

Risk Associated with Construction of Large Diameter Bored Piles in Cavernous Marble

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SUMMARY: The methods used for constructing large diameter bored piles in cavernous marble for the Light Rail Transit Development project in Hong Kong are described. The major risks and problems involved in the construction include the formation of sinkholes, collapse of soil cavities and the problem of soil piping. Techniques for minimising these risks and problems will be discussed in the paper.

1. INTRODUCTION

Marble was not discovered in Hong Kong until the late 1970s when site investigations for building developments in northwest New Territories revealed the existence of marble formations concealed by a thick cover of superficial deposits. Marble was first discovered in the Yuen Long area (1),(8), (9),(10). It was also found later in northeast New Territories in the Tolo Channel (11) and more recently in the Ma On Shan reclamation.

Cavities are present in the marble formations although the extent of cavitation varies from site to site. Very often, the cavities are small and the presence of cavities does not prelude the development of heavy foundations for tall buildings. A number of buildings, supported by driven-cast-in-situ piles (8) or steel H-piles (4), have been successfully completed in the marble formations in Hong Kong.

In 1987, site investigations carried out for the Light Rail Transit (LRT) Development project in Yuen Long indicated the presence of large cavity systems in the marble bedrock at the site (2,3). Some of the cavities were believed to be connected for as far as 30m horizontally and 20m vertically, and one of the cavity systems was found to have a volume well in excess of 350m³. Driven piles could not be used for this project because the heavy foundation loads might cause collapse of the large marble cavities. Large diameter bored piles were considered to be a suitable choice for the foundation. The bored piles were 2m in diameter and founded at levels below the large cavities. The design of the foundation

for the LRT Development has been discussed by Holmes & Keung (2) and Holmes, Keung & Li (3). This paper addresses the risks and problems associated with the construction of large diameter bored piles in cavernous marble, with special reference to the conditions in Hong Kong. Although this paper draws the experience from the LRT Development project, some of the risks and problems discussed in this paper are based on the author's assessment and do not necessarily relate to what had actually happened at the LRT site.

The geology of the LRT site is described in (2,3,7) and is similar to other marble sites in Yuen Long area described by Houghton & Wong (4). Some typical geological sections of the LRT site can be found in (7).

2. CONSTRUCTION

The LRT project was the first project in Hong Kong, and perhaps one of the very few projects of this kind in the world, involving the construction of bored piles in cavernous marble. The methods of construction used for the project have been described by Holmes, Keung & Li (3). A more detailed description is given in this section. The terminologies used in the following discussion are defined in Fig.1.

2.1 Piles with no cavity

A temporary casing is driven into the ground by a heavy-duty vibrator or by an oscillator. The soils in the casing are then removed by a grab. The casing can be extended if necessary until the marble bedrock is reached. If the pile is to be socketed only a few metres into the marble bedrock, rock excavation can be effected by chiselling. For a longer socket length, it is more efficient to use reverse circulation drilling (RCD). Efforts should be made to prevent soil piping at the bottom of the casing using a method described later in Section 3.1.

2.2 Piles with small cavities

Fig.2 shows the method of construction for a pile with a small cavity. The marble above the cavity is excavated by chiselling or RCD. When the cavity is reached, two different methods can be used.

Method A: The soft materials inside the cavity is removed and the emptied cavity is then filled with concrete. Excavation continues when the concrete has hardened. If there are more

