Recent Developments of Drilling Techniques for Construction of Foundation Works

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doi: https://doi.org/10.21467/proceedings.159.3

ABSTRACT

The sinking of a drillhole into the ground (or overburden drilling) for installation of pipe piles for shoring works and cased excavation for construction of pile foundations is an important type of geotechnical works. The Odex system, which was the dominant technique for overburden drilling in Hong Kong some 20 years ago and notorious for causing problems such as ground subsidence and sinkhole formation, is seldom used nowadays. There have been significant developments in the technology of overburden drilling since the introduction of the Odex system. In this paper, the problems associated with the traditional techniques of overburden drilling are discussed. Two pieces of recently introduced equipment which can mitigate or eliminate the problems caused by conventional equipment are described. They include the Spiral Flush pilot bit which can reduce the likelihood of air leakage and an entirely different system named the Airless Flushing system which uses water instead of compressed air as the flushing medium for removal of cuttings. A case study which demonstrates the benefits of the Spiral Flush drillbit will also be described.

Keywords: Overburden drilling, Airless Flushing, SpiralFlush

1 Introduction

Geotechnical works often involve overburden drilling which is the formation of a circular drillhole in the ground such as for installation of pipe piles as embedded walls for shoring works or cased excavation for construction of king posts and pile foundations. Overburden drilling is conventionally conducted with the help of a steel casing and an assembly of equipment placed inside the casing comprising the drill rod, a down-the-hole (DTH) hammer and a drillbit connected to the hammer. The compressed air will lift and drop the piston of the DTH hammer to produce percussive action of the drillbit. The combined percussive and rotatory action of the drillbit will cause the soils, rocks or hard obstructions below the casing toe to be broken up. The cuttings produced by the drillbit will then be air-lifted and removed by the compressed air, hopefully through a path confined entirely within the steel casing.

There are inherent problems associated with drillbits operated by compressed air. The compressed air may leak outside the steel casing, causing overbreaks to be formed around the casing and below the casing toe. Further air leakage may be exacerbated by these overbreaks. The end results are that ground subsidence and formation of sinkhole are frequently found to occur next to the drillhole, particularly for deep overburden drilling. If there are existing buildings close to the drilling operation, excessive building settlements may also be induced.

In this paper, problems associated with conventional techniques of overburden drilling are discussed. Recent developments which can mitigate some of the adverse effects will be described, including a recently developed pilot bit named the Spiral Flush system which can better control the leakage of compressed air and a new technique called the Airless Flushing (ALF) system which uses water instead of compressed air as the flushing medium for removal of cuttings.

Proceedings DOI: 10.21467/proceedings.159; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-965621-6-8

2 Conventional Techniques

The Odex system (which stands for overburden drilling excentric) used to be the most popular technique for overburden drilling in Hong Kong. The Odex drillbit comprises a pilot bit and an excentric reamer. During overburden drilling, the drill rod will rotate in one direction. When the assembly of reamer and pilot bit has protruded entirely outside the casing toe, the excentric reamer will swing out to form a hole larger than the external diameter of the steel casing. The oversized drillhole enables the casing to be advanced in phase with the drillbit. When drilling is completed, the drill rod will rotate in an opposite direction and the excentric reamer will retract to become smaller in size than the inner diameter of the steel casing allowing the drillbit to be retrieved from within the steel casing.

In the past, the Odex system had often led to problems of ground subsidence, sinkhole formation and building settlement and/or tilting for geotechnical projects in Hong Kong. Figure 1 presents two examples of such problems reported by Li *et al.*, (2018) caused by overburden drilling using the Odex system. Figure 1(a) shows a masonry wall with more than 0.5m of settlement observed during construction of mini-piles in front of the wall using 219mm diameter steel casing. Figure 1(b) is an example of sinkhole formed during construction of rock-socketed H-piles using 610mm diameter steel casing. It is therefore not surprising that the Odex system is now seldom permitted for geotechnical projects in Hong Kong.

(a)

(b)

Figure 1: *(a) Settlement of masonry wall and (b) formation of sinkhole* (Li *et al.*, 2018)

There are two main problems associated with the Odex system. The first problem concerns the use of compressed air for removal of cuttings from the drillhole. The second problem arises from the Odex drillbit protruding entirely outside the toe of steel casing during overburden drilling.

