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ORIGINAL PAPER

Emerging Trends in Foundation Engineering in India: Case Study

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Abstract Underground construction in a busy urban setting has always been a daunting task. Space constraints, noise level restrictions, working time restrictions, movement restrictions, utility identification and relocation, proximity to sensitive structures, and clearing old establishments with minimum disturbance are just a few of the challenges that one faces when working inside a large city. With the underground Metro being constructed in most of the larger cities in India, civil contractors have to constantly deal with such situations. The use of newer technologies in underground construction to deal more effectively with geotechnical challenges can save time, project costs and may even help us cater to the typical demands of urban construction. To demonstrate the usefulness of such technologies, one successful case study is presented in this paper. The case study is about rock-socketed secant piles, which were used for the construction of underground metro stations in Mumbai. The case study is expected to provide confidence to the industry for the adoption of such new technologies in future.

Keywords Earth retaining structures · Rock-socketed secant pile · Secant pile · Deep excavation support system · Underground metro station

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Introduction

The infrastructure sector has always been a key driver for the Indian economy. Rapid urbanization, changing demographic requirements, and accelerating GDP growth have given the infrastructure sector a massive push. Govt. of India projects total capital expenditure in infrastructure sectors in India during the fiscals 2019–2025 at over Rs. 102 lakh crore as per National Infrastructure Pipeline (NIP) program [1]. After the devastating pandemic, the sector has gained even more importance from the Government of India to boost employment and revive economic growth.

In recent years, most of the projects are utilizing underground space to compete with surface space, overcome topographic challenges, preserve the environment, or provide natural thermal and acoustic protection. Historically, economical aspects remained a major barrier to the development of the use of the underground space. Now, increased demand for improved infrastructure is resulting in better utilization of underground space irrespective of economic barriers. The underground spaces are being used for transport (road and railway tunnels, metro rail tunnels, etc.), urban utilities (sewage tunnels, shafts, pipelines, etc.), and other subsurface facilities such as public buildings, good storage, industrial facilities, military facilities, etc.

Rapid growth in underground construction is also posing new challenges. The projects are now being built with accelerated construction periods, at densely urbanized areas and having complex geological strata. These challenges demand newer construction technologies to optimize construction costs and time. The emerging trend in foundation engineering shows the introduction of new technologies such as Precast Spun Concrete Piles, Barrette Piles, Continuous Flight Auger (CFA) Piles, Compaction Grouting, and Secant Piles. The new construction technologies often improve quality, durability, safety and help save environmental degradation. In order to establish usefulness, this paper discusses one such technology viz. rock-socketed secant piles.

Rock-Socketed Secant Piles

Secant pile system is a very useful application of bored piles where the groundwater table is shallow and soils are permeable. Secant pile technology comprises of formation of retaining walls by overlapping (interlocking) piles.

Secant piles are installed in a series of Primary or Soft (Unreinforced) and Secondary or Hard (Reinforced) piles that are installed in a configuration such that they overlap one another. The primary piles are constructed in the first stage with a designed concrete mix that can be cut. The secondary piles are constructed in the second stage with the required concrete grade with reinforcement as per design.

Hard piles shall be designed to take up the lateral earth pressure and surcharge whereas soft piles are provided to serve as a watertight barrier. In exceptional cases, soft piles can also be reinforced or provided with a steel section inside the concrete. Secant walls are mostly used as an alternative to diaphragm walls. The development of powerful high torque drilling equipment has led to an increase in the range of ground conditions and obstructions that can be penetrated, and the wall thicknesses that can be constructed. Secant piles can be used to construct a circular shaft of a small radius for launching or retrieval of a tunnel boring machine (TBM); the circular shape only experiences compressive stresses from the hoop and axial forces, making it a self-braced system. As the struts are not required for a circular shaft, the excavation can be carried out without any obstruction. In softer soils, secant piles can even be constructed with the technologies such as continuous flight auger (CFA), which can reduce the construction time significantly. Some of the merits and demerits of the Secant Pile system are given in Table 1.

Case Study: Mumbai Metro Line 3 Project

Mumbai Metro Rail Corporation Ltd (MMRC) is constructing line 3 of the metro from COLABA to SEEPZ with a distance of approximately 33.5 km. Part of the project (UGC-04) comprises huge underground stations namely Siddhivinayak, Dadar, and Shitladevi in densely populated areas involving challenges to safeguard the locality and adjacent structures some of which are 70–100 years old.

