Journal of Building Technology, 2024, Volume 6, Issue 1
DOI: 10.32629/jbt.v6i1.1636
ISSN Online: 2717-5103
ISSN Print: 2705-1390

A Conveyor-Based Earthmoving Machine for Deep, Top-Down Excavations

Haibin Li

Postgraduate, Xinjiang Changji Vocational and Technical College, Changji High-tech Development Zone 831100, Xinjiang, China.

Abstract: This paper reports the development and testing of an innovative type of earthmoving machine. The track-type belt conveyor (TTBC) can remove soil horizontally from deep excavations. The TTBC is more flexible than traditional conveyors used in factories, because it is self-moving (via two tracks) and foldable. Moreover, several TTBCs can work together to transport a continuous stream of soil over long horizontal distances, which can significantly improve earthmoving efficiency. Field tests were performed to assess the practical feasibility of single and multiple TTBCs. They were used in a long, narrow, deep excavation below a railway station. The site was constructed using a top-down method with a single soil exit at one end. The tests showed that the new TTBC is flexible and efficient for removing non-cohesive soils from deep excavation sites.

Key words: track-type belt conveyor; foldable structure system; collaboration; earthmoving equipment; deep excavation

1. Introduction

The earthwork involved in deep excavations includes several stages: soil must be excavated, collected, loaded onto vehicles, and transported away from the excavation site. Excavation efficiency is largely dependent on the efficiency of each earthmoving procedure. If the site used for excavated soil collection is restricted by the surrounding environment, in top-down deep excavations for instance [1], the excavation efficiency will be decreased because of the long horizontal transportation distance required. To improve excavation efficiency, it is essential to develop new types of earthmoving equipment for use in deep excavations [2-4].

In the 20th century, more than seven completely new forms of earthmoving equipment were introduced subsequent to technological advances. Tatum et al. analyzed the introduction of five new forms, including the track-type tractor, off-highway truck, wheel tractor scraper, hydraulic excavator, and loader-backhoe [5]. Moreover, Tatum et al. analyzed these technical advancements in relation to the five systems relevant to earthmoving equipment: implementation, traction, structure, powertrain, and control and information [6]. Analyses of such systems consider their purpose and operation, technical limitations and key technologies, and a chronology of major advancements. In this century, few earthmoving equipment innovations have been reported in the literature.

This study reports the development and testing of an innovative type of earthmoving machine. Hereafter referred to as the track-type belt conveyor (TTBC), it was developed for removing soil from deep excavations. The new TTBC is flexible due to being foldable and self-moving. Moreover, several TTBCs can work together to move excavated soil in a continuous stream over long horizontal distances. Field tests and applications were performed to check its practical feasibility.

2. Development and Production of the TTBC

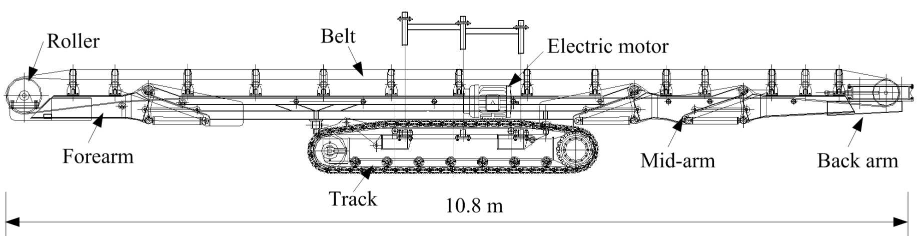
2.1 Analysis of requirements and proposed design

In conventional earthmoving methods, several small excavators are used to collect excavated soil. Their efficiency decreases significantly with increasing transportation distance as it is a discontinuous transportation method. If the excavated soil can be delivered continuously, efficiency can be improved significantly. Conveyors, which deliver materials or products continuously, are a highly efficient type of transportation equipment and have been widely used in various industries. However, they are typically inflexible due to being fixed in place. In deep excavations, earthmoving equipment has to move to remove excavated soil. Thus, conventional conveyors cannot be applied to deep excavations.