The first problem also occurs to a differing degree for other drilling systems operated by compressed air. The air pressure required to overcome hydrostatic water pressure will be about 100 kPa (or 1 bar) for every 10m depth of water. For deep overburden drilling, say, to a depth of 50m or more which is not uncommon for socketed H-pies in Hong Kong, the air pressure required to overcome the water pressure alone will be 500 kPa (or 5 bars). The air pressure needed to both overcome the water pressure and flush out the cuttings will be even higher. For this reason, air compressors capable of generating an air pressure of 10 to 15 bars are commonly used for overburden drilling in Hong Kong.

Under a high air pressure, high velocity air/water jets will be formed at the flushing holes in the drillbit in a manner similar to that shown in Figure 2. Such air/water jets can easily cause overbreaks to be formed in soft soils. Overbreaks can also occur in dense soils if subjected to prolonged water jetting when blockage occurs in the steel casing making advance of drilling very slow. When overbreaks develop into progressively larger soil cavities with time, ground subsidence may happen due to loss of ground and a sinkhole will eventually occur if collapse of a large soil cavity occurs.

Figure 2: *Water jet created by high pressure at outlet holes of drillbit*

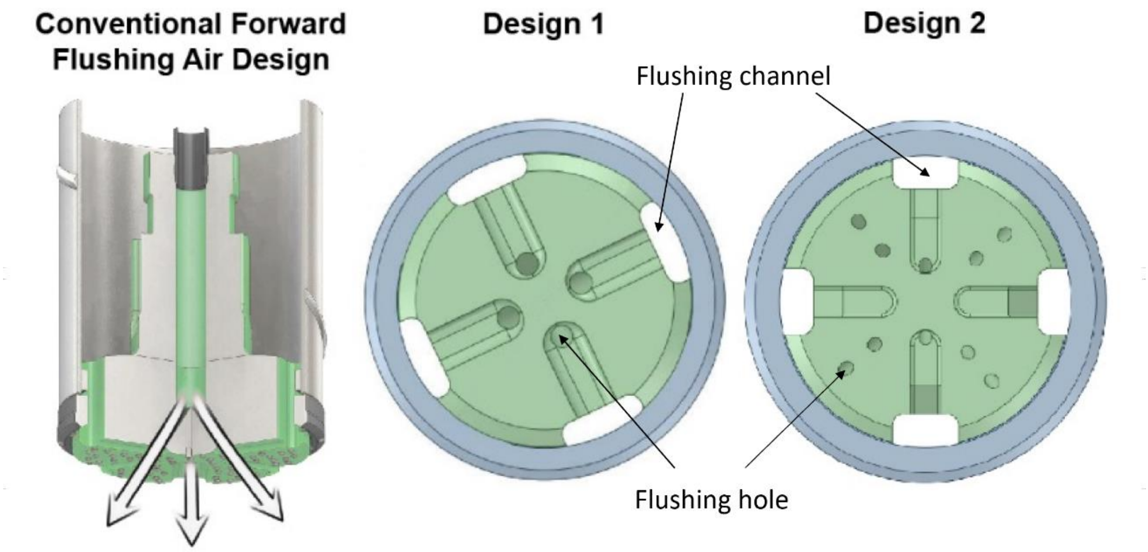
There have been improvements made to the design of drillbit by foundation equipment companies since the introduction of the Odex system. For instance, a revised design with a smaller retractable reamer is used in the Super Maxbit system . However, the reamer will still protrude beyond the casing toe during overburden drilling and hence will suffer from a similar albeit lesser drawback as the Odex system.

To prevent the drillbit from protruding beyond the casing toe, the ring bit system has been developed by various manufacturers to be used in conjunction a pilot bit. Figure 3 shows an example of a ring bit used for installation of interlocking pipe piles. A ring bit is a sacrificial ring-shaped rotary drillbit fixed onto the steel casing by welding. The outer diameter of the ring bit is slightly larger than the outer diameter of steel casing to create a slightly oversized drillhole to allow the casing to advance smoothly in phase with the drillbit. For installation of interlocking pipe piles, the size of the ring bit needs to be sufficiently large to accommodate the interlocking joints within the drillhole.

