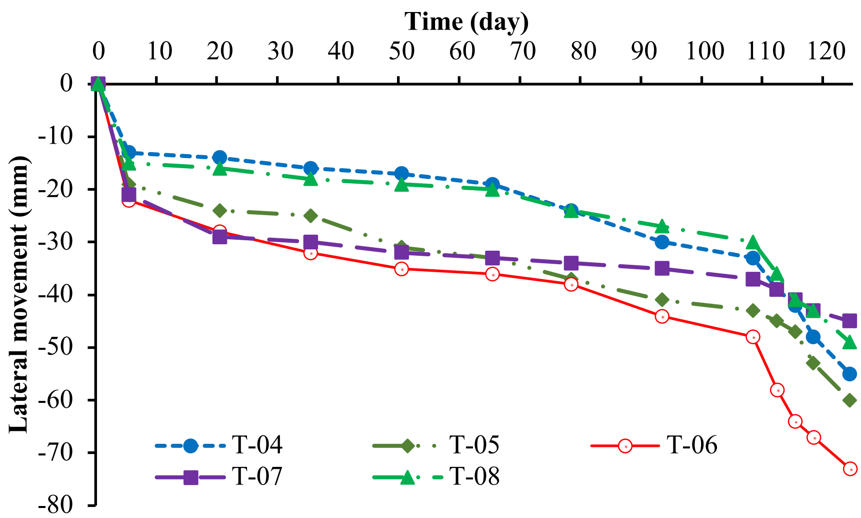
5. Field Performance of Pile-Supported Bracing Systems

5.1. Lateral Movement of Support System and Adjacent Building

Figs. 6(a), (b), and (c) illustrate the lateral movement of the shore pile retaining wall system during excavation for Phases-2, 3, and 4, respectively. A prism reading was taken during each phase of excavation to track the lateral movement of the support system. The lateral movement increases with the increase in the depth of excavation. Maximum capping beam movement was measured at 90 mm in the direction of excavation for Phase-2 and 73 mm and 55 mm for Phases-3 and 4, respectively. Due to additional excavation for the lift core, Phase-2 has a more significant movement than Phase-1. However, there is no considerable damage due to the excavation of the adjacent property. In compliance with the previous findings, if the ground movement is within a tolerable limit, there will be no or no damage to the surrounding property [18].



(a)



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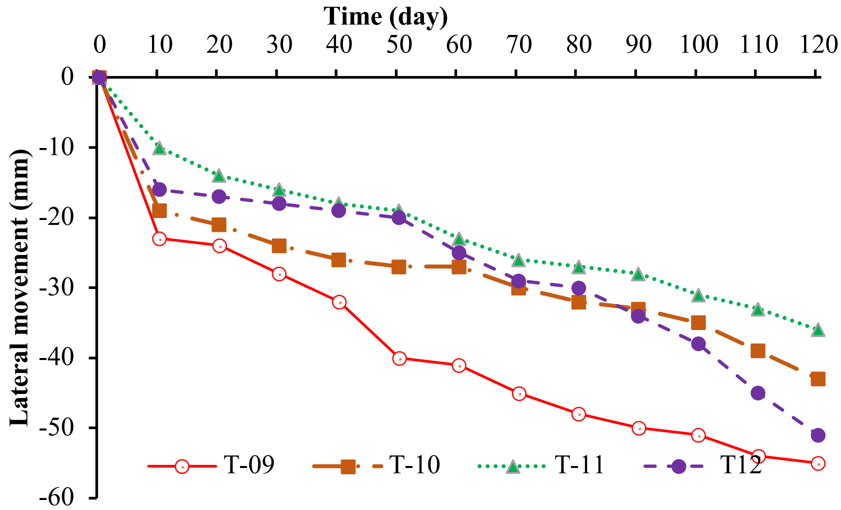


(c)

Fig. 6. Lateral movement of shore pile (a) Phase-2, (b) Phase-3, and (3) Phase-4.

