# COMPARISON OF DIFFERENT HARD ROCK DRILLING METHODS FOR BORED PILES

**Martin Larisch**
*Piling Contractors Pty Ltd, Brisbane, Australia*

## ABSTRACT

Drilling penetration into rock becomes more difficult with increasing hole diameters and rock compressive strength. In piling applications, hard rock formations have to be cut and excavated prior to the installation of the foundation piles and/or piled retaining walls. Commonly, conventional rotary drill tools are used for bored piles in medium to very high strength rocks. For harder rock formations different methods have to be adopted as much larger cutting energy and force input are normally required to break the material at the rock tool interface.

Cluster drilling is a proven method to penetrate rocks with strengths exceeding 100 MPa. The method has been used successfully for decades in America, Asia and Europe for applications in the mining and construction industry with diameters usually ranging from 600 to 2400 mm. In Australia cluster drilling has recently been used for mining and modest construction applications. However, in 2010 Piling Contractors Pty Ltd has started utilizing innovatively designed and built cluster drills for the penetration of extremely high strength rock formations. Since then, more than 1,000 linear meters of extremely high strength rock (most of it with UCS in excess of 200 MPa) was successfully excavated using this technology for the installation of bored piles.

Air roller core barrels were also utilized in the past for various projects involving hard rock drilling. Basic working principles and limitations of these two traditional techniques compared to cluster drilling are identified and discussed in this paper.

**Keywords:** air roller core barrel, cluster drilling, down hole hammer, hard rock drilling, piling

## 1 INTRODUCTION

### 1.1 GENERAL

The installation of bored piles of various diameters (usually from 450 mm to 3000 mm) into rock formations can be carried out using conventional rotary drill tools, air roller core barrels or cluster drills. All methods can be used in dry conditions or under drilling fluid (usually water, polymer or bentonite slurry). When drilling with cluster drills under fluids it is critical to apply a suitable backpressure to the cluster drill in order to prevent drilling fluid from entering the pistons of the individual hammers, which will cause increased wear and tear or unrepairable damage of the same.

The collection of rock cuttings can be carried out using augers and / or cleaning buckets for conventional rotary drill tools. For air roller core barrels or cluster drills calyx baskets (spoil baskets) will be utilized which are commonly placed on top of the drill barrel. Usually the calyx baskets need to be emptied from drill cuttings every 1-3 m of drill progress. Alternatively, reverse-circulation-drilling (RCD) methods can be adopted which will enable the drill tool to penetrate into the rock in one bite without lengthy extraction periods to empty the calyx baskets. Particularly for deep excavations RCD is an attractive option to optimize drilling times on site.

### 1.2 SELECTION OF SUITABLE DRILL TOOLS FOR BORED PILES

As a general rule for rock drilling, it can be noted that the higher the energy input into a unit volume of rock (via drill bit or drag pick pressure), the more penetration is expected of an appropriately selected sharp cutting tool. For conventional drill tools, e.g. core barrel, auger and drill bucket, as shown in Figures 1 and 2, it can be stated that with increasing pile diameters the number of required drill bits have to increase proportionally. As a result, the individual drill bit pressure decreases, if the vertical thrust of the piling rig remains constant. Thus, drilling with conventional tools is limited by the maximum vertical thrust and will rapidly become uneconomical in rock strengths exceeding 100 MPa However, in certain rocks with compressive strengths around 50MPa and more, alternative drilling techniques, generally beyond the capabilities of the conventional tools, can be used to achieve more economical production rates. This paper will discuss two proven hard rock drilling techniques using (a) air roller core barrels and (b) cluster drills to penetrate hard rock with UCS even greater than 100 MPa, which is beyond the capabilities of the conventional drill tools for rocks of the order of 50 to 100 MPa compressive strength. Figure 1 show suitable drilling techniques correlated to the rock uniaxial compressive strength (UCS).