For the construction of underground stations and the TBM launching shaft, it was necessary to excavate to about 27 m of depth from the existing ground level to facilitate the construction of station buildings hence a vertical peripheral embedded soil retention system was necessary for such deep excavations. Initially, the Diaphragm Wall system was thought of as all the earlier metros in India had adapted this system and the experience was available locally. However, ITD Cementation, after careful evaluation of space constraints and other local challenges decided to adapt the Secant Pile system instead. Besides the advantages stated above, the choice of secant pile wall over diaphragm wall was particularly made in order to pass/divert multiple scattered utilities between two secondary piles and to be able to work efficiently within the very limited space. The present case study highlights details of the secant pile for Siddhivinayak Station, which was the first station in the entire underground Line 3 where this system was approved and adopted.

Siddhivinayak station is a large underground station built in a congested area with a cut and cover method. The plan area and typical excavation section(half portion) are shown in.

Figures 1 and 2, respectively. The approximate station area is 320 m × 120 m and the excavation depth is 27.3 m from ground level. The excavation area is surrounded by very busy roads, residential/commercial buildings, and is adjacent to a very reputed temple premises having a special status in the society. All this demanded careful planning and execution. The excavation support system consisted of secant piles with varying depths as per the varying rock profile and was supported by rock anchors and internal struts.

Site Stratigraphy A detailed geotechnical investigation for Siddhivinayak Station was carried out consisting of 7 geotechnical boreholes accompanied by associated field and laboratory tests. The stratigraphy can be marked in two broad lithological units.

- Unit-1: Overburden Soils (from 0 to 10.5 m)
- Unit-2: Rock Strata (from 10.5 m to 35.5 m, end of exploration depth)

Overburden Soils. Since the city of Mumbai was formed through multiple land reclamations, the upper sub strata up to a depth of 4.5 m were mostly filled up with a variety of materials ranging from coarse sand to gravel having silt and clay in minor proportions. The subsequent layer consisted of firm silty clay to gravelly clay extending to a depth of 10.5 m below ground level. Groundwater was observed at about 2 m below existing ground level.

Rock Strata. Rocky strata of different weathering grades, ranging from a fresh rock (Grade I) to a highly weathered (Grade IV) have been encountered, consisting predominantly of breccia. Bands of basalt and tuff were also present in some of the boreholes. A summary of the various rock types encountered with depth considering four geotechnical boreholes and two probe holes is shown in Table 2.

Table 1 Merits and demerits of secant pile system

Merits	Demerits
1. Secant pile can be successfully installed in the most difficult ground conditions	1. Secant Pile produces more hard joints than the Diaphragm wall method and hence may lead to multiple points of leakages if the workmanship is not proper
2. This method is ideal for urban construction projects, as it can be installed in relatively tighter spaces and is more flexible in shape	2. Secant piles require heavier reinforcement as compared to the Diaphragm wall to generate the same moment of resistance
3. Secant piles can also be designed as load-bearing (vertical load) structures	3. Secant piles require special tools, especially for dealing with rock such as in the present case
4. Diaphragm wall equipment for rock socketing requires large capital investment. Whereas Secant Pile requires conventional bored piling rigs along with modified tools and methodology	4. The overlap of piles provided at the top does not extend into rock due to the reduction in diameter of the secant pile in the rock portion. The diameter is reduced because of the termination of casing at top of rock level
5. In Diaphragm wall construction, before commencing trenching with a 'Trench cutter', the upper few meters have to be excavated with conventional grab, therefore both types of rigs are required for the construction of each panel. On the other hand, the secant pile requires only one type of conventional hydraulic rig	5. Waler beam is mandatory for effective distribution of anchor/strut forces, whereas in the case of Diaphragm wall, the waler beam may not be necessary