To monitor the lateral movement of the adjacent existing property (i.e., a school building) due to deep excavation, a series of eight prisms (B-01 to B-08) have been fixed on the existing school building. As shown in Fig. 7, the maximum horizontal movement of the adjacent building due to excavation is observed at the location of prism B-08, with a magnitude of around 8mm. This is because prism B-08 is located very close to the excavation, and the depth of the excavation is relatively higher than in other locations. Additionally, it was observed that the minimum movement appeared at the locations of prisms B-04 and B-05 because the depth of excavation adjacent to them is relatively shallower. However, the 8mm lateral movement due to deep excavation is within the code tolerance (i.e., allowable 75mm).

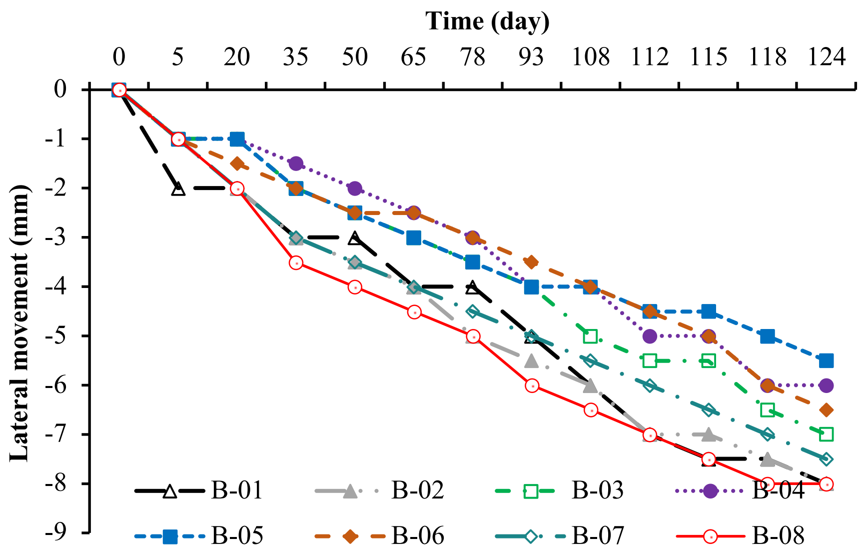
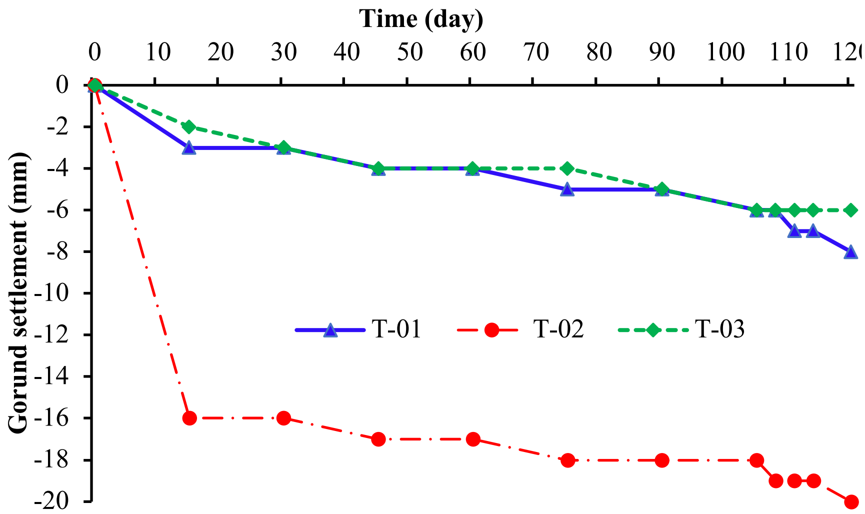