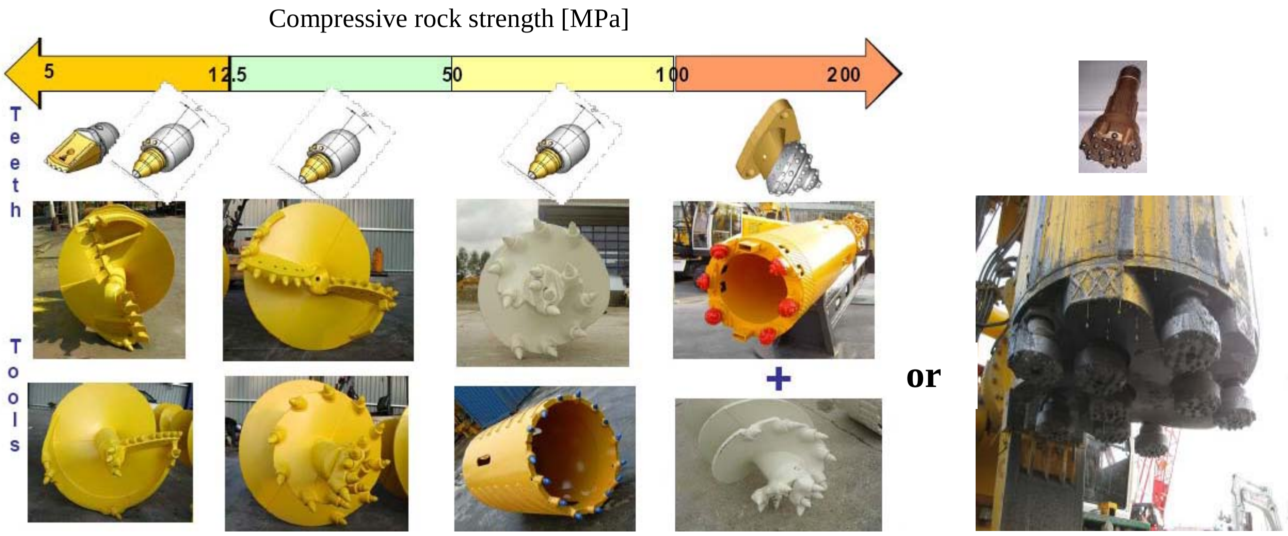


Figure 1: Different drill teeth and tools correlated to compressive rock strength (UCS) for bored piles (left section of the figure from Bauer Maschinen GmbH, Germany)

It should be noted that not only the compressive rock strength (UCS), but also the degree of fractures and number of joints in the rock mass as well as the material's resistance to tensile, frictional, shear and abrasive forces are also factors that influence both rock drillability and tool durability.

## 2 WORKING PRINCIPLE OF DIFFERENT ROCK DRILLING METHODS

### 2.1 CONVENTIONAL DRILL TOOLS (CORE BARREL, DRILL BUCKET AND AUGER)

Conventional drill tools used for the installation of bored piles like core barrels, augers and drill buckets, as shown in Figure 2, are commonly used to penetrate rock with a compressive strength up to 100 MPa. A simplified working principle of cutting rock by bullet shape drill teeth (or drag picks, which is the correct term in rock mechanics) is shown in Figure 2. There are three force components acting on a single bullet tooth bit, which are the vertical thrust force (V) normal to cutting direction, a cutting force (C) along the cutting direction, and a lateral force (M*) normal to the plane going through V and C. The torque (M) is normally proportional to the cutting force (C); M = C * lever arm length (drill tool radius). The process strongly relies on applying sufficient rotary torque M and pull-down force (thrust) V at a constant rotation of the drill tool. This is important to maintain an adequate bit pressure for effective cutting action. The ratio $V / M \approx 0.5$ for soil and low strength rock (Kuehn 1980) meaning that M has more impact than V when using conventional techniques with bullet teeth (drag picks).

If the applied thrust (V) and rotary torque (M) are insufficient, the bullet teeth won't be able to bite and break the rock into cuttings or chips; instead it will produce fine grinding particles, resulting in low penetration rates and high bit wear.