Figure 3: *Example of a ring bit*

Another drillbit called the pilot bit will be placed inside the steel casing. When the drill rod rotates in a specified direction, the pilot bit will engage the ring bit such that both drillbits will rotate in phase for forming the drillhole. After completion of drilling, the rotation of the drill rod is reversed to disengage the pilot bit with the ring bit to allow the pilot bit to be retrieved from within the steel casing. With this setup, the task of creating an oversized drillhole will now be undertaken mainly by the ring bit as compared with retractable reamer in the Odex system. There is now no need for the pilot bit to protrude extensively beyond the casing toe. Such a drilling system is commonly called the "concentric method" in Hong Kong.

There are also a variety of pilot bits developed by different manufacturers for the concentric method of overburden drilling. Examples of such systems include Rotex Symmetrix, Robit, Bulroc, Stabotec, Elemex and etc. They differ in the layout of contact surfaces at the end face of the pilot bit, the design return paths for compressed air and the extent of protrusion beyond the casing toe. Figure 4(b) and (c) show the end view of the pilot bit/ring bit assembly for two conventional overburden drilling systems in the market, named Design 1 and Design 2 in this paper. The tungsten carbide inserts on the drillbits are not shown for clarity. The majority of pilot bits in the market have the flushing air discharged from the flushing holes in a vertical or subvertical direction as shown in Figure 4(a). The air/water jets created by the flushing air can have significant erosion power to cause overbreaks to be formed if the air pressure is not properly controlled during drilling. Although there must be flushing channels provided at the pilot bit for the flushing air to return to the steel casing, leakage of flushing air can occur through the easier alternative paths if there are overbreaks outside the steel casing. Such uncontrolled leakage of flushing air can cause the overbreaks to become even larger and more extensive.



(a) Direction of flushing air (b) Design 1 (c) Design 2

Figure 4: *Details of some conventional drillbits in the market*

3 Recent Developments

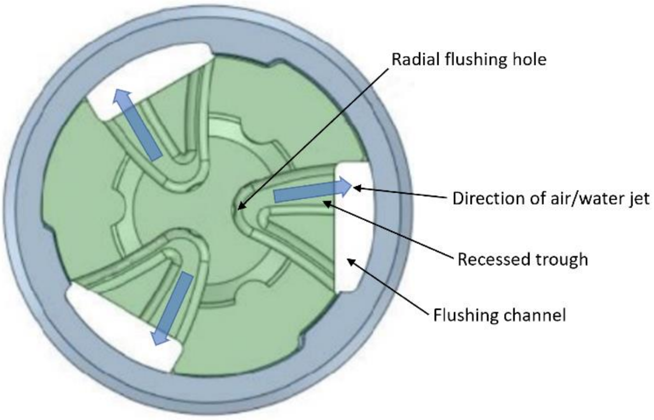
Two recent developments for overburden drilling are now discussed, including the Spiral Flush pilot bit which has a different design for the return path for the flushing air and the ALF system which utilize water as the flushing medium.

3.1 Spiral Flush pilot bit

The Spiral Flush pilot bit recently introduced to the market have two distinct features. First, the Spiral Flush pilot bit is practically flush with the ring bit. This can reduce the chance of the flushing air leakage out of the steel casing. Second, the flushing air design is such that the flushing holes are placed in a radial direction at the pilot bit. This will avoid direct impact of the air/water jets onto the materials to be excavated and allow the flushing air to return to the casing more easily in a shortest possible path to reduce the chance of air leakage.

Figure 5(a) shows the anticipated return paths of flushing air to the steel casing and Figure 5(b) a schematic view of the end face of a Spiral Flush pilot bit/ring bit assembly.

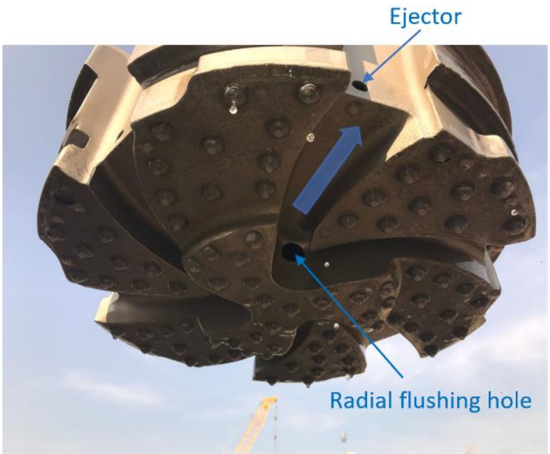
(a)