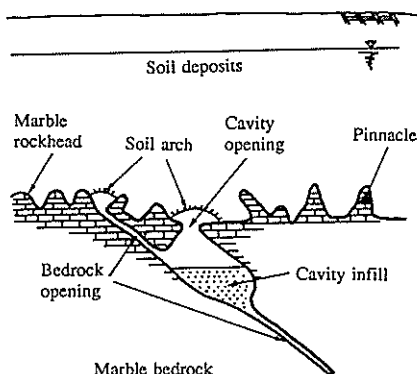


Fig.1 Features of cavernous marble

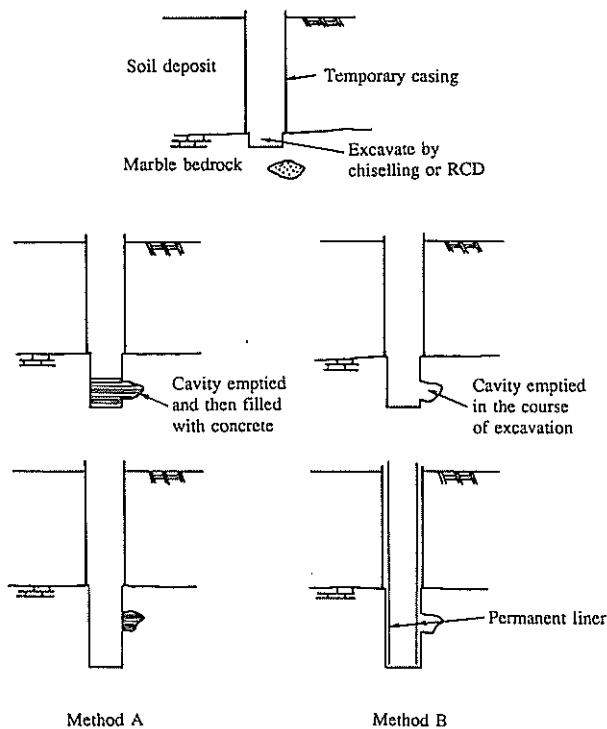


Fig.2 Piles with small cavities

than one small cavities along the pile, the same procedure can be repeated for the next cavity.

Method B: Excavation proceeds as if no cavity is present. When excavation is complete, a permanent liner is placed inside the bored hole. At the LRT site, a 2mm thick corrugated spiral tubes with a nominal diameter of 2m were used. The spiral tube would terminate at point A if a 2m diameter drill bit was used for excavation and at point B if excavation was effected by chiselling or a 2.1m diameter drill bit. Without the permanent liner, soft materials may be drawn into the bored hole from the small cavity or other sources through bedrock openings connecting the small cavity when the base of the bored hole is being cleansed by air-lifting. Despite the use of a permanent liner, this method requires a longer period of time for cleansing. For the LRT project, the cleansing process might sometimes take more than one day before the bored hole was clean enough for concreting.

2.3 Pile with large cavities

If the cavity is large, it is not economical or practical to plug the cavity with concrete. The technique of telescoping casing can be used (Fig.3). Initially, an outer casing is sunk into the ground until the marble rockhead is reached. The bottom of the outer casing should be sealed using concrete to prevent soil piping, again using the procedure described in Section 3.1. The marble above the cavity can be excavated by chiselling or RCD to create a bored hole large enough to accommodate the inner casing. On reaching the cavity, an inner casing is sunk onto the bottom of the cavity. The cavity infill materials inside the casing is then removed by grab.

At the LRT site, a 2.5m diameter outer casing was used. If the marble above the cavity was to be excavated by RCD, a 2.3m diameter drill bit would be used. This would create a sufficiently large bored hole to accommodate a 2.2m diameter inner casing.

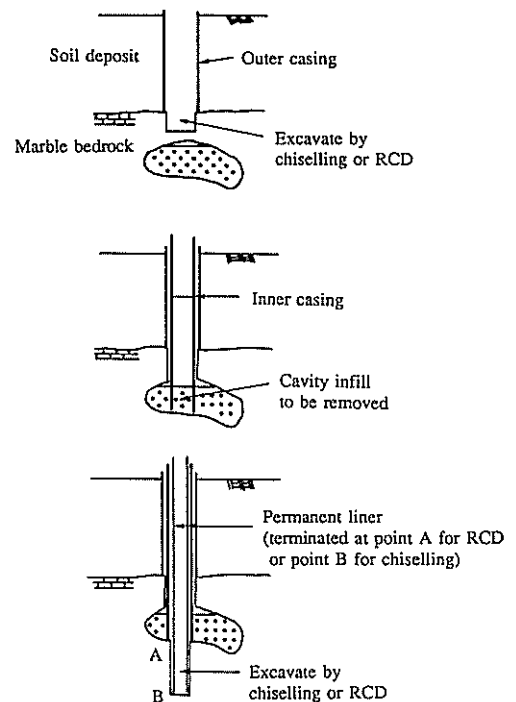


Fig.3 Piles with large cavities

The bottom of the inner casing should also be sealed using concrete to prevent future ingress of soft materials into the bored hole. A permanent liner has to be used for forming the pile in the cavity. The inner casing is to be extracted section by section in the course of concreting while the outer casing can be extracted when concreting is complete.

A gap between the permanent liner and the soil layer may remain when the outer casing is extracted. This gap should be backfilled with soils to prevent it from developing into a soil cavity when construction of other adjacent piles commences later.