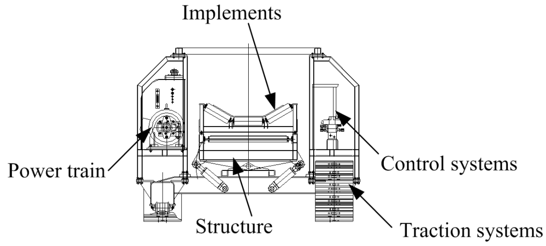
To overcome the inflexibility of traditional conveyors, a new foldable and walkable conveyor was required. The new conveyor needed to be compact, and be able to work with several others to deliver excavated soil continuously over a long distance. Moreover, the new conveyor needed to be electrically powered to achieve energy savings and emission reductions.

2.2 Key systems and function description

Tatum et al. pointed out that the operational capability and production rate of earthmoving equipment are determined by five systems [5, 6]. These are the implement, traction, structure, powertrain, and control systems. In this section, the new TTBC conveyor is described in terms of these five systems. The TTBC is designed to be 10.8 m in length. Figure 1 presents its longitudinal profile and a cross-section. The implement system applies force and performs the actual earthmoving operations. In this case, a belt is used to carry the excavated soil. The TTBC's traction system uses two tracks for traction with the ground, allowing the machine to apply force and move around. The structure system connects the various components, transmits loads, provides attachment points for implements, and allows the machine to travel over uneven ground. The TTBC's structure system includes rollers, arms and a frame above the chassis. The powertrain delivers power to move the machine and its implements. Considering the typical poor air circulation in deep excavations, an electric motor is used to power the conveyor. Finally, the conveyor is monitored and controlled by the control and information systems. These systems enable the operator to direct and control all the other systems, provide information to guide operations, and monitor the performance and condition of the equipment.



(a) Longitudinal profile



(b) Cross section

Figure 1. The new TTBC conveyor: (a) Longitudinal profile showing the major components; (b) cross-section showing the five key systems.

Considering the complex construction environment in deep excavations, the TTBC conveyor is designed to be foldable to improve its flexibility. Figure 2 shows the folding process, which has three stages. In the first stage, the forearm is folded. In the second and third stages, the back arm and then the mid-arm are folded. Figures 3(a) and (b) show photos of the conveyor in unfolded and folded states, respectively. After the conveyor is folded, its length reduces from 10.8 to 6.8 m.

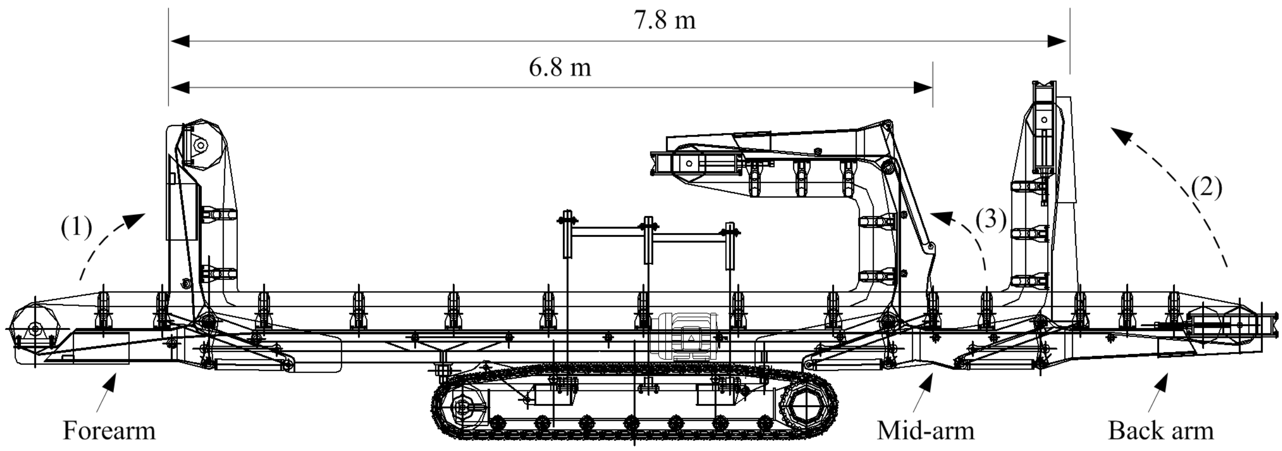


Figure 2. Folding process of the track-type belt conveyor.