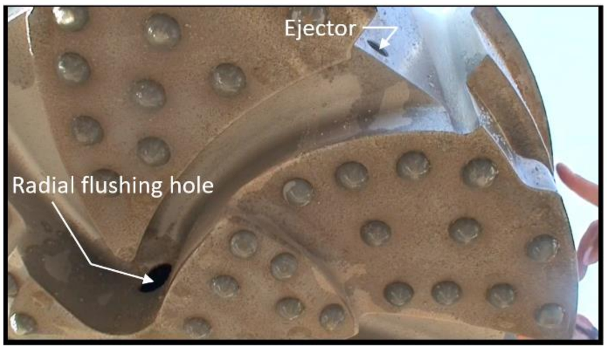
(b)

Figure 5: *Details of Spiral Flush bit (a) direction of flushing air; (b) end face of pilot bit/ring bit assembly*

As indicated in Figure 5(a), there are two groups of release holes for the compressed air, including the flushing holes and the ejectors. The radial flushing holes are located at the bottom of the pilot bit. The radial air/water jet created by the flushing holes will flush the cuttings along the recessed trough or groove provided at the end face of the pilot bit toward the flushing channels. The cuttings will then be removed by air lifting from within steel casing. The ejectors are upward inclined holes located on the pilot bit at a higher level inside the flushing channel. The compressed air supplied to the pilot bit will be partially discharged through ejectors to create a vacuum in the flushing channel. This will enable the flushing water mixed with the cuttings to enter the flushing channels more easily and become subsequently removed by air lifting inside the steel casing.



(a)



(b)

Figure 6: *Photographs of Spiral Flush pilot bit (a) overall view; (b) close-up view showing the horizontal nozzle for compressed air*

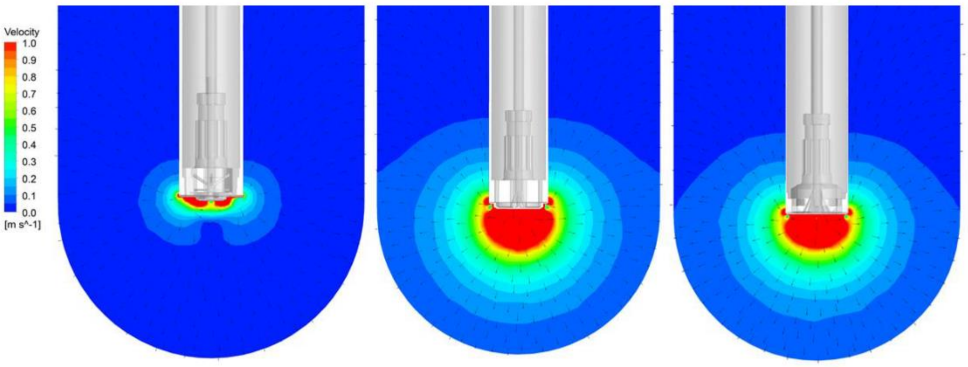
Figure 6 presents photographs of the prototype Spiral Flush pilot bit, giving a better indication of the flushing holes, the ejectors and the recessed trough between flushing holes and the flushing channel.

The major problems associated with overburden drilling operated by compressed air are the potential of air leakage and the likelihood of overbreak. To assess whether the Spiral Flush pilot bit will lead to a better performance than conventional pilot bits, computational fluid dynamics (CFD) analyses have been conducted by ECE (2019) using the program Ansys Fluent to simulate the release of compressed air into the pilot bit. The program is a general-purpose software for modelling fluid flow, heat and mass transfer, Three performance indicators are used for evaluation, including the amount of mass flow penetrating the soils, the velocity of the soil medium and the induced pressure below the pilot bit. Three pilot bits are considered, including the Spiral Flush and two other pilot bits named Design 1 and Design 2 shown earlier in Figure 5(b) and 5(c) respectively. The ease with which air can penetrate through a soil medium can be characterized by the intrinsic permeability of soil to air, or simply air permeability of soil, k_a. It has the SI unit of m^2. The meaning and measurement of air permeability are discussed in Carter & Gregorich, (2008). In the study by ECE (2019), simulations have been performed for two different air permeabilities. In this paper, the results are presented only for an air permeability of 10^{-5} cm^2 which corresponds to well sorted sand or sand and gravel according to classification by Bear (1972). The analyses were conducted based on an air flow rate of 66 m^3/min.