Fig. 7. Lateral movement of adjacent school building due to excavation

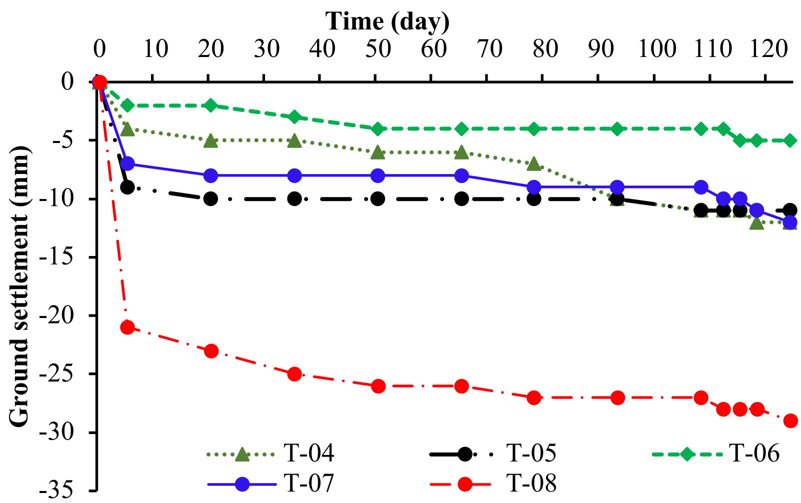
5.2. Settlement of Ground Surface

The degree of safety during excavation is contingent upon the surrounding ground settlement. A total of twelve prisms have been constructed along the boundaries of the project. Figs. 8 (a), (b), and (c) depict the extent of settlement observed during the excavation stages corresponding to Phases 2, 3, and 4, respectively. The reported average settlement for the prism T-02 during Phase-2 was 20 mm, but the prism T-08 demonstrated a maximum settlement of 29 mm during Phase-3. The prism T-12 demonstrates a maximum settlement magnitude of 39mm during Phase-4. However, the extent of the settlement was limited to 1.0m, excluding the capping beam. The main factor contributing to the settlement observed in Phase-4 of this study was the infiltration of soil slurry into the shore pile before the construction of the protective face of the wall. Prior to commencing any excavation, it is imperative to do a thorough risk assessment and implement appropriate precautionary measures. Nevertheless, the occurrence of ground settling during excavation is an inevitable hazard that has the potential to cause harm to the adjacent structure [19].

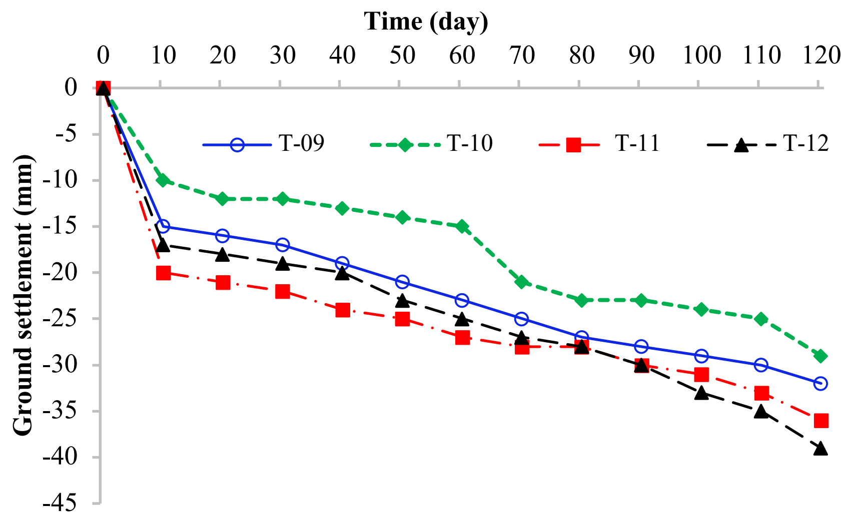
The adjacent school building has eight prisms (B-01 to B-08) installed to monitor movement during excavation. The measured prism reading is displayed in Fig. 9, and for the B-06 prism, the maximum ground settlement was 9 mm. Every curve was also found to move vertically, which may be the result of vibrations from excavation.