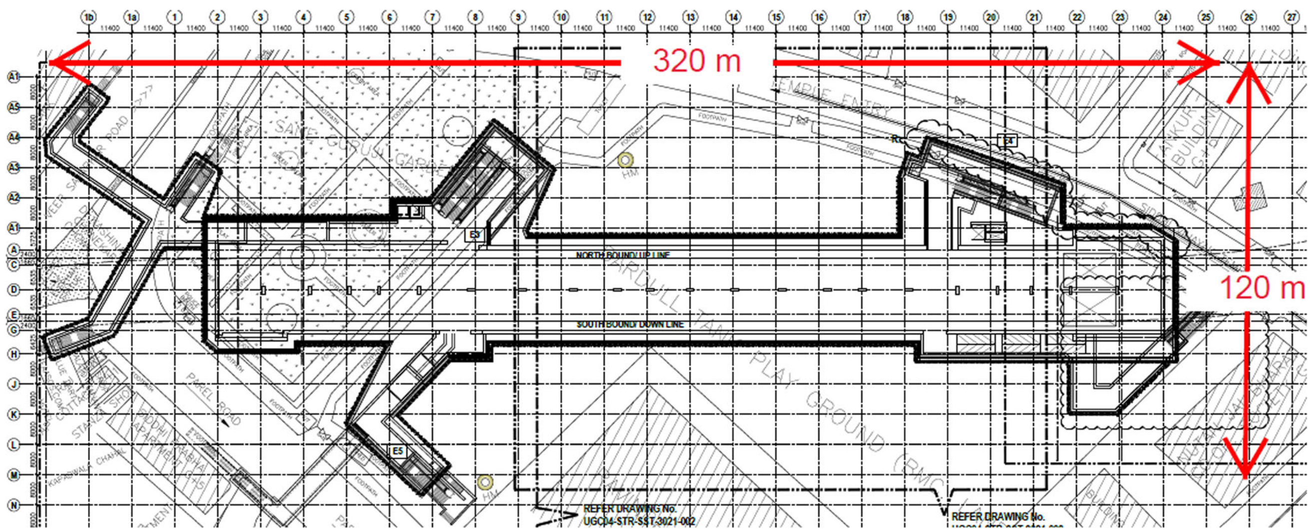

Fig. 1 Siddhivinayak station—Plan view

Construction Details The work in the Siddhivinayak station area was carried out in stages as per available front and priority of work. In total, 765 soft piles were installed having a diameter of 880 mm at a spacing of 1410 mm c/c and with an average depth of about 18.5 m. An equal number of hard piles were installed with an overlap of 175 mm between soft and hard piles to avoid leakage from the wall. Other construction details are summarized below.

Guide wall Once utility identification and diversions were planned, the guide wall was constructed first along the alignment (Fig. 3). The usefulness of the guide wall must be emphasized here, as it helps ensure better vertical alignment thereby reducing the chances of seepages of groundwater through the junctions of soft and hard piles. While drilling the hard pile through adjacent soft piles, the drilling tool is confined by soft piles on two opposite sides but free to move toward the remaining two sides, this often causes verticality issues. There have been instances where guide walls have been avoided leading to significant seepages during excavation thereby causing delays and additional expenditure on seepage control at a later date. Construction of guide wall before construction of pile installation ensured proper alignment, location, and verticality in this project.

Grade of Concrete The grade of concrete for the guide wall was M-25, for soft pile-M-10, and hard pile M-40. The concrete grade of M-10 for soft piles was carefully arrived at after several trials considering the rate of strength gain and execution aspects while cutting the soft pile. The early high strength of soft pile may reduce the production rate for