Table 1: *Amount of mass flow penetrating the soil*

Type of pilot bit	Mass flow to soil (%)
Spiral Flush	8.8
Design 1	54.0
Design 2	44.5

Table 1 summarizes the percentages of air by mass penetrating the soils for the three pilot bits studied. It can be observed that the mass flow of air to soils for Design 1 and Design 2 are higher than that of the Spiral Flush pilot bit by 6.1 and 5 times respectively. This suggests that leakage of air to soil tends to be higher for conventional design with flushing air discharged in the vertical direction for soils of the same air permeability.



(a) Spiral Flush (b) Design 1 (c) Design 2

Figure 7: *Velocity contour and normalized velocity vectors of the soil domain*

Figure 7 shows the velocity contour and velocity vectors in the soil domain obtained from the simulation study. As expected, the velocity of the soil domain is higher for Design 1 and Design 2 as the soils are impinged directly by the vertical or subvertical air/water jets for such pilot bits whereas the soils are less disturbed by the radial air/water jets created by the Spiral Flush pilot bit.

Figure 8 shows the results for soil pressure at the bottom of the pilot bits. The soil pressure for Design 2 is less than that of Design 1 because compressed air is spread over 10 flushing holes for the latter and only 4 for the former. Hence, a lower contact pressure is expected. In comparison, the Spiral Flush pilot bit will induce significantly less soil pressure than the two other pilot bits and this can be attributed to the difference in the direction of air jet for Spiral Flush pilot bit. The trend for induced pressure is similar to that of velocity shown in Figure 7, being highest for Design 1 and much lower than for the Spiral Flush pilot bit.

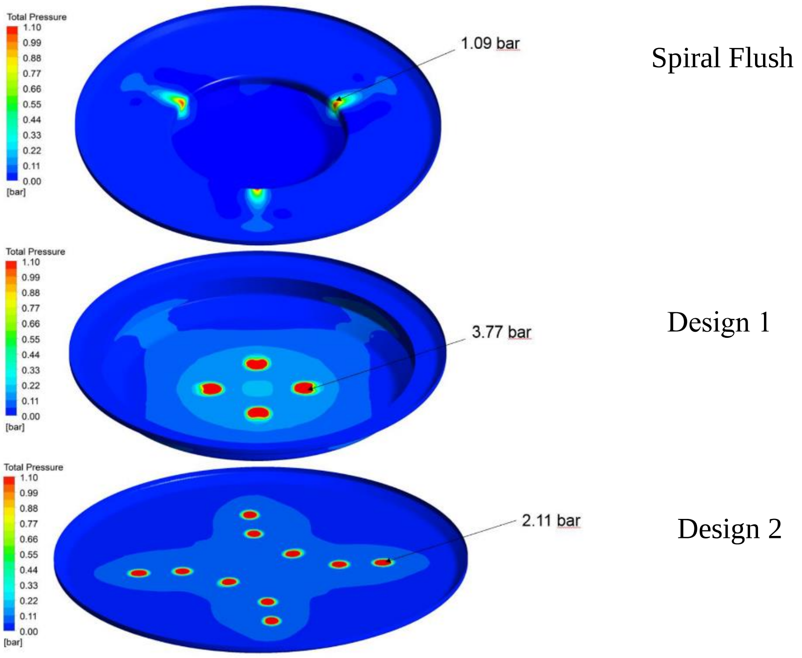


Figure 8: *Pressure contours at the interface of soil domain and the pilot bit*

According to the simulation study, the three performance indicators suggest that the Spiral Flush pilot bit should offer benefits over conventional pilot bits due to the difference in the direction of flushing in the equipment design. With similar operating conditions and soil types, the Spiral Flush pilot bit tends to have lower air loss to the soils and induce lower velocity and pressure on the soil domain. The end results are that air leakage and soil overbreaks should be less likely for the Spiral Flush pilot bit from a theoretical standpoint.

Figure 9: *A large-sized Spiral Flush pilot bit*

Field trials using the Spiral Flush pilot bit have been conducted in Hong Kong, including the trial report by Li *et al.*, (2018) and another trial conducted for a public works project. The feedbacks from contractors are that the Spiral Flush pilot bit tend to cause less ground disturbance than conventional pilot bits.