(a)



(b)



(c)

Fig. 8. Adjacent ground surface settlement due to excavation (a) Phase-2, (b) Phase-3, and (c) Phase-4

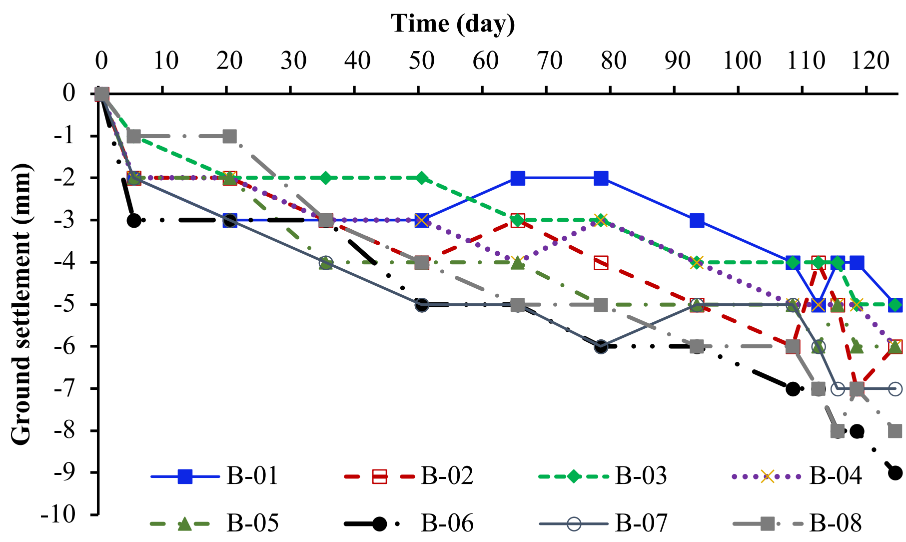
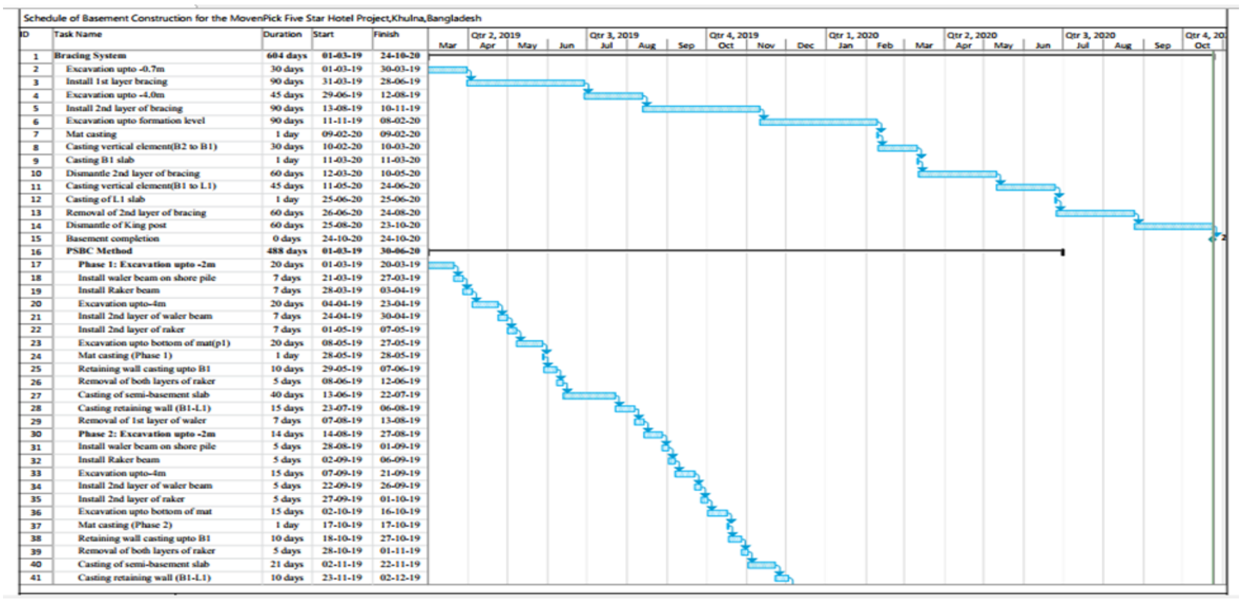