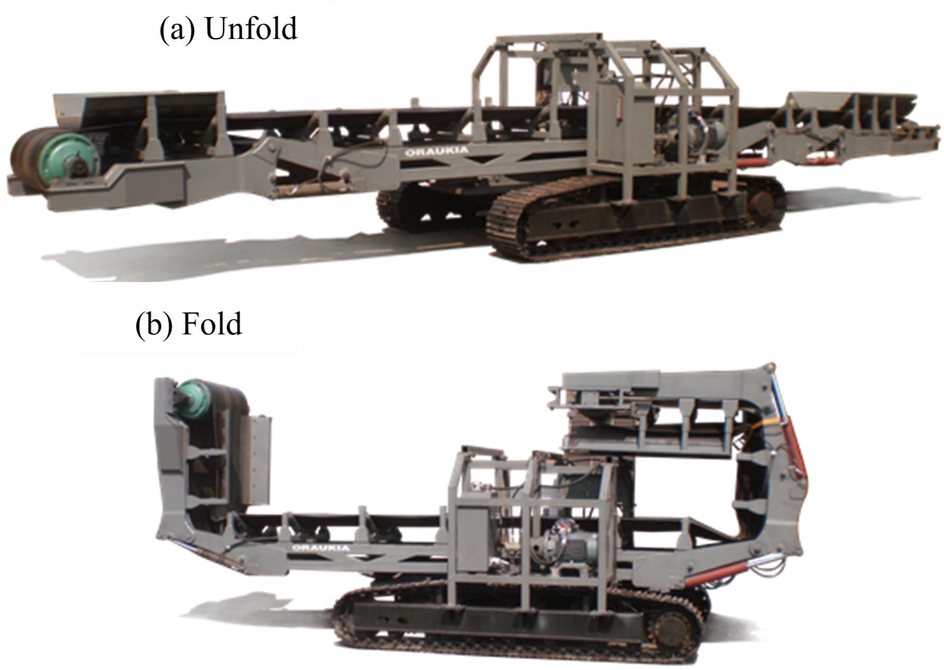


Figure 3. Track-type belt conveyor in (a) unfolded and (b) folded positions.

Long-distance transportation of excavated soil can be achieved by joining multiple conveyors. To achieve this collaboration function, the conveyors are inclinable so that each conveyor can overlap the end of the next one. Figure 4 shows two inclined conveyors working together to achieve long distance transportation. Figure 5 shows a photo of two overlapped TTBCs.

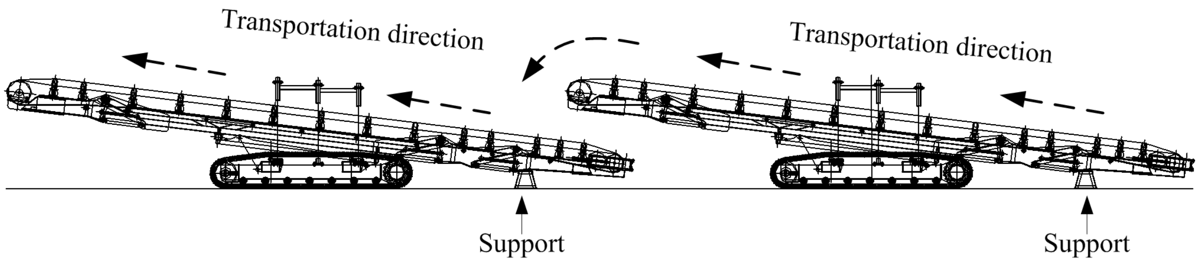


Figure 4. Collaboration between two track-type belt conveyors.

Figure 5. Photograph of two overlapped TTBCs.

3. Field Investigation

3.1 Site information

The developed conveyor will be applied to a metro station excavation on Line #15 of the Shanghai Metro system. This excavation is part of a comprehensive transportation hub project and uses a top-down construction method. The transportation hub, located at Shanghai West Railway Station, includes the railway station and two underground metro stations. A north-south underpass was constructed to connect two sides of the railway, and a transfer channel was constructed to connect the railway station and the two metro stations (Figure 6). The Shanghai West Railway Station and the metro station on Line #11 were already in operation.