The Spiral Flush system is now widely in Finland, Scandinavia, Middle Europe and North America. This is also a demand for a larger Spiral Flush pilot bit for forming large drillholes for which conventional drillbits are likely to cause significant problems. Figure 9 shows a large-sized Spiral Flush pilot bit that can fit in a 1.524m diameter steel casing.

3.2 Overburden drilling using Airless Flushing

Due to the inherent problems associated with compressed air for overburden drilling, alternative drilling techniques using water as the flushing medium have been developed in the past. Examples of such drilling systems are discussed in Li *et al.*, (2018). Unfortunately, such techniques are still not common in Hong Kong. This may be attributed to the unwillingness of foundation contractors or subcontractors to change or that there is no such requirement specified by the Engineer or the client in the foundation contract of banning compressed air for overburden drilling.

A new technique for overburden drilling, named the ALF system, has recently been developed by the first author. Similar to some existing systems, the ALF system utilizes compressed air for operating the DTH hammer and water for flushing of cuttings.

Proceedings DOI: 10.21467/proceedings.159
ISBN: 978-81-965621-6-8

Series: AIJR Proceedings
ISSN: 2582-3922

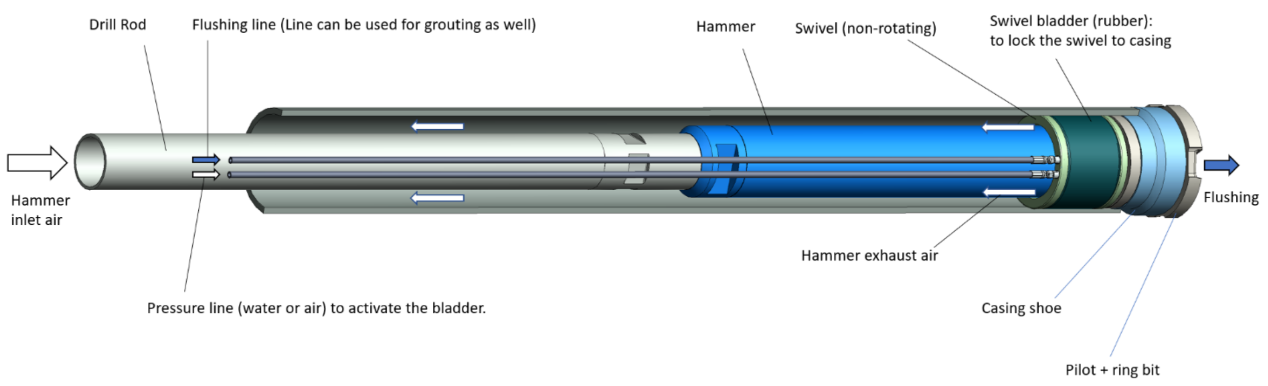


Figure 10: *Details of ALF system*

Figure 10 shows details of the ALF system. The compressed air is fed through a central hollow drill rod for operating the DTH hammer. There are swivels with a bladder near the end of the steel casing. Two pressure lines connected to the upper swivel are provided, one supplying flushing water to the pilot bit for removal of cuttings and the other supplying pressured air or water to activate the bladder. When activated, the bladder will seal the steel casing so that the compressed air released by the DTH hammer can only return to ground from inside the steel casing.

During overburden drilling, the ring bit will form a small annular gap or thin zone of weakened soil outside the steel casing. The pressurized flushing water supplied to the pilot bit will mix with the cuttings to form a slurry with suspended particles. The slurry will percolate through the void space outside the steel casing to the ground surface as shown in Figure 11.