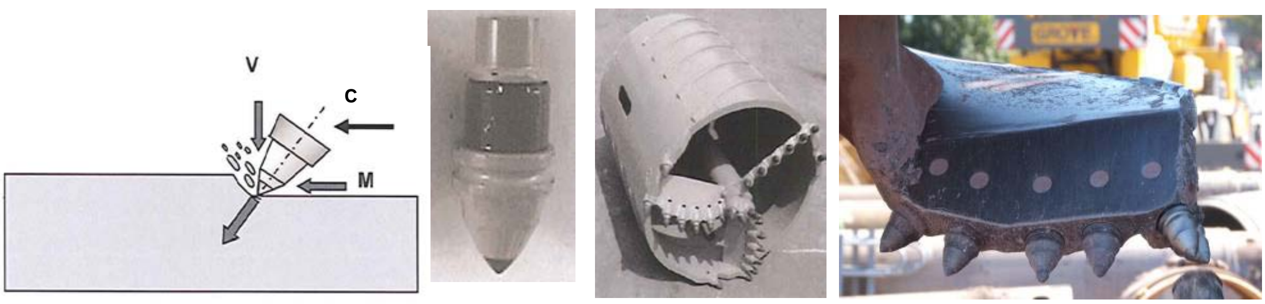


Figure 2: Working principle of a bullet tooth / drag pick (left), typical bullet tooth with tungsten carbide tip (centre left), typical core barrel with cross cutter (centre right), auger starter with bullet teeth (right)

If the rock strength is too high for conventional drill tools, the energy transferred from the drill bit into the ground won't be sufficient to produce an adequate fracturing stress field at the rock surface where the carbon tungsten tip of the bullet tooth is in contact with the rock. Instead of cutting and producing large chips, tool blunting and rock grinding will occur. Increasing the thrust (V) and torque (M) will only increase the risk of damaging the machine and breaking off the tungsten carbide bits. Hence alternative drill methods should be considered when encountering harder and tougher rocks.

## 2.2 AIR ROLLER CORE BARREL

Air roller core barrels are designed to operate on the principle of cutting by thrust indentation and shearing rotation, also called the “twisting and tearing” method resulting in a “rock crushing” mechanism depending on the rock strength and other rock characteristics. An air roller core barrel can be described as a cylindrical steel casing which is fitted with a series of single cone shaped roller bits at the bottom end (Figure 3) to drill rock sockets for bored piles. Each roller bit is fitted with a series of tungsten carbide insert buttons for drilling. Compressed air is used to clean the rock cuttings from the rock face. Alternatively, reverse circulation drilling methods can be applied to remove rock cuttings.

Air roller core barrels are used to cut an annulus into the rock mass by applying thrust V and rotational torque M. The number of rollers has to be matched with the barrel diameter and the rotational speed of the drilling operation. After cutting the annulus, the rock core has to be removed by either breaking it with the barrel or by the use of chisel, rock augers or DTH hammers. The time for breaking the core has to be considered in determining the productivity of the process and depending on rock characteristics it could take longer to break and to remove the core than drilling the annulus. Different ground conditions require different drill parameters for this particular technique.

Figure 3: Typical air roller core barrel (left & centre) and single roller cone drill bit (right).

Air roller core barrels work using the “twisting – tearing” principle (Figure 4) in rock formations with compressive strength (UCS) ranging from about 50 MPa to 100 MPa. The roller is usually fitted with tungsten carbide drill buttons which will cut into the rock as it rolls along. It is important to apply sufficient thrust force V for biting or indentation as well as cutting force through the rotational torque M to produce sufficient damaging stress in the rock resulting in cracks and chips at the contact area between the drill button and the rock face. While entering the rock face, the material in front and below the button will be initially compressed by loading. However, on the way out of the ground the drill button will loosen the material and lift out the chip (Australian Drilling Industry, 1997; Alehossein and Hood, 1996; Alehossein and Boland, 1995). Alternatively, if the roller wheel is pushed at the same time as it rolls along; larger chips will be cut in soft to medium strength rock by “skidding” (Figure 4).