If a large cavity is present, bursting of the permanent liner during concreting can cause very serious consequences. This can happen when the portion of the permanent liner within the large cavity loses its lateral support while the inner casing is being extracted in the course of concreting. If rupture of the permanent liner occurs, the concrete will flow quickly out of the liner to fill up the cavity, causing a very sudden and significant drop in the levels of water and concrete in the casing. At the same time, the outflow of concrete will cause a rise in the water level outside the permanent liner. The difference in water levels inside and outside the liner will result in a significant pressure on the permanent liner. If the liner is not strong enough, necking will occur and the pile will be damaged. Therefore, for long piles passing through large cavities, a strong permanent liner is strongly recommended.

In principle, piles with many large cavities can be constructed by multiple telescoping using three or more temporary casings. However, it is preferable not to construct any pile at a location with more than two large cavities because the operation of multiple telescoping is very tricky and perhaps dangerous.

2.4 General rules

The methods described above may need to be adjusted to suit particular conditions of a pile. However, there are some

general rules which apply for all situations.

As the method of construction to be adopted depends on the number and size of the cavities, it is desirable to have at least one site investigation drillhole at every pile location so that the contractor can use an appropriate construction procedure for each pile.

Piles close to each other should not be constructed at the same time whenever practicable because it will increase the risk of formation of sinkholes and lead to other serious consequences. In one instance, driving of the temporary casing by a heavy-duty vibrator caused collapse of rocks and cavity infill into the bored hole of an adjacent pile. In another instance, concrete flowed from one pile during concreting to another pile in its vicinity through the cavities connecting the two piles. The drill bit inside the second pile was totally engulfed by concrete.

When a pile is being concreted, all excavation works by RCD near to the pile must be stopped because RCD will create movements of water within the marble bedrock, washing away the cement paste of unset concrete.

Excavated rock samples should be examined frequently so that any unexpected solution features or cavities, if present, can be detected and the method of construction be changed accordingly.

3. RISKS AND PROBLEMS

3.1 Soil piping

One of the major risks of bored piling in cavernous marble is the formation of sinkholes. Soil piping is often responsible for the initiation of soil cavities and subsequent formation of sinkholes (5,6). In bored piling, soil piping can be caused by fluctuation of the water level within the casing. Positive pore-water pressures generated in response to water-level fluctuations cause dislodgment of soil particles and subsequent formation of soil cavities. Rapid circulation of water within the casing can also result in erosion of soil deposit.

Soil piping tends to start near the bottom of the casing. The size of soil cavities induced by soil piping can be very large. In one instance, about 20m³ of concrete was lost during concreting when the casing was slightly lifted above the marble rockhead in the course of concreting. Concrete was believed to have flowed out of the casing and filled the soil cavity outside it.

A useful and effective method to prevent soil piping is to seal the bottom of the temporary casing by concrete. On reaching the marble rockhead, a small rock socket is formed by chiselling. A small soil cavity may be created during this stage. A suitable amount of tremie concrete is then placed inside the casing. The concrete will flow out of the casing to fill up the soil cavity around it. Sometimes, the casing may need to be slightly lifted to allow an easier outflow of concrete. When concreting is complete, the casing is driven downwards before the concrete is set to ensure as tight an interface as possible between the casing and the marble bedrock. When the concrete has hardened, an impermeable annular barrier will be formed around the bottom of the casing. Excavation of rock can commence after removal of the concrete inside the casing. Sealing of casing will help minimise if not totally eliminate the problem of soil piping. The concrete inside the casing is later excavated. The forming of the initial rock socket is important to ensure that solid

marble bedrock is reached, and not the pinnacles, before concreting commences. This will provide a more effective sealing.

If the problem of soil piping is ignored, the soil cavity formed near the bottom of the casing will enlarge and progress upwards along the casing until it finally collapses. Even if the soil cavities are stable at the initial stage of construction, each soil cavity in the soil profile will contribute to the risk of a large scale ground subsidence or the formation of a large sinkhole occurring at a later stage of bored piling.

Although the sealing of casing may appear to be time-consuming and costly at first thought, it is more economical in the long run when one considers the damages that may occur without this measure. The following case study is a good example to illustrate this point. For a particular pile, 18m of marble were required to be excavated before reaching the founding level. The casing was not sealed before rock excavation began. When the founding level was finally reached, a large quantity of soils suddenly oozed into the bored hole from the bottom of the casing. Luckily, the drill bit had been removed from the pile before the incident occurred. The bored hole had to be concreted in order to fill the soil cavity around the casing. The concreted section, which was in excess of 20m in length, had to be excavated to reach the founding level again. Sealing of casing also makes cleansing of the bored hole easier because a lesser amount of soils will enter the bored hole from the bottom of the casing.