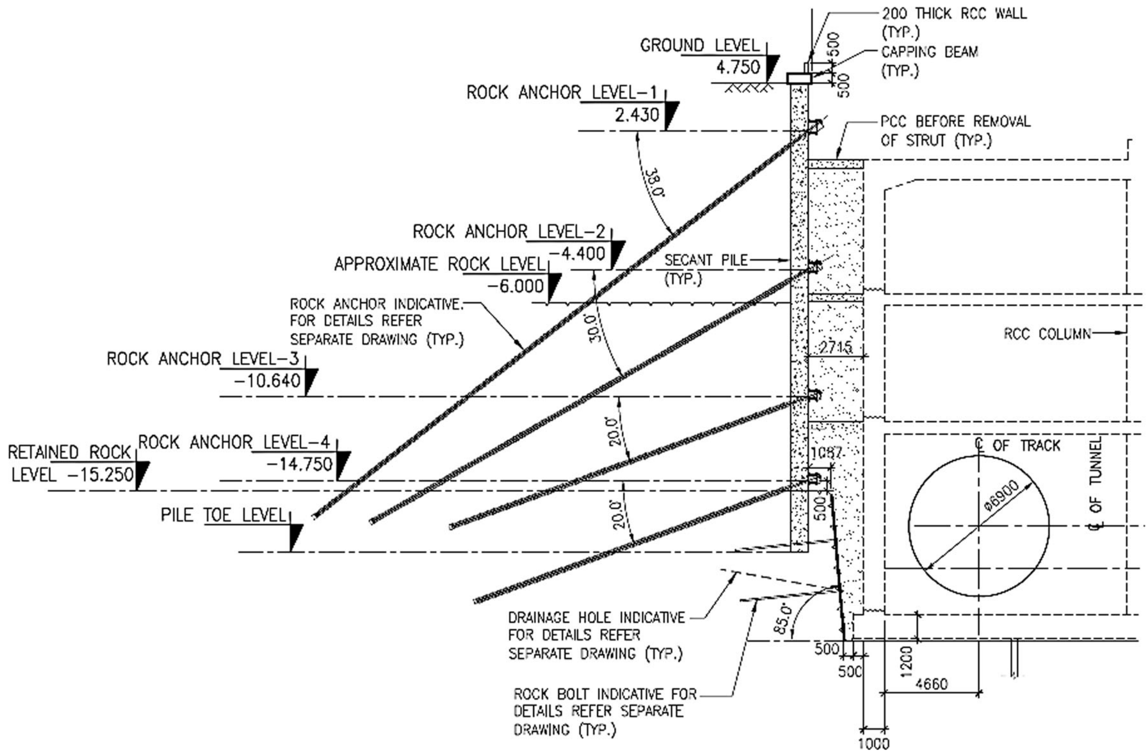

Fig. 2 Siddhivinayak station—typical sectional view (half section)

Table 2 Description of rock strata

Sl No	Rock strata	Weathering stage	Weathering grade	RQD [%]	Rock mass rating
1	10.5 m–15.0 m Tuff/Volcanic Breccia	Highly weathered Rock	IV	< 10	27
2	15.0 m–18.0 m Tuff/Volcanic Breccia	Moderately weathered Rock	III	< 25	32
3	18.0 m–22.0 m Tuff/Volcanic Breccia	Moderately Weathered Rock	III	25 to 50	39
4	22.0 m–30.0 m Volcanic Breccia/Basalt + Shale	Slightly Weathered Rock	II	50 to 75	51

Fig. 3 Construction of guide wall for installation of secant piles

hard pile and may cause problems related to verticality. On the other hand, late strength may cause numerous quality issues related to the joint between the soft pile and hard pile.

Working in congested areas with heavy traffic poses logistical challenges for concrete supply; hence, most attention was given to concrete supply. Consistency in pile concreting, through rigorous monitoring, ensured good pile wall alignment and water-resistant interlock throughout the project.

Reinforcement Thermo-mechanically treated Fe 500D grade bars were used for the project. Since secant piles are part of a temporary excavation support system, a clear cover of 50 mm was provided.

Unlike conventional pile, where the direction of lateral load is often unknown and hence the position of reinforcement bar in a cage is not relevant, in the case of secant pile, the direction of lateral load is known hence reinforcement can be optimized. The secant pile typically requires higher reinforcement on the soil and excavation sides to resist higher bending moments in that direction. Hence, during fabrication and lowering of the reinforcement cage, proper attention was given so as to keep the number of bars, their position, and diameter as per drawing.

Termination Depth The minimum depth of termination for piles at various locations was pre-determined as per the geotechnical investigation report. However, termination levels were also confirmed in the field based on pile penetration rate achieved for a given piling rig Kelly pressure, torque, and RPM of the hydraulic motor. This ensured that the piles were extended into strata of required competency at all locations.

Excavation Support System Rock anchors were used at various levels to secure the secant pile (refer to Fig. 4). Struts and waler beams were also used where the distance in between opposite walls was relatively less (refer to Fig. 4 and Fig. 5).

Average Time Cycle It took about 12 h and 16 h for the installation of soft and hard secant piles, respectively, with an average pile length of 18.5 m. This progress was achieved with a 20 Tm torque hydraulic rotary rig. This cycle time allowed at least one pile to be constructed during extended dayshift hours as night work was not permitted due to very close proximity to residential buildings. A significant amount of boring time (almost 5 h) out of the total cycle time was required for boring in rock. This time can easily increase with the wrong choice of tools and construction technology. Hence, the use of proper tools for rock cutting must be emphasized here as this can significantly save time and cost on a project of this nature.

Use of Special Tools Secant pile construction being unconventional or not so popular in India meant special tools required for the same were not readily available. While imported tools were an option, however, it was decided to work with the local agencies and help them develop these tools in India. Hence, many such tools were specially developed and improved upon during secant pile construction on this project; some of them are illustrated here.