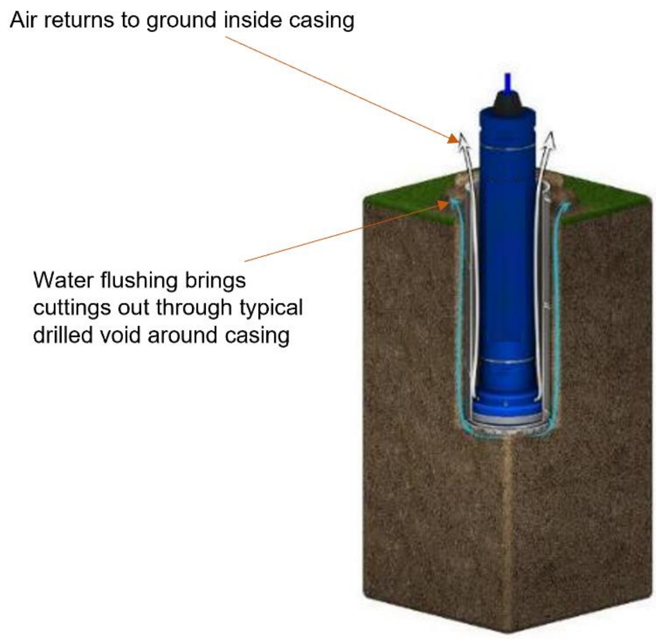


Figure 11: *Flow paths of cuttings in ALF system*

Figure 12 shows photographs of typical overburden drilling using the ALF system. The slurry containing the suspended particles of the cuttings escapes to the ground through the drilled void outside the steel casing as shown in Figure 12(a) while the compressed air is exhausted through the inside of the steel casing as shown in Figure 12(b).

Figure 12: *Flow paths of air and water during drilling using the ALF system*

When drilling is stopped, the suspended particles in the slurry will settle and fill up the voids outside the steel casing. When drilling is resumed after temporary suspension of works, flushing using water only will be carried out for a suitable period of time to re-create a water flow path in the filled-up voids outside the steel casing before re-commencement of overburden drilling.

To a certain extent, there exists a self-healing process when carrying out overburden drilling using the ALF system. Voids or overbreaks which are created during overburden drilling will initially provide drainage paths for discharge of the slurry. Such void space will later be filled in part or in full by the cuttings, thus reducing the chance of such voids from developing into large soil cavities or consequent ground subsidence.

If it is desired to strengthen the soils or to fill up the voids if any outside the steel casing upon completion of drilling, grout can be used in lieu of water for carrying out the final stage of airless flushing.

4 Case Study

Although the Spiral Flush pilot bit has only been used in limited number of trials in Hong Kong to date, it is popular in Finland and many other parts of the world for overburden drilling for projects close to or abutting sensitive receivers such as old buildings vulnerable to damage caused by settlement. To eliminate the adverse effects of using compressed air as the flushing medium, the ALF system can be adopted to further reduce the risk of ground settlement caused by overburden drilling.

A case study involving the use of Spiral Flush pilot bit is now described. The project was an office building in Helsinki, Finland, completed in 2019. The development has a three-level carpark basement. The soil profile at the site is characterized by very compact till with a sloping bedrock varying from a depth of 6 to 10m below ground. The site is abutted by two old buildings, one of which was built in 1928 supported by a raft footing and the other was built in 1962 supported by driven concrete piles.

Pipe piles of 610mm diameter and 711mm diameter were used as the embedded wall for supporting the basement excavation. It was of prime importance to prevent settlement of the adjacent old buildings. To achieve this objective, the measures taken included:

(a) Installation of jet grout columns along the two sides of the site along the old buildings prior to installation of pipe piles;

(b) Use of Spiral Flush pilot bit for installation of pipe piles as an added precautionary measure to minimize ground loss or disturbance during overburden drilling;

(c) Use of interlocking joints for connecting pipe piles to prevent loss of ground between pipe piles during excavation. The interlocking joints were formed using the male and female connectors;

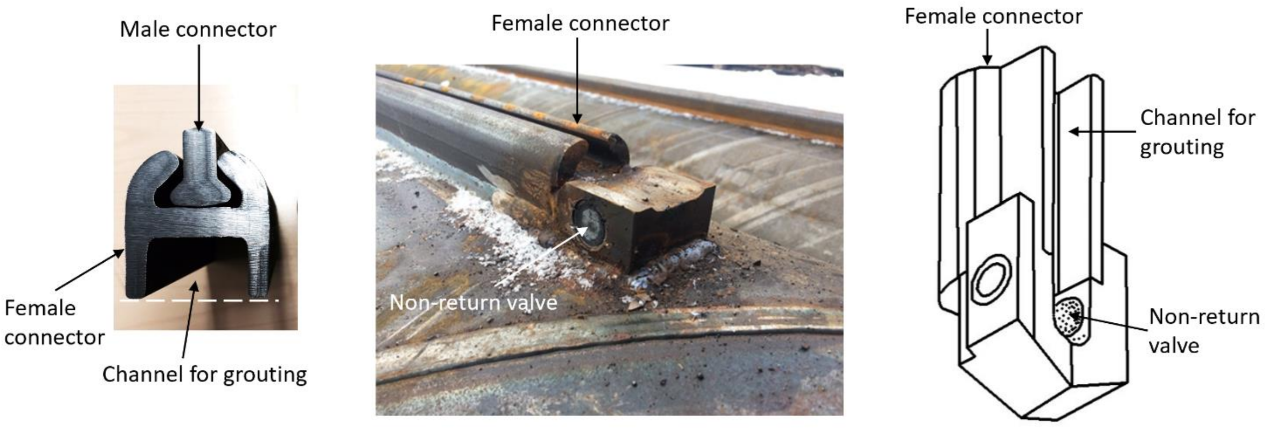
(d) Sealant was placed in female connector before installation. The sealant will then cut off the water flow in the interlocking joint during and after excavation;