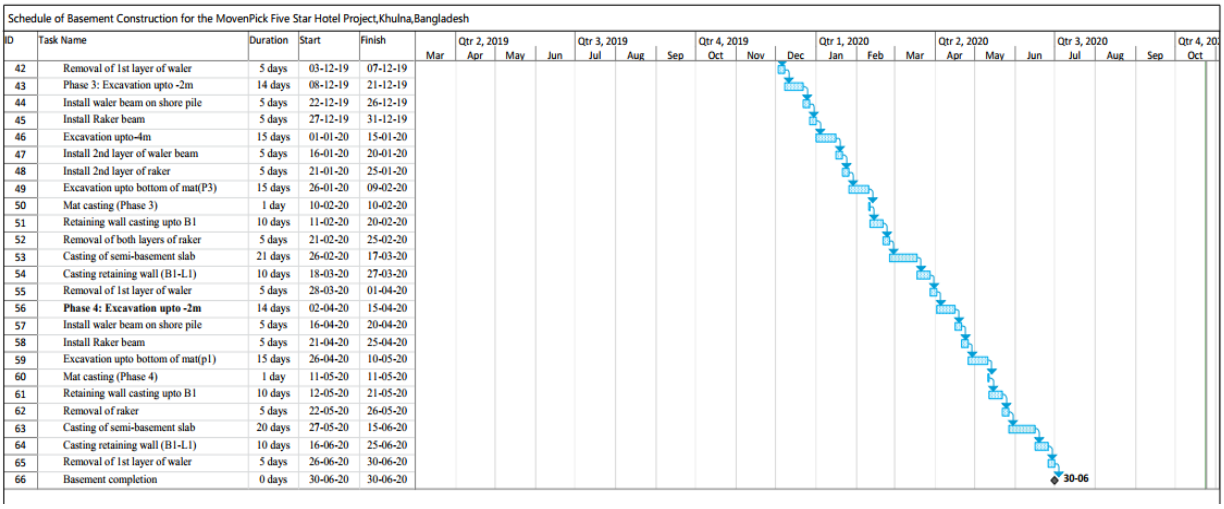
Fig. 9. Ground settlement of adjacent school building due to excavation

5.3. Schedule Comparison

Fig. 10 illustrates the duration necessary to complete basement construction while employing the original internal bracing system and the PSBS. Based on the findings of the PSBS, it is observed that the duration for basement construction spans a period of 331 days, but the installation of the internal bracing system requires a timeframe of 603 days. To clarify, the PSBS system reduces time by 272 days compared to the internal bracing method. Research has revealed that the elimination of the three-layer bracing system is a significant determinant in the time-saving capabilities of the PSBS system. The utilization of internal bracing in



(a)



(b)

Fig. 10. Comparison of schedule between (a) bracing and (b) PSBS system

construction projects has resulted in lower productivity levels compared to the implementation of the proprietary PSBS system. This discrepancy can be attributed to the increased number of preparatory operations required prior to excavation when employing internal bracing.

5.4. Comparison of Cost

The PSBS approach is a cost-effective solution, exhibiting a significant 50% decrease in construction prices compared to an internal bracing system, as depicted in Fig. 11. Significantly, the PSBS approach eliminates the need for a king post, optimizing the construction process and reducing the material necessary. A comparatively low steel I-beam is adequate for attaining structural stability, leading to cost reductions and enhanced efficiency.