Double-walled Casing. Overburden soil depth varied for different stations as well as within the same station area footprint. The casing support overburden soils and was designed to take torque and down thrust required for cutting into soft piles with cutting teeth at their tip (Figs. 6 and 7).

The casing is made of three parts i.e., casing adapter (top-most part), casing joint (middle part), and casing shoe (bottom-most part). The length of the casing can be extended by using multiple casing joints of suitable length, the assembly can be done using screw ring joints. The casing has additional rigidity and strength that helps transmit high torque to the casing shoe to cut the soft pile easily. It may be noted that casing is provided until rock level is reached and further boring is carried out without casing. This causes a slight reduction in the diameter of the pile in rocky strata, and hence effective overlapping of the soft pile and hard pile may be reduced. During execution, especially during the initial installation of the casing, proper care was taken to maintain the verticality of the casing to prevent any leakage through the wall at a later date.

Replaceable teeth blocks. The cutting shoe of casing and core barrel was fitted with replaceable teeth. The teeth are made with forged alloy steel and have flat projections made of tough tungsten carbide, which reduces the wear and tear of tools saving maintenance time. The solid-casted teeth have a short tooth tip length and have a short moment arm, which effectively prevented breakage of teeth. Teeth blocks attached to the casing shoe of the double-walled casing (refer to Fig. 8) allowed cutting through the soft pile without any overcut or damage to the soft pile. Different types of such teeth were attached to core barrels; this provided significant time-saving in rock socketing. Typical teeth blocks are shown in Fig. 9. Replaceable Teeth Blocks.

Auger Cleaner Clayey soil often sticks to the soil auger and is generally cleaned using the oscillating rotational movement of the auger, which produces significant noise. A specially made auger cleaner was developed and used to clean soil augers without much noise. The cleaner scraps the helical surface of the tool effectively removing the soil off (refer to Fig. 10a and b). The rig operator from his cabin can actuate the cleaner through hydraulic means. This auger cleaner allowed us to reduce noise pollution and also marginally improve productivity (Fig. 11).

Contribution of secant pile system to the overall project

Fig. 4 Station area showing secant piles and rock anchors at various levels

Fig. 5 Waler beam and strut arrangement

Fig. 6 Double-walled casing—casing adapter

The secant pile system constructed with the help of technology as described above produced an excellent quality of watertight shoring system right in the heart of a Megacity. The traffic plying less than a meter away could be kept unhindered after the construction of the piles. There were only three locations of seepage along the entire length of the Siddhivinayak station and these could be controlled very easily. Similarly, the secant pile system provided efficient temporary excavation support for Dadar station, Shitladevi station, and Nayanagar launching shaft. With the quick implementation of this system, ITD Cementation became the first to launch TBM for Mumbai Metro's Line-3[2]. With proper seepage control, the project

Fig. 7 Double-walled casing—casing joint

Fig. 8 Double-walled casing—casing shoe with replaceable teeth blocks

team could concentrate on permanent work rather than maintenance work, and hence, the construction of Siddhivinayak station is almost on the completion stage and is the fastest among other stations of this size for Mumbai Metro Line-3.

This experience has clearly demonstrated the utility and advantages of using secant piles as a shoring system in busy urban settings, especially in presence of hard rock underneath. It is the wish of the authors that this technology finds much greater acceptance and popularity on future projects in India.

Fig. 10 Auger cleaner—during boring

Conclusion

There is an infrastructure deficit in India, which the government is trying to close by investing significantly in infrastructure projects. The current trend shows the introduction of newer technology in foundation engineering, however, adoption still remains a challenge. Adopting newer technologies and improved methodologies can greatly augment productivity and help us cater better to the increasing demands. Besides this, new technologies also improve quality, result in better environmental health and help us maintaining better safety standards on the project.

Fig. 9 Replaceable teeth blocks

Fig. 11 Auger cleaner—during cleaning

The case study presented herein demonstrates the successful execution of one such technology. Construction details and experiences are also shared with the idea that this case study will encourage more engineers and the Foundation Engineering fraternity to adopt this technology on their projects.

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Declarations

Conflict of interest There's no conflict of intrest evident from the article.

References

1. Ministry of Finance (2019) Report of the task force on national infrastructure pipeline for 2019–2025, https://pib.gov.in. Retrieved 2020–03–07.
2. "Mumbai Metro's 1st TBM Lowered at Nayanagar Shaft". The metro rail guy (2017), https://themetrorailguy.com. Retrieved 2020–06–10.