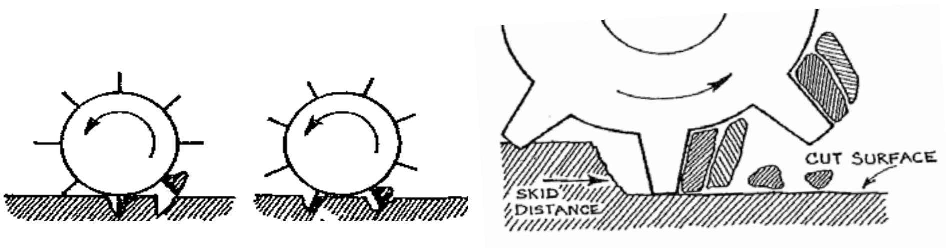


Figure 4: Principle of twisting and tearing (left) and skidding (right); Australian Drilling Industry (1997)

In rock formations with compressive strength (UCS) exceeding 100 MPa, roller core barrels operate by the same “rock crushing” principle as the “down the hole” (DTH) hammer (Figure 5). The tool is lowered down to the levelled and cleaned rock face of the excavation, which is usually prepared by conventional core barrels with cross cutters. It is important to use sharp drill buttons to minimize the contact area between the button inserts and the rock. A smaller contact area results in a higher contact stress or pressure causing the concentrated button pressure to break and crush the rock most effectively. Any additional thrust V applied on the drill button increases the critical damaging stress (or critical pressure) of the rock under the button contributing to its further damage and breakage, as illustrated in Figure 5. The higher the loading or the external pressure from the additional thrust V, the higher is the indentation penetration of the cutting tool into the rock until the threshold rock strength is reached and the cracks created due to thrust damage coalesce to major cracks and chips producing the drill cuttings. It is critical to remove and clear the chips and rock cuttings quickly and effectively, otherwise rock cuttings will be crushed over and over again (pulverisation) and penetration rates into the fresh rock will slow down.

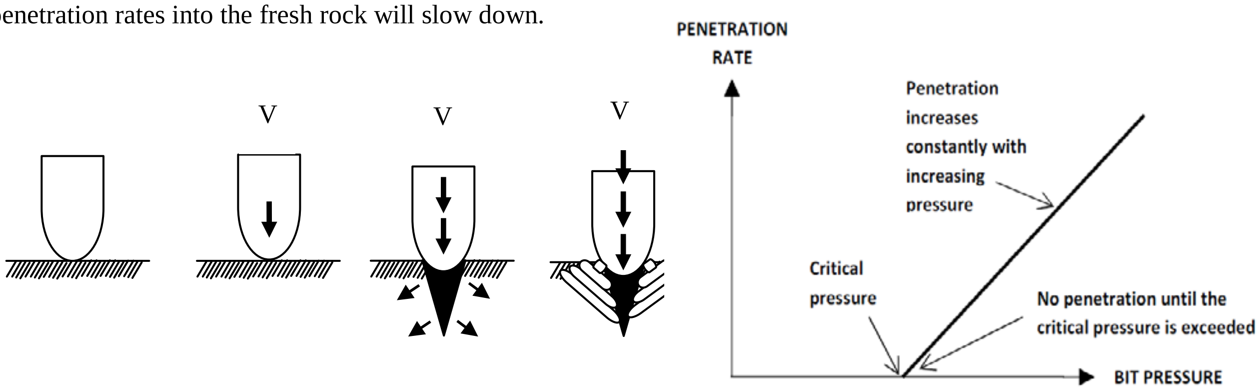


Figure 5: Schematic principle of "rock crushing" (left) and critical drill bit or button pressure (right).

## 2.3 CLUSTER DRILLS

Cluster drills are most effective in high to extremely high strength rock formations, usually ranging from 100 to 200 MPa UCS and beyond. A cluster drill is a dynamic assembly of several individual down the hole (DTH) hammers, combined in one individual steel barrel. The basic working principle of a cluster drill is shown in Figure 6, for a cluster drill which is used with a calyx basket to collect the drill cuttings. Cluster drills can also operate under fluid or in a reverse circulation drilling mode.