3.2 Collapse of soil cavities

An increase in surface loadings during construction may cause the collapse of soil cavities formed during bored piling. In one instance, a heavy crane had sunk suddenly into the ground by about 2m due to the sudden collapse of a shallow soil cavity beneath it.

To minimise the damage caused by a sudden collapse of a soil cavity, it is useful to detect the presence of such cavities before and regularly during construction, say, by SPT tests or other types of dynamic penetrometers. If soil cavities are found, it is desirable to strengthen the ground by dynamic compaction, i.e. breaking the soil cavities before the damage is done, or filling the cavities by grouting.

The existence of a sizeable soil cavity around a pile can be indicated by the presence of a shallow depression or a vertical opening adjacent to the pile. In one instance, a 15m deep vertical opening was observed in the ground next to the temporary casing. Rapid movements of water in response to changes in the water level inside the casing can be seen around the pile. If action is not taken at this stage, a collapse of soil cavity is imminent.

Excavation for the construction of pile caps results in thinning of the soil profile and the chance of collapse of a surface soil cavity due to increased loading will be higher.

3.3 Removal of cavity infill

Removal of cavity infill from a cavity may induce an inflow of soft materials from other cavities or the soil profile through openings connected to the cavity. Although the emptying of a small cavity may not necessarily have any immediate serious consequence, it is preferable to plug an emptied cavity by tremie concrete before proceeding with further excavation. Otherwise, if more and more emptied cavities are created,

water movements in the marble bedrock will become more rapid and affect a larger area. A large-scale ground subsidence or the formation of a large sinkhole becomes more likely.

Plugging of cavities also has other advantages. It will block the openings connecting the cavity and help prevent the problem of soil piping. As more and more cavities are plugged, the cavity systems in the marble bedrock become less and less inter-connected. This will make the construction of bored pile less problematic at the later stage of construction. Ingress of soft materials from the cavity during excavation may have serious consequences because the materials may jam the chisel or drill bit in the bored hole, making its retrieval difficult. Plugging of cavities reduces this risk. It also makes cleansing of the bored hole easier because less materials will enter the bored hole through the plugged cavity. Because of the above reasons, Method A discussed in Section 2.2 is preferred to Method B for bored piles with small cavities.

Emptying of a large cavity is dangerous because it may result in loss of support and collapse of the cavity. In this case, a temporary casing will need to be driven through the infill material (Fig.3). The material encased by the casing can be removed by grab. It is desirable to seal the inner casing before proceeding with further excavation of marble so as to prevent ingress of infill materials into the bored hole.

3.4 Assessment of rock quality

The surfaces of weathered marble are pitted, and usually yellow to brown in colour, although they may sometimes have the same colour as unweathered marble. The weathered surface zone is usually thin and a thickness of 2 to 3mm is not uncommon.

When excavation is effected by chiselling, the presence of solution features in the marble bedrock can be detected quite easily by examining the rock fragments mucked out from the bored hole. However, if RCD is employed, the thin weathered surface can easily be removed by abrasion before the marble is broken up by the drill bit. As a result, it is difficult to detect the existence of solution features by examining the small marble flakes collected from the discharge hose of the reverse circulation drill. For this reason, the determination of the founding level of a bored pile cannot be based on the examination of rock samples or fragments retrieved from the bored hole. One has to rely on the site investigation information. It is important to have at least one site investigation drillhole for each pile to ensure that there is no large cavity beneath the founding level.

In judging the presence of cavities at a pile location, one should not rely solely on the drillhole log for the pile. Other site investigation data collected at nearby locations should also be considered. In one instance, the drillhole log of a particular pile did not indicate the presence of a cavity and the method of construction used was based on the assumption of no cavity. Rock samples collected at a level of about 43m below the ground surface indicated the presence of solution features at that level. The contractor ignored the implications of this finding and also the fact that the drillhole logs at adjacent locations did reveal the existence of a large cavity system close to the pile. When the pile was being concreted, about 350m³ of concrete had flowed out of the bored hole at the level where the solution features were detected earlier during excavation. It was believed that a bedrock opening connecting to the large cavity system was present at that location.

4. CONCLUSIONS

Construction of large diameter bored piles in cavernous marble is feasible although it requires more efforts and precautions than ordinary bored piling. Many of the risks and problems associated with the construction of bored piles in cavernous marble can be minimised or solved using the methods described in the paper. It is suggested that some of the recommended construction procedures, such as sealing of casing and plugging of cavities, be stipulated in the specifications or drawings to ensure that they will be implemented by the contractor. A suitable method of measurement should also be devised so that the contractor can be suitably rewarded for implementing these procedures.

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