The underpass measures approximately 82 × 108 m in plane, and its bottom slab is 9.5 m below the ground surface. It was recently constructed and partly undercrosses the 64 m-wide Huning High-Speed Railway, which means that the top slab of the underpass is the subgrade of the operating railway. The metro station on Line #15 is 240 m long and 23.5 m wide, and will be constructed after the underpass is finished and the railway commences operation. The excavation of the metro station was divided into five parts (Parts A-1 to A-5 in Figure 7), considering metro Line #11 and the Huning High-Speed Railway. After the construction of the underpass and completion of the transfer channel, Part A-3 was constructed, then the excavation of Part A-2 was carried out. Part A-2 is a two-floor metro station beneath the underpass with in-plane dimensions of approximately 23.5 × 84 m. The excavation depth of Part A-2 is 23.5 m below the surface, which is about 14 m below the bottom slab of the underpass. Since the underpass is located under the railway station and the excavation of Part A-2 is located under it, the top-down method was adopted, and only one soil exit was provided in Part A-3. The maximum transportation distance of the excavated soil was about 90 m. Such a long horizontal transportation distance can decrease the excavation efficiency significantly. To improve excavation efficiency, the new TTBC conveyor was used in this deep excavation site.

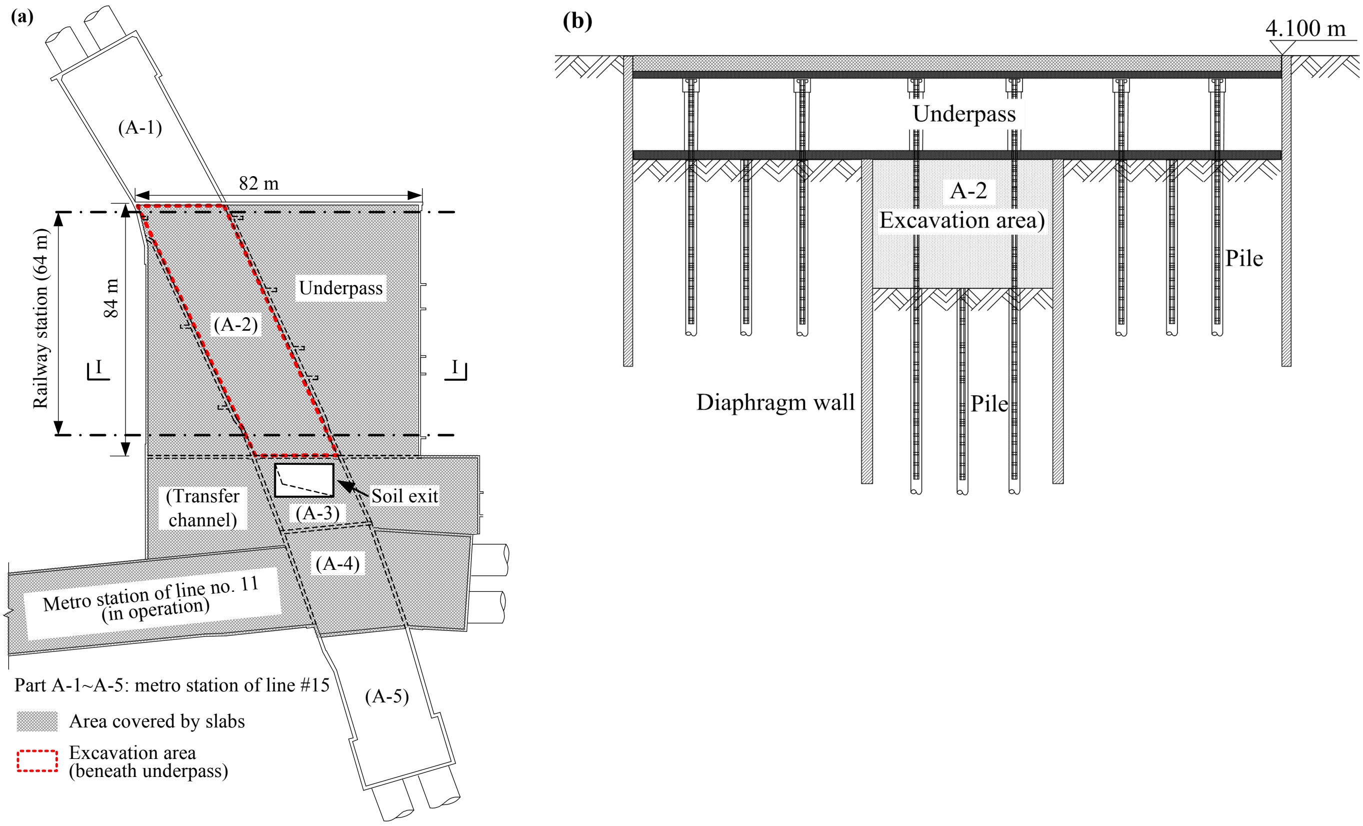


Figure 6. Excavation site and surrounding environment: (a) plan view; (b) profile of section I-I.

