Managed Pressure Drilling and its Application to Cross Passage Tunnel Construction

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Abstract: *This paper is concerned with the use of managed pressure drilling (MPD) in civil engineering applications. The purpose of this is to permit drilling from below the water table while avoiding problems of uncontrolled water and soil outflow from the borehole and in preventing liquefaction of the ground around the borehole. The application discussed is of drilling through a tunnel lining into unconsolidated ground for the purpose of injecting grout to consolidate the soil so that cross passages may be excavated from tunnel to tunnel. The technique could also be used for drilling below the water table through sheet piled walls for the purpose of installing anchors.*

Keywords: *Drilling, Groundwater, Tunnelling, Liquefaction, Hydrofracture, Piping*.

1. INTRODUCTION

All excavations, caissons and tunnels constructed below the groundwater table act as potential drains. Control of groundwater during excavation has and will continue to present significant engineering challenges for these constructions. In the extreme cases in tunnels, inrush of ground water may exceed the drainage capacity of the excavation and pumping systems or may cause liquefaction of soils or running sands at the face, or collapse of weak rocks. These cases may have catastrophic consequences to the construction and any surrounding infrastructure.

Groundwater control has traditionally been done by exclusion. This is achieved historically for caissons and tunnels through soft soils by air pressurisation through systems of air locks for workers and materials handling. The air lock methodology, developed by trial and error for the construction of 19th century tube tunnels in the UK, has its engineering merits, while the short and long term effects of this system on the health and safety of workers have been well documented. However it has been largely surpassed by modern groundwater exclusion systems such as barrier walls, dewatering wells to depressurise the ground, changing the soil or rock properties by the injection of stabilising fluids (grouts) and more recently the freezing of soft soils and sands to stabilise the ground to enable excavation. For tunnels, the control of groundwater and the need in many instances to enhance the strength of in-situ soils for support, has led to the development of advanced drilling techniques as discussed herein.

In modern cities, population growth has led to the demand for improved public transport infrastructure, access and amenity. The constraints of existing surface infrastructure and its ownership, combined with the prohibitive cost of land resumption, have restricted the development of major surface transport routes. Tunnelling for new road and rail extensions can be the most viable option. The late 20th century saw the development of purpose built tunnel boring machines (TBM's) with various levels of sophistication to enable drilling through "all materials found" and to provide a permanent, sealed structural lining to the tunnel.

With the use of TBM's, the control of groundwater, while a significant engineering consideration, does not pose the same constraints on construction as the dewatering techniques required for conventional tunnel construction. TBM's operating in soft soils can be designed with balanced fluid pressure chambers at the cutting head with controlled removal of spoil via a choke system. Similarly the ingress of excessive groundwater at the face can be controlled in a temporary way through balanced pressure at the cutting head and ground stabilisation in advance of the cutting face.

Nevertheless a unique engineering requirement exists where penetration of the completed tunnel lining is required for services shafts, egress or in the case of the typical twin bore tunnels for road or rail traffic, in the construction of cross passage tunnels.

Cross passage tunnels pose unique design requirements where there is a need for the penetration of the tunnel wall in to less than optimal ground for tunnelling. In their optimum form in low permeability rock the cross passage is advanced progressively with strata support after initial structural strengthening and then penetration of the tunnel wall. Cross passages can also be formed using small TBM's and by pipe jacking.

However, drilling or any penetration from a lined tunnel below the water table in unconsolidated ground poses two potential problems that must be addressed. The first is that uncontrolled inflow may occur leading to piping and with a potential sink hole formation. The second is that too high a fluid pressure in a drilling operation may lead to liquefaction outside the tunnel wall. In addition to the needs to control water inflow and excavation stability there is just as important a requirement to prevent settlement of the surface and of foundations caused by either deliberate pre-drainage or consequential drainage caused by excavation. Prevention of damage to third party surface infrastructure has become a major design consideration.

Cross passage tunnelling in soft soils requires ground stabilisation in some form to increase the structural strength of the material, to reduce its permeability, to lower its pore pressure, or all of the above. The lowering of pore pressure may not be an option because of the effect this will have on other structures or in some cases water supply. The current Uma Oya project in Sri Lanka is a prime example where a tunnelling operation in rock has captured the ground water supply for an area. The inflows of 0.5 m^3/s into a 4.2 m diameter tunnel have also made the tunnelling operation difficult and hazardous.

Various techniques have been used to deal with water in tunnelling including:

1. Underground
    - Drainage
    - Grouting
    - Stabilisation by spiles, bars or other reinforcement
    - Ground freezing

2. From surface
    - Dewatering
    - Stabilisation from surface
    - Ground freezing from surface
    - The use of diaphragm walls as cut offs

The selection of the technique will be based on the specific engineering requirements and cost constraints for each site. The drainage option may not exist because of the complications associated with dewatering. Any cross passage development requires penetration of the main tunnel wall, which is an inherently risky process. It requires multiple lines of defence to prevent or at best mitigate any ingress of groundwater or soil into the main tunnels. Many associated accidents have been reported in literature. Precautions are required. For instance on the construction of the Tu-chen Line, Taipei, four lines of defence were employed (Fang et al, Ref 1) including ground stabilisation from surface, testing and secondary grouting from main tunnel, compressed air and safety gates to close off the main tunnel.

1.1. Managed Pressure Drilling

Drilling is frequently used in all of the underground stabilisation methods. For it to be accomplished safely some form of pressure control is required to prevent problems associated with uncontrolled water ingress, possibly with associated pipe formation. It is also required to prevent excessive pressure within the borehole causing problems with hydrofracture of the ground, possibly to surface, liquefaction of finer granular soils and excessive fluid loss.

Figure 1 shows the pressure distribution along the length of a horizontal borehole being drilled from an underground opening without any form of pressure control. In this case the hydrostatic pressure in the hole is zero along its length. The dynamic pressure in the annulus due to flow reduces from a maximum at the drill bit to the collar of the hole. Without the effects of injection or dewatering the groundwater pressure is constant and may be subtracted from the pressure in the hole to arrive at a net pressure difference while drilling. This shows an area of net positive pressure (overbalanced drilling) behind the drill bit and net negative pressure (underbalanced drilling) closer to the hole collar.

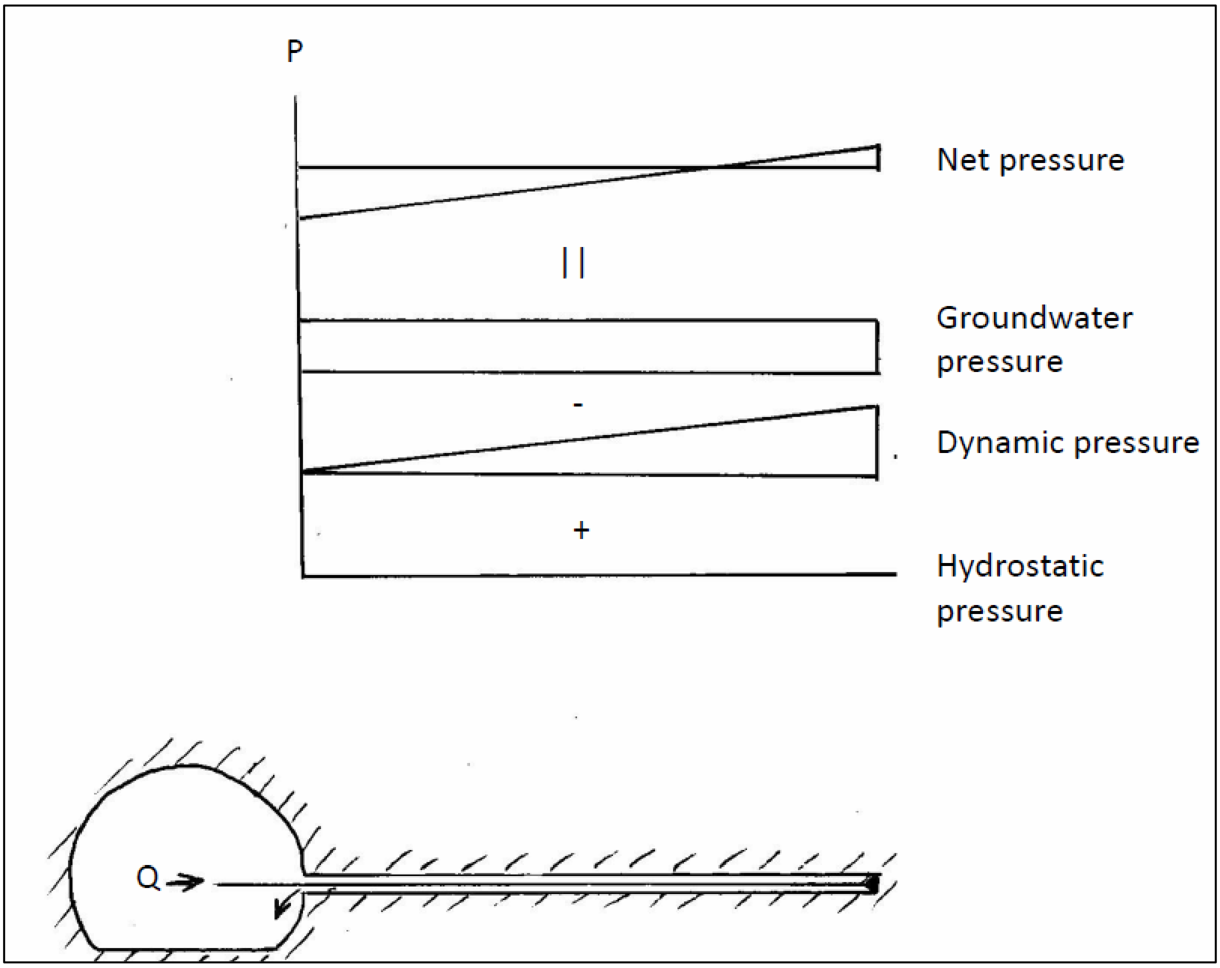

Figure 1. Pressure distribution around a borehole being drilled from an underground opening.

The pressure distribution in the hole could be better managed by placing some pressure control at the hole collar. This would permit the pressure to be raised. This would avoid groundwater inflow near the collar but would raise the total pressure while drilling in the deeper zones of the hole. Whether this is a problem or not depends on the circumstances.

The oilfield has coined the term Managed Pressure Drilling (MPD) in its approach to the problem. Frink (Ref 2) describes MPD as "*an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly".* This definition also precisely fits needs in drilling from underground for tunnelling or other purposes such as mining.

The essence of managed pressure drilling is to ensure that the drilling fluid pressure within the drill hole, (air or drilling mud), is constrained within a pressure range that will minimise inflow to the borehole with possible soil piping, and at the same time avoid excessive fluid loss into the ground. Provided pressures are maintained below the level that may cause hydrofracture, the latter may be prevented by the use of drilling muds which form a filter cake on the borehole wall.

The concept of over or underbalanced drilling is shown graphically in Figure 2.

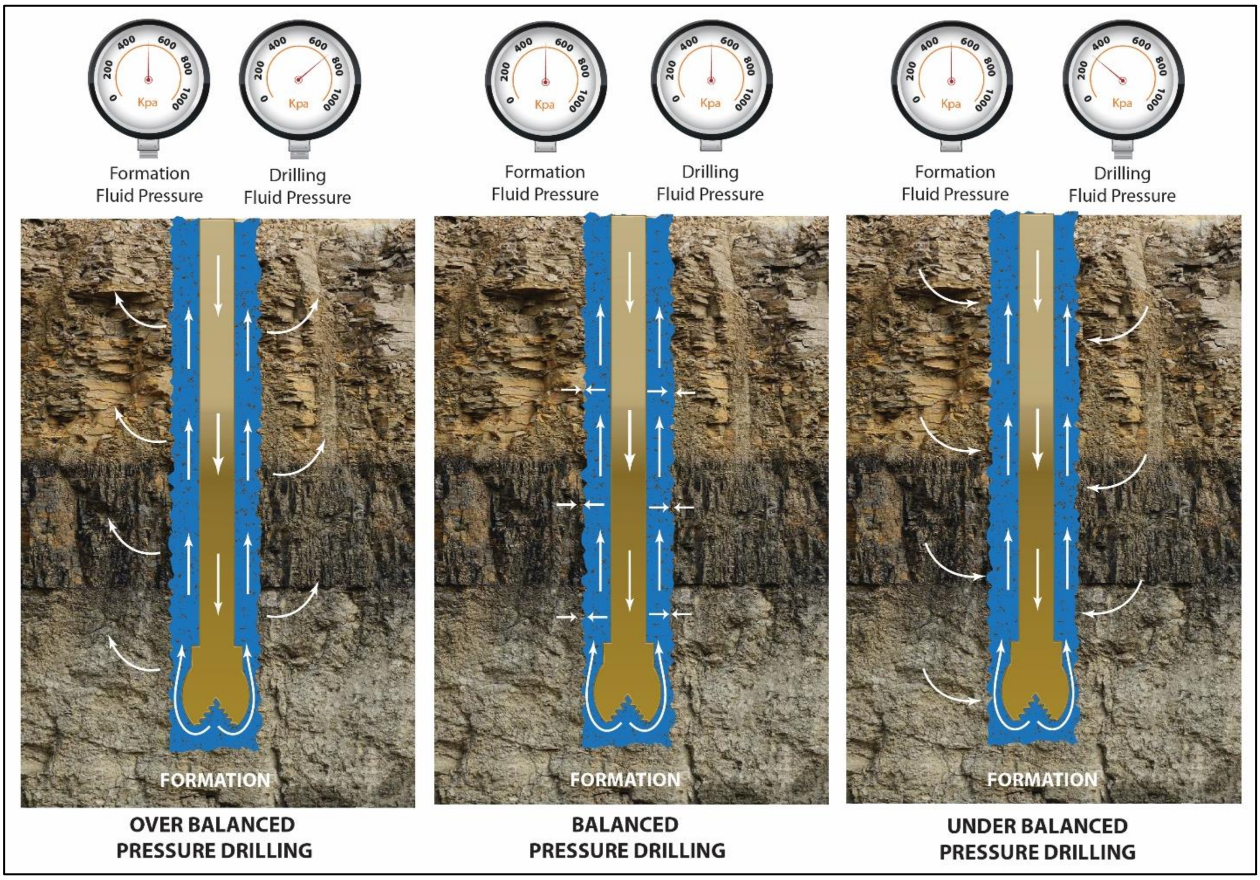

Figure 2. The concept of overbalanced, balanced and underbalanced drilling.

2. LIANG TANG TUNNEL CASE STUDY

Sigra was requested to build a MPD system for use by VSL-Intrafor in the Liang Tang tunnel project in Hong Kong. This project involves two large tunnels created by mixed ground TBM, and mined through volcanic rock, some of which was totally decomposed to form soil. These tunnels needed to be connected by cross passages. To create the cross passages through the decomposed volcanic rock (granular soil with some clay minerals) some form of ground stabilisation was required. The stabilisation process was planned to be by drilling a series of boreholes through the concrete tunnel lining segments left by the tunnel boring machine and then grouting the holes. This was achieved using a tube-a-manchette staged grouting system. Once stabilisation had been achieved the cross passages were to be excavated. Ground freezing could have also been used to achieve stabilisation.

The MPD equipment used was put together in short time and was based upon surface well control equipment built for the coal seam gas and gas industries. This had in turn been developed from equipment developed in 1994 (Ref 3) to drill from underground in coal mines into gassy coal seams.

3. THE EQUIPMENT

The equipment used had to be small so that it and the drill would fit into the tunnel which was still being excavated by the TBM machine. Sigra was given 0.8 m length in which to fit the seal component of its MPD system. The installation involved drilling into the 0.5 m thick segmented tunnel lining left by the TBM and using an epoxy resin to set a section of HWT casing in place. On to this was screwed a flange. Bolted to this flange was a knife valve and blow out preventer (BOP) element. Behind this came a lip seal.

Between the knife valve and the BOP was an outlet that took all mud and cuttings to a choke. This comprised an energised elastomeric element that only opened to permit cuttings flow when the pressure reached a certain level. However once this pressure was reached the choke opened very rapidly, allowing cuttings up to 40 mm diameter to pass through it while maintaining a constant pressure behind. When the pressure dropped below the pre-set pressure the choke simply shut to prevent flow from the hole.

The annular blow out preventer (BOP) was an annular elastomeric element that could be closed on the drill pipe in the event that the lip seal wore excessively. It was closed by releasing hydraulic fluid, held under pressure in an accumulator, on to the outside of the BOP element. The lip seal was a very much larger version of a typical hydraulic seal. It was designed to pass drill rods and to permit drilling with these. A non-return valve was fitted behind the bit to prevent backflow through the bit into the drill pipe.

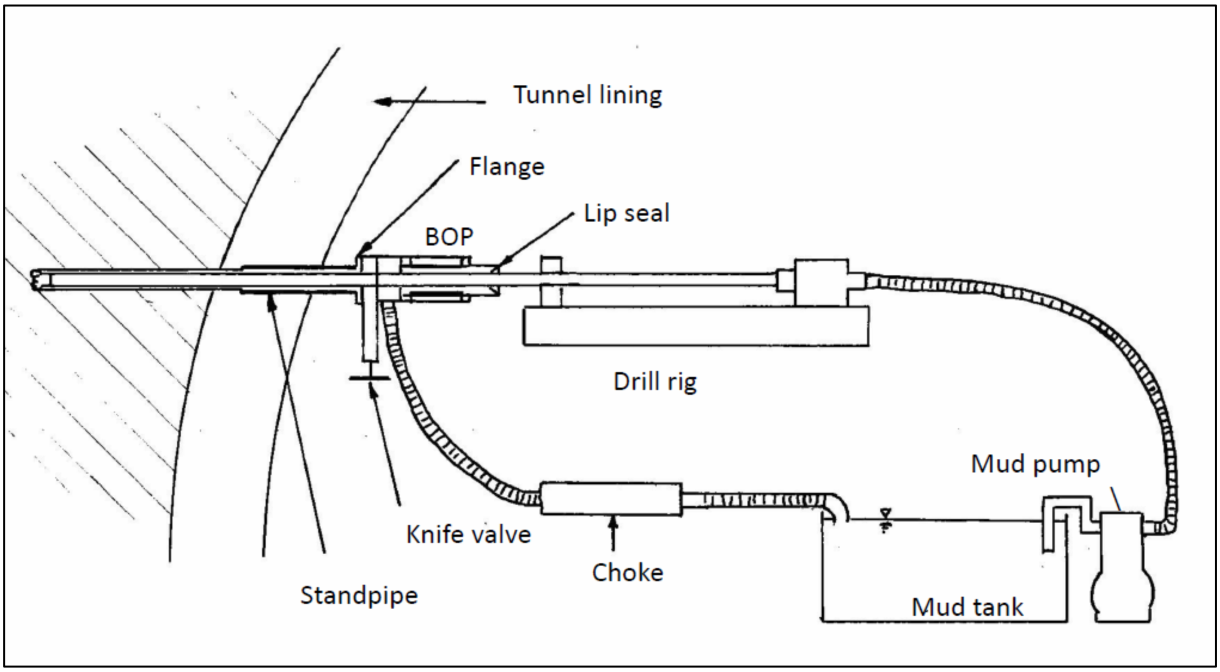

Figure 3. Schematic layout of drilling equipment used in the Liang Tang tunnels.

The entire two sets of equipment were built from bits and pieces of existing BOP's and newly designed and manufactured parts, in three weeks.

4. THE OPERATION

The operation involved attaching the seal unit to the casing with the choke attached. A tricone bit, non-return valve and drill rods (76 mm diameter) were then used to drill out the remainder of the concrete lining segment. Drilling continued into the ground while maintaining constant pressure within the hole equivalent to the hydrostatic head to surface (15 to 20 m). This worked extremely well. The holes were only of 20 to 30 m length and were easily drilled. During the drilling process only minor wear of the lip seals occurred and the BOP was not really required.

The holes were then cement grouted through the drill pipe at a pressure that was sufficient to cause some soil displacement and penetration by grout. The drill pipe was then withdrawn far enough that the knife valve could be closed, shutting in the borehole. Once this had been achieved the drill pipe was removed.

After this the difficult part of the process started. In this case it involved the insertion of tube-a-manchette through a reduced diameter lip seal into pressurised cement grout. This required significant force both to overcome the grout pressure and to overcome friction within the hole and the grout. Complicating the process further was the wish of the operator to use centralisers on the tube-a-manchettes, as these enabled grout leakage during insertion through the lip seals.

Two lip seals would have prevented this grout loss problem. However lip seals were generally not satisfactory for use with the tube-a-manchettes. The reason for this was not only the centralisers but also the fact that these units had externally upset rubber valves over the PVC pipe. It was practically impossible to withdraw these through the energised lip seals. The result was that if the tube-a-manchette could not be pushed up the hole because of some obstruction it could not be withdrawn either. This required it to be subsequently drilled out after the grout had set and replaced. This was a time consuming operation that could have been avoided by adequate total system design.

Figure 4. Drilling through a seal in a Liang Tang tunnel.

5. CONCLUSIONS

The managed pressure drilling system used at Liang Tang worked. It was quite possible to use the managed pressure drilling system developed for the job to maintain a constant pressure at a borehole collar during the drilling operation. The static lip seals were adequate for operation on drill rods and the elastomeric choke worked perfectly. Where the total system ran into problems was with trying to get tube-a-manchettes of varying diameter through the lip seals and into the hole. If these had been of constant diameter, as originally envisaged, then the whole process would have proceeded more smoothly.

In the event that irregular diameter devices have to pass through seals into the hole then a dual seal arrangement should be used. The seals would preferably be of a type that could be energised separately from borehole pressure, not lip seals. One option is inflatable seals that open and close internally using air or water pressure for their operation. In this event they could also be used to grasp and push the tubular item up the borehole. This is quite a feasible option though one that would have required more than three weeks to design and build.

Another addition that would have assisted the operation is one where pumping into the hole is stopped automatically when outflow from the hole ceases during drilling. This would prevent fluid loss and the consequences of hydrofracture or liquefaction occurring. This feature is fairly straightforward to implement.

An alternative proprietary system to that used is a complete pressurised circuit including a pressurised mud tank. This has little advantage other than saving the need to re-pressurise drilling fluid. Another option to the choke is to use a surge pipe to surface to maintain pressure. This is likely to be a far more expensive option than the chokes that were successfully used at Liang Tang.

While the MPD systems supplied for the Liang Tang operation were only designed for operation to 300 kPa, Sigra has manufactured systems designed for up to 7 MPa use.

6. REFERENCES

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