(e) Grouting was carried out to seal the annular voids created by the ring bit in the rock socket and in soils outside the pipe pile.

The installation procedures of interlocking pipe piles using the Spiral Flush pilot bit for this project were similar to those discussed by Li *et al.*, (2018), except that a slightly different design had been adopted for the female connectors. To enable grouting to be carried out after drilling, a special female connector as shown in Figure 13 was used. The female connector has two ribs which will form a channel for grouting when the two ribs are welded onto the casing. A non-return valve was provided to seal the end of female connector. When cement grout was fed into the channel of the female connector, the grout would emerge from the non-return value in a bottom-up manner to gradually fill up the annual voids in the rock socket and in soils.

The grouting operation was found to be very successful as the annular voids were observed to be fully filled during excavation. Figure 14 shows a photograph of the hardened cement grout observed in granite of the rock socket exposed during excavation.

The excavation and lateral support works for the project had been completed successfully in a water-tight manner and without causing any settlement of the adjacent old buildings. Figure 15 shows a photograph of the pipe piles which had been installed using the Spiral Flush pilot bit.



(a) (b) (c)

Figure 13: *Joint details (a) interlocking joints; (b) Female joint welded onto casing with non-return value at its end; (b) 3-D diagram of female joint and non-return valve.*

Figure 14: *Grout observed in the rock socket during rock excavation.*

5 Discussions And Conclusions

In Hong Kong, geotechnical designers are not as familiar as they should with foundation construction and equipment. As a result, the construction procedures or equipment specified in the drawings or specifications may not necessarily be appropriate for ensuring that the adverse effects associated with overburden drilling are kept to a minimum.

Geotechnical works in Hong Kong are also highly competitive. The works are usually subcontracted by the main contractor to various sub-contractors of different trades and often on a lump-sum or fixed rate basis for them to share the risks. To win the contract, the main contractor and/or the sub-contractors may sometimes take risk in order to keep the bidding competitive. Even if the right equipment has been specified by the Engineer, it is not uncommon for contractors to only keep limited sets of the specified equipment on site for display purpose and actually use cheaper counterfeit or copycat equipment, which may have doubtful performance, for construction in order to keep the costs down.

Figure 15: *Pipe piles installed using Spiral Flush pilot bit adjacent to the 1962 old building*

Improved construction equipment such as those described in this paper has been available in the market for some time. The costs of remedial works are often much higher than those of using the right equipment and adopting the appropriate procedures for construction. If our goals are to advance the

Proceedings DOI: 10.21467/proceedings.159
ISBN: 978-81-965621-6-8

Series: AIJR Proceedings
ISSN: 2582-3922

practice of overburden drilling, geotechnical engineers, including those working in regulatory authorities, should be more acquainted with the new developments of foundation equipment so as to stipulate and only approve the suitable techniques for construction. Efforts should also be made by the Engineer to ensure that once an appropriate equipment or construction procedures have been specified or approved, contractors/sub-contractors should be discouraged from cutting corners to risk causing unwanted effects during construction.

More trials of overburden drilling using newer and safer techniques should be conducted by contractors or specified/encouraged by the Engineer to build up a wealth of experience for the selection of the right drilling equipment for different ground conditions in Hong Kong.

6 Declarations

6.1 Acknowledgements

The authors are grateful to Mr. Falco Chu of Unicon Ltd. for his assistance in preparing this paper.

6.2 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in institutional affiliations.

How to Cite

Ahonen & Victor (2023). Recent Developments of Drilling Techniques for Construction of Foundation Works. *AIJR Proceedings*, 19-31. https://doi.org/10.21467/proceedings.159.3

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