3.2 Field test

Before application, field tests were carried out at the construction site to check the applicability of the new conveyor. Figures 7(a) and (b) show two photos of the test site. It can be seen from Figure 7(a) that an excavator was used to excavate soil and stow it in the conveyor. The conveyor delivered the soil from one end to the other. In Figure 7(b), two conveyors work together to deliver the excavated soil. It can be seen that the soil is delivered from one conveyor to another. These field tests indicate that the new TTBC can successfully remove soil from deep excavations.

Figure 7. Field tests of the track-type belt conveyor.

3.3 Application

The excavation of Part A-2 was divided into four stages in the vertical direction. The depths of soil excavated at each stage were 4.5 m, 3.2 m, 3.5 m, and 2.8 m, respectively. In each stage, the soil was removed by the channel-type excavation method, as proposed by Li et al. [7] A work channel was first excavated in the middle of the whole excavation area from south to north. The width of the channel was 6 m, considering the excavator's size. Then, the remaining soil on both sides of the channel was quickly excavated from north to south in segments, and the excavated soil was delivered through the channel. After a segment of the excavation was completed, struts or slabs were constructed immediately to minimize the deflection of the diaphragm wall.

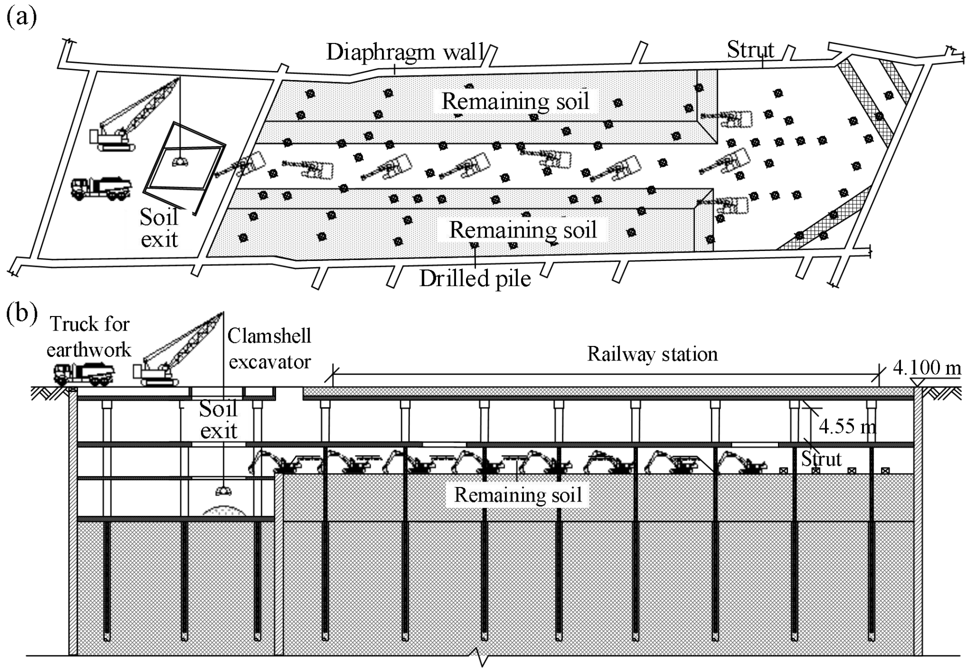


Figure 8. Earthmoving scheme with multiple small excavators.