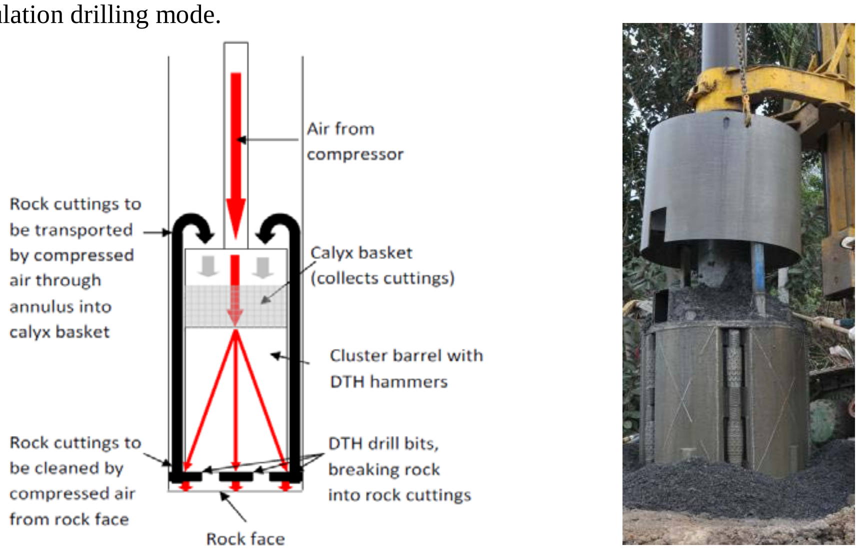


Figure 6: Cluster drill working principle (left), cluster drill with calyx basket on site (right)

In order to penetrate the rock, the pistons of the individual DTH hammers of a cluster drill are mobilized by air pressure and the button inserts of the drill bits crush the rock with the same principle as described in Figure 5. The piston stroke of an individual hammer, a vertical force V, is far larger than the thrust V of the most powerful piling rigs in the world, and it has a superior effect with respect to the crushing of rock formation. The critical stress at the rock face is exceeded at every blow and the penetration rates are stable as long as the rock cuttings are removed quickly and constantly.

Cluster drills lose efficiency in softer rocks and are generally unsuitable in rocks with compressive strength (UCS) less than 100 MPa, because the energy from the vertical impact force V will be dampened much quicker in a softer rock. Cluster drills and DTH don't operate at the same ranges of small ratios of the thrust V and rotational torque M as the conventional drill tools in soils or weak rocks. For harder rocks, vertical forces become far more important than rotational torque and hence the V/M ratio increases significantly. The torque M is not critical for breaking harder rocks; its value has to be sufficient and suitable to keep the drill rotating at a constant rate. However, due to the dynamic effect of the hammer impact on the rock mass, any substantially additional thrust V from the drill rig is not required, since typical cluster drill assemblies can operate under their own self weight. Drill bits of DTH hammers consist of several individual drill button shape inserts (Figure 7). Arrangement and size of the buttons are critical for optimal penetration rates into different rock types. Blunt drill buttons with larger contact areas to the rock face mostly pulverise the old rock fragments rather than producing any new rock cuttings or chips. It is important to watch the wear and tear process of the drill bits carefully and regularly. Early indications of the worn drill bits are (i) the reduced bit axial speed or decreasing penetration rates, and (ii) observing smaller rock cuttings.

Figure 7: typical drill bits and button inserts (left) for DTH hammers, assembly of individual DTH hammers and base plate of cluster barrel (centre), individual drill bits of a cluster barrel (right).

# 3 OPERATIONAL PARAMETERS FOR CLUSTER DRILLING

## 3.1 AIR PRESSURE AND AIR VOLUME

Air pressure will activate and move the piston of the DTH hammers and introduce a vertical force V into the drill bit. With optimal air pressure the hammer can fire several thousand times per minute with impacts of up to 4 MN per blow per hammer. It should be noted that losses in air pressure will occur when drilling under water. Air hoses should be kept as short as practical as losses will occur due to friction inside the hoses.

Sufficient air volume is required to transport cuttings from the base of the excavation through the annulus between the cluster barrel and borehole wall (Figure 6). Since damping coefficient of dust is much higher than that of its original rock, cuttings must be removed and pushed upwards, usually under high velocity for effective and efficient drilling. Insufficient air volume won't clean the base properly and the hammers will grind existing rock cuttings until they turn to dust. Eventually the hammers will be unable to penetrate through the compacted dust, which can't be blown out and hence the excavation progress will halt and cannot proceed normally.