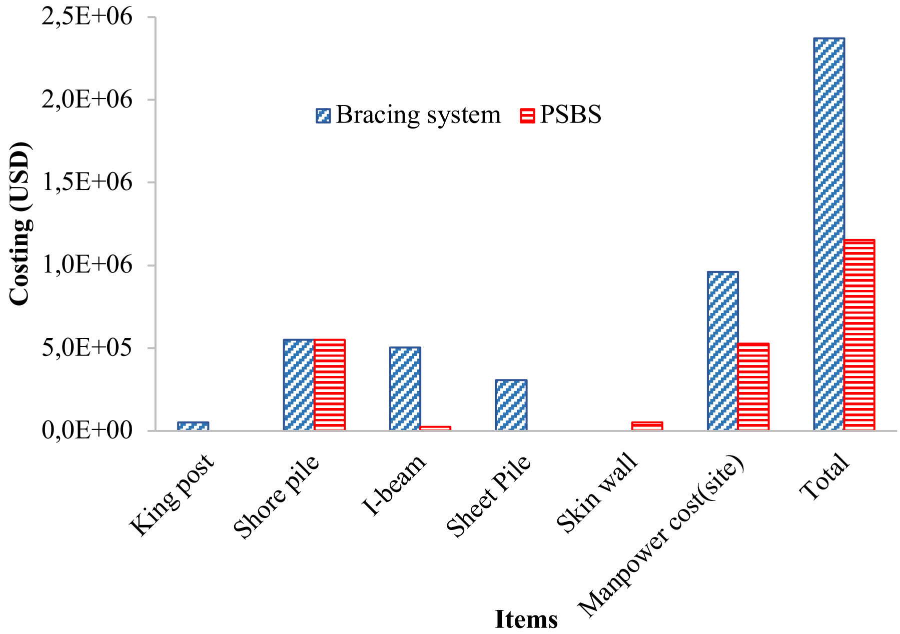


Fig. 11. Comparison of cost between bracing and PSBS

On the other hand, the utilization of the internal bracing technique presents the benefit of obviating the need for a reinforced concrete wall, thereby resolving particular construction considerations. It is important to note that in the original design, supports for sheet piles were built into the shore pile from the outside. This gives the structure more flexibility to adapt to site conditions and building needs. Implementing the PSBS method in a planned manner not only results in significant cost reductions but also improves the general flexibility and durability of the building methodology.

6. Conclusions

Deep excavations conducted in urban environments pose significant risks due to the substantial settlement of the surrounding soil. This settlement can result in the failure of retaining wall systems, ultimately leading to the collapse of adjacent properties. The inclusion of a retaining wall and bracing system is crucial in the successful execution of deep excavations for a basement construction endeavour. The total station was monitored three-dimensionally, like the adjacent school building, ground surface settlement, and lateral movement of supporting systems. The implementation of the PSBS was undertaken in order to effectively resolve the challenges associated with the first internal bracing strategy. The two-level basement of a 27-storied five-star hotel complex was completed using the unique PSBS technology. The use of the PSBS methodology in constructing a basement resulted in a reduction of 272 days in the project timeline and a 50% decrease in costs compared to the implementation of an internal bracing solution. The maximum lateral displacement of the supporting shore pile structure is measured to be 90 mm, but the maximum settlement observed on the ground surface is recorded at 39 mm. The primary cause of this type of settlement was the infiltration of soil slurry into the shore pile before constructing the surface wall. The lateral displacement of the support system, adjacent building, and ground settlement were found to be within the permissible limits. The present study employs a cost-effective and innovative pile-supported bracing system (PSBS) for the purpose of deep excavation in the building. The PSBS excavation method was developed and subsequently utilised for constructing a two-level basement using the bottom-up technique. The proposed PSBS approach may be employed for the construction of both deep and shallow basements.

Author Contributions

Md. Alhaz Uddin: Performed the analysis, Wrote the paper, Modified the paper.

Mizanoor Rahman: Conceived and designed the analysis, Collected the data, Contributed data or analysis tools.

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