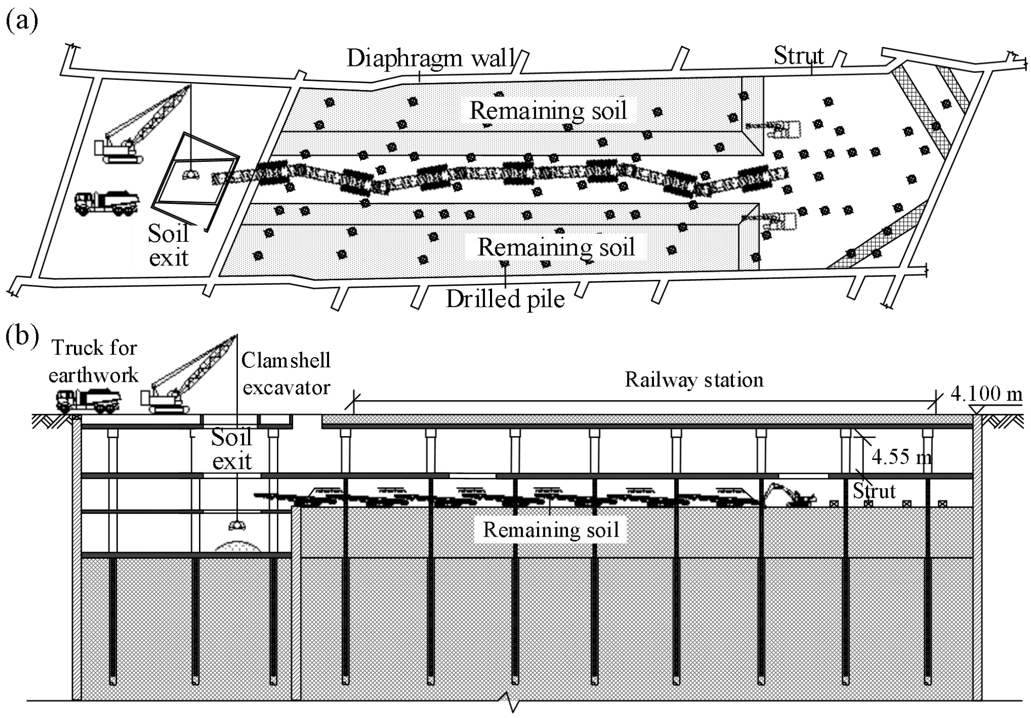


Figure 9. Earthmoving scheme with multiple track-type belt conveyors.

4. Results

Both the new and traditional soil removal schemes were used in this deep excavation project. Traditional excavators were used in stages 1, 3 and 4 with the earthmoving scheme shown in Figure 9(a), while new TTBCs were used in stage 2 with the earthmoving scheme shown in Figure 9(b). Figures 10(a) and (b) show two photographs of the excavated soil being delivered by excavators and conveyors, respectively. It is clear that the excavation environment is very complex. Both the excavators and the conveyors were surrounded by columns. Because of the proximity of the columns, rotation of the excavators was restricted. Table 1 lists the earthmoving efficiency of the excavators and the new TTBC conveyors. In stages 1, 3 and 4, excavators removed soil with efficiencies of 268 m^3/d, 475 m^3/d and 389 m^3/d, respectively. In stage 2, the TTBCs removed soil at an efficiency of 537 m^3/d, which is obviously higher than that of the excavators. The results indicate that the TTBC can improve earthmoving efficiency significantly. Moreover, since the TTBCs are electrically powered, they produce much less air pollution than diesel-powered excavators, which significantly improves the health and safety of the worksite.