## 3.2 OTHERS

The design of the base plate of the cluster drill is important for optimal production rates. The shape of the base plate is designed to transport rock cuttings and debris away from the base of the excavation towards the borehole walls and from there through the annulus towards the calyx basket, which is located on top of the cluster barrel (Figure 6). The faster the base can be cleaned, the earlier the hammers can produce new cuttings and the excavation will proceed smoothly.

# 4 MAJOR RISKS RELATED TO CLUSTER DRILLING

## 4.1 TECHNICAL RISKS

One of the major technical risks besides the use of incorrect operational parameters is the running off of the cluster barrel. It is the most important consideration to start drilling from a clean, levelled rock face to ensure the rock socket is straight and stable. The cluster drill will follow a sloping rock face and it requires special measures and methodologies to prevent it from running off when the initial rock face is not level. Once run off, it is difficult to re-direct the cluster drill. An off line cluster drill can result in non-compliant rock sockets.

Bands of soft material sandwiched between hard rock layers can cause the drill to run off as well. Once the cluster has run off the alignment, the excavation should be backfilled with a high strength concrete and should be re-drilled after the concrete reached at least 50MPa ultimate compressive strength.

## 4.2 ENVIRONMENTAL RISKS

Dust is one of the worst environmental impacts created by a cluster drill. In remote areas dust emissions might be more acceptable than in suburban areas, however dust is a serious occupational health and safety risk and should be reduced to a minimum. Usually there are two effective actions to reduce dust during cluster operations: (a) drilling under water, which requires a minimum drill depth to accommodate sufficient pressure head for dust suppression. Penetration rates are usually slower when drilling under water. (b) Using a dust collector. Dust collectors are effective in reducing dust; however production rates will be slower due to regular dust removal.

Noise levels of Piling Contractor's cluster drill equipment are comparable with noise emissions caused by conventional drilling operations or air roller core barrels. On site vibration monitoring indicated that no critical vibrations in excess of Queensland Main Roads criteria and international standards (DIN4150-3:1999-2) occurred during cluster drilling operations with Piling Contractor's cluster drill equipment.

Cluster drilling requires the use of high pressure equipment. Economical production rates of cluster drills or DTH hammer operations can only be achieved by high air pressure which controls the energy input into the rock by the drill bit and button. In the author's opinion, it is crucial for any cluster drill or DTH operation to ensure that all air compressors are fitted with automatic switch-off devices and all high pressure hoses are connected and secured with additional whip check connections (Figure 8).


Figure 8: Automatic switch-off at compressor (left), typical whip check connection for high pressure air hoses (centre), casings should be installed as fall protection even if rock is close to surface (right)

# 5 CONCLUSION

Rock drilling for piling applications using conventional drill tools is usually limited to rock strengths of 100 MPa compressive strength (UCS) or less. The paper presents two alternative hard rock drilling methods which are suitable to penetrate rock when conventional drill tools become either ineffective or reach refusal.

The use of air roller core barrels is generally suitable for extremely high strength rocks in excess of 100 MPa compressive strength (UCS) - in some rock formation in excess of 50MPa. However breaking the core might slow down production rates significantly and drilling refusal is usually reached at 200 MPa compressive rock strength (UCS), governed by the maximum vertical thrust V of the piling rig.

Operating as an air-piston-driven dynamic drill tool, cluster drilling is a very economical and efficient technology for penetrating rock formations in excess of 100 MPa compressive strength (in some rock formations 50 MPa compressive strength is suitable for this technique). However, cluster drilling becomes most efficient in rock formations exceeding 200 MPa compressive strength (UCS), where other techniques will reach refusal. Cluster drilling provides superior energy input into the rock and creates a full face excavation.

Over the last two years, Piling Contractors excavated more than 1,000 linear meters of extremely high strength rock in excess of 200 MPa compressive strength (UCS) using innovatively designed and built cluster drills. The cluster drills achieved up to ten times faster production rates than conventional drill tools and up to four times faster production rates than air roller core barrels in similar rock formations and are therefore attractive options for hard rock drilling requirements for bored piles.

Both cluster drilling and air roller core barrels are operated using compressed air. It is absolutely crucial to implement robust safety principles, procedures and measures to ensure that drilling operations will be carried out compliant to highest safety standards.

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