# EPB excavation of less than five meters below the historic structure of Chandpole Gate on the Jaipur Metro Project

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ABSTRACT: The tunnels excavated by Continental Engineering Corporation (CEC) for the underground section of the Jaipur Metro project faced the usual challenges posed by metro projects worldwide, including small site footprints, and the associated problems regarding segment and muck storage space, etc. These challenges were, however, relatively straightforward when compared to the challenges faced by the tunneling operations. The Earth Pressure Balance (EPB) TBMs were required to bore under extremely low overburden, alongside and beneath several culturally sensitive historic structures. The age of these structures and their construction methods/materials were of great concern when considering the possible consequences of tunneling-induced ground settlement and vibrations. This paper will describe the measures taken regarding TBM operations and surface monitoring to ensure that these historic structures suffered no adverse effects due to tunneling.

## 1 INTRODUCTION

Jaipur, also known as ‘The Pink City”, is the capital of the Indian state of Rajasthan and has a population of just over three million people. It has almost one million registered motor vehicles, of which approximately 70% are motorcycles and an estimated 2.7 million vehicular trips are generated daily (Jaipur Metro Environmental Impact Assessment, 2013). In order to alleviate the city’s chronic traffic congestion a metro rail system is under construction and part of this system is an underground section of 1,800 m of twin tube tunnels driven by Earth Pressure Balance (EPB) TBMs. The tunnels pass in close proximity to five structures with historic and cultural significance including the Jantar Mantar observatory, which is listed as a UNESCO world heritage site. The most critical structure relating to tunneling was Chandpole Gate, which the TBMs passed directly beneath.

## 2 GEOLOGY

The alignment of the tunnels traversed geology that can be generally divided into two types. The first type is composed of a mixture of silty sands and the second type of silty sands with minor quantities of clay and gravels. Based on the observed N values, which are greater than or equal to N=41, the strata can be described as relatively dense. Each soil type is either dominated by fine sands or a fairly equal mixture of silt and sand. The geology containing clay is still dominated by the sands and silts, with less than 10% clay content. The complete length of the underground section of the project is above the water table so there were no concerns regarding ground deterioration or running sand due to water ingress. Due to the low moisture content of the soil it was considered to be non-plastic.

## 3 TBM SELECTION

CEC were already in possession of two Robbins 6.65 m EPB machines and Back-up Systems that had previously been utilized on the Delhi Metro BC-16 project, so a decision was taken to refurbish and modify these machines for the Jaipur project.

### 3.1 *Cutterhead*

There are two main theories on how best to deal with the type of geology and low overburden faced on the Jaipur Metro project when utilizing an EPB type TBM. The first of these theories is based on controlling the amount of excavated material by restricting the opening ratio of the TBM cutterhead, which in effect relies heavily on utilizing the TBM cutterhead as a major component in supporting the ground ahead of the tunnel face. The second main theory is based on the TBM cutterhead having a greater opening ratio. This allows a much less restricted flow of muck through the TBM cutterhead, which enables the plenum bulkhead to interact directly with the tunnel face via the medium of the excavated material. After discussions between CEC and The Robbins Company it was decided that the latter option was the most appropriate choice considering the geological conditions and low overburden; hence, an open spoke-type cutterhead with an opening ratio of 60% would be utilized.

### 3.2 *Articulation*

The alignment of the underground section coupled with the location of the launch shaft dictated that the TBMs were required to negotiate a 430 meter radius curve during the actual launch phase (see figure 1, appendix). A curve radius of 430 m is not considered to be excessive but, bearing in mind it was to be negotiated as the machines were launched and the contractor required the TBMs be upgraded with the latest technology, it was decided to install active articulation on both machines.

The original design of the machines did not include any form of articulation hence the modification involved cutting the main shield circumferentially. An additional ring was then installed to facilitate mountings for articulation cylinders and to form an articulation joint and articulation seal housings (see figure 2).

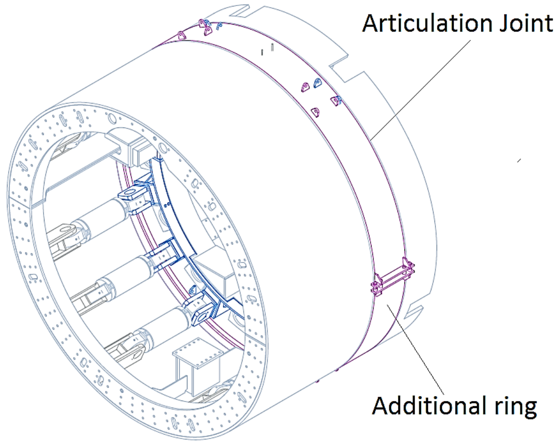


Figure 2. Articulation modification

The main advantage of active articulation over passive articulation is that TBM steering is far easier with active articulation. This is because the steering forces acting through the articulation are approximately 70-80% of the total thrust force applied by the main thrust cylinders, whereas passive articulation only enables around 50% of the thrust force for steering. Active articulation also distributes the TBM thrust forces evenly around the circumference of the segmental lining, whereas passive articulation produces uneven thrust forces and hence is more likely to cause damage to the segments.

The final specification of the refurbished machines is shown below.

- Spoke-type cutterhead equipped with soft ground tools; opening ratio of 60%
- Excavation diameter: 6550 mm
- Maximum cutterhead torque: 5,148 kNm
- Exceptional cutterhead torque: 6,178 kNm
- Number of thrust cylinders: 16
- Thrust cylinder stroke: 1750 mm
- Maximum operating main thrust: 32,000 kN
- Active articulation

- Number of articulation cylinders: 12
- Articulation cylinder stroke: 250 mm
- Maximum articulation thrust: 32,000 kN
- Screw conveyor internal diameter: 900 mm

## 4 CHANDPOLE GATE

In general terms, it was not anticipated that the geology in itself would cause any major problems to the TBM tunneling operations. However, the geological conditions coupled with the extremely low overburden in the area of the launch shaft (especially the section passing beneath Chandpole gate) was cause for major concern. Chandpole gate was built along with the city walls in 1727 when the city was founded by Maharaja Jai Singh II. It is one of the seven original gates and leads directly onto Tripolia Bazar Road, which is the main arterial road in the walled city (see Figure 3). The construction materials of the walls and gate consist of irregularly-sized pieces of stone cemented together with lime mortar and faced with a sand and lime mortar render. The foundations consist of irregular sized stone blocks that provide little or no resistance to tunneling-induced settlement. Contractually the allowable limit for surface settlement was set at 4 mm. To make life more interesting for all concerned with the task of boring beneath the gate, the following archeological law is also in place: *"whoever destroys, injures, mutilates, defaces, alters, removes, disperses, misuses, imperils or allows to fall into decay a protected monument, or removes from a protected monument any sculpture, carving image, bas-relief, inscription or other like object, shall be punishable with imprisonment for a term which may extend to six months with a fine which may extend to five thousand rupees or with both*"(Rajasthan monuments archeological sites and antiquities act, 1961).

Figure 3. Chandpole gate

The overburden between the design level of the crown of the tunnel excavation and the road surface at the Chandpole gate section is only 7.0 m (see Figure 4, appendix). In order to ascertain the size and depth of the gates foundations a total of eleven trial pits were excavated both alongside and inside the structure. The trial pits revealed that the foundations on each side of the main gate archway extended to a depth of 2.4 meters. As these sections are located directly above the centerline of each tunnel the distance between the underside of the foundations and the crown of the excavation is only 4.6 meters. Inspection of the foundations in the vicinity of the trial pits identified that the lime mortar joints between the foundation stones were in extremely poor condition and could be crushed by hand, and also that the joints were riddled with cavities and rat holes.

### 4.1 *Mitigation Measures*

Several options were considered regarding ground consolidation by pre-injection, both beneath the gate and throughout the zone of influence either side of the gate. However, concerns were raised that injection operations may in fact disturb the dense silty sand, resulting in a reduction of its structural integrity rather than improving its properties. Finally, it was decided to restrict treatment operations to sealing and filling of the voids and cavities in the stone foundations of the gate. This was achieved by injection of OPC grout pumped under low pressure.

Control of surface settlement and vibrations would now be the main mitigation measure in preventing damage to the gate. This would be achieved by undertaking a strict regime of surface monitoring, the results of which would then be conveyed directly to the TBM operator's cabin to enable decisions to be made on the necessary adjustments to the TBM operating parameters.

### 4.2 *Monitoring System*

A traditional manual surveying system consisting of a comprehensive array of surface datum points was installed above the alignment of both tunnels. The frequency of the surface monitoring points varied but leading up to and past the gate's zone of influence up to 4 points were installed per meter of alignment for each tunnel. An automatic system consisting of 12 prisms installed on each side of the gates structure, vibration monitors, and 8 borehole extensometers gave constant readings that were evaluated and recorded via a computerized control station. Existing cracks in the structure were monitored via traditional glass strips and crack meters.

## 5 INITIAL DRIVE

In addition to carrying out the TBM refurbishment and modifications The Robbins Company provided a team of key personnel including TBM operators to supervise the boring operations until both machines had passed beneath Chandpole gate and beyond the zone of influence.

Due to the restricted site footprint, the size of the launch shaft dimensions would only facilitate a short startup procedure. This involved the TBM backup gantries being placed on the surface adjacent to the shaft and the TBM operating via umbilical cables. The plan for each TBM was to bore 85 m by this methodology and cease boring 10 m from the zone of influence, which was a total of 20 m from Chandpole gate. The 85 m of boring facilitated the installation of all back-up gantries, hence the TBM would be fully functional prior to boring beneath the gate. It also allowed room for installation of a rail switch in the tunnel portal area.

TBM I was launched in April 2015 and almost immediately the cutterhead became jammed. Upon investigation, it was discovered that sections of concrete piles that had been installed behind the shaft wall, above the alignment of the tunnel to provide ground stabilization, had broken off and become lodged in the cutterhead. The only option available for resolving this issue was to excavate the area behind the shaft wall and remove the concrete piles. This operation was carried out, the piles were removed, the excavation was backfilled and consolidated and the TBM launch was then continued. It soon became apparent that the machine exhibited a strong tendency to rise above the design level of the tunnel due to reduced resistance in the backfilled material in the upper section of the face. This problem was exacerbated by the fact that the temporary rings used for the launch consisted of half rings rather than whole rings.

This is a common practice in shafts with limited space as it provides additional access for lifting and lowering of muck cars and segments; however, this meant that the traditional methodology of increasing thrust force on the upper quadrant of thrust cylinders to steer the machine in a downwards direction could not be fully utilized. By the time the whole of the TBM had passed through the tunnel eye the machine was 240 mm above design alignment. It was also left of center due to the majority of steering efforts having been concentrated on preventing the machine from rising. At this point, additional longitudinal supports were installed between the first permanent ring and the reaction frame (see Figure 5).


Figure 5. Temporary rings

Installation of the additional supports made it possible to substantially increase the thrust force in the upper quadrant of thrust cylinders and as the machine was now fully launched the articulation could now also be fully utilized. The TBM steering become far more responsive; however, the average gradient of the machine over the following five rings (6.0 m) of boring was -1.28%, whereas the design gradient of the tunnel was -1.77%, hence the machine was in relative terms still rising above the alignment (see Figure 6, appendix).

The TBM articulation during the boring of the initial 5 rings was extended only in the left-hand upper quadrant as shown in Table 1. During the boring of rings No. 6 & 7 the extension of the articulation cylinders was gradually increased up to a vertical differential of approximately -30 mm and an average horizontal differential of - 9 mm. (see Table 1). The TBM responded almost immediately and its downward gradient increased to an average of - 3.54% between Rings 6 to 10.

Table 1. TBM Articulation Differentials

| Ring # 5 | | Ring # 6 | | Ring # 7 | |
|---|---|---|---|---|---|
| 48 | 27 | 48 | 37 | 71 | 61 |
| 27 | 27 | 27 | 22 | 39 | 31 |

The TBM continued boring at this gradient through rings 11 and 12 but after reviewing the design tolerances for the rail track gradient it was discovered that the tunnel gradient was now out of tolerance and that the downward gradient of the TBM needed to be reduced. In order to achieve this the TBM articulation differential was gradually reduced in the upper quadrants and subsequently extended in the lower quadrants until by the completion of ring No. 20 the vertical differential was approximately + 40 mm and the horizontal differential -10 mm. (See Table 2). This had the desired effect, reducing the average gradient of the TBM between rings 10 to 21 to -2.58%. The machine was now running almost parallel to the design gradient.

Table 2. Articulation Differentials

| Ring # 18 | | Ring # 19 | | Ring # 20 | |
|