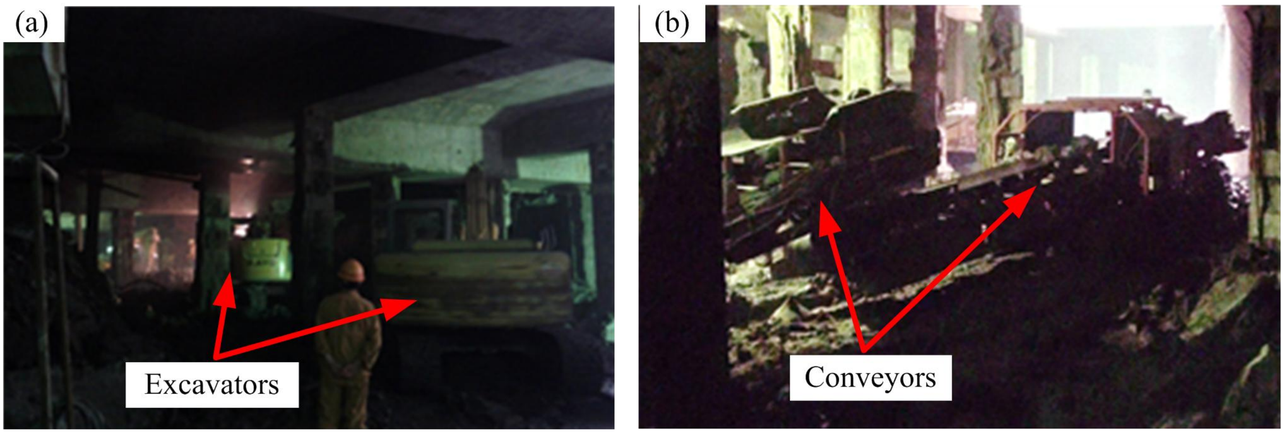


Figure 10. Horizontal transportation of the excavated soil with (a) traditional excavators; (b) the proposed conveyors.

Table 1. Comparison of earthmoving efficiency between excavators and TTBC conveyors.

Construction stage	Event	Volume (m^3)	Time (d)	Efficiency (m^3/d)	Equipment
Stage 1	ECS	1340	5	268	Excavator
	ERS	4558	17		
Stage 2	ECS	1611	3	537	Conveyor
	ERS	4835	9		
Stage 3	ECS	1425	3	475	Excavator
	ERS	5701	12		
Stage 4	ECS	1168	3	389	Excavator
	ERS	4673	12		
Note: ECS = excavation of channel soil; ERS = excavation of remaining soil.					

5. Limitations

Although the field tests indicated that the TTBC can greatly improve earthmoving efficiency, it was found that clay soil stuck to the belts and cannot drop onto the overlapped area when multiple TTBCs were used. Therefore, in its present form, the TTBC is more suitable for use with cohesionless soil. It requires further improvement for use with sticky soils.

6. Conclusions

This study reports the development of a track-type belt conveyor for removing soil from deep excavations. Field tests indicated that the TTBC is flexible in practice because it is self-moving and foldable. Moreover, several TTBCs can work together to move soil continuously over a long distance. Compared to conventional earthmoving methods using small excavators, the TTBC is more efficient and provides a healthier workplace. However, further improvement is needed before it can be used for cohesive soils.

Acknowledgments

The financial support from the National Natural Science Foundation of China (NSFC Grant No. 41977216) is gratefully acknowledged.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Hong WK, Kim JM, Lee HC, et al. 2010. Modularized top - down construction technique using suspended pour forms (modularized RC system downward, MRSD). *The Structural Design of Tall and Special Buildings*, 19(7): 802-822.

[2] Kim SK, Seo J, Russell JS. 2012. Intelligent navigation strategies for an automated earthwork system. *Automation in Construction*, 21: 132-147.

[3] Li MG, Zhang ZJ, Chen JJ, et al. 2017. Zoned and staged construction of an underground complex in Shanghai soft clay. *Tunnelling and Underground Space Technology*, 67: 187-200.

[4] Tan Y, Huang R, Kang Z, et al. 2016. Covered semi-top-down excavation of subway station surrounded by closely spaced buildings in downtown Shanghai: building response. *Journal of Performance of Constructed Facilities*, 30(6): 04016040.

[5] Tatum C, Vorster M, Klingler M. 2006. Innovations in earthmoving equipment: new forms and their evolution. *Journal of Construction Engineering and Management*, 132(9): 987-997.

[6] Tatum C, Vorster M, Klingler MG, et al. 2006. Systems analysis of technical advancement in earthmoving equipment. *Journal of Construction Engineering and Management*, 132(9): 976-986.

[7] Li MG, Chen JJ, Xu AJ, et al. 2014. Case study of innovative top-down construction method with channel-type excavation. *Journal of Construction Engineering and Management*, 140(5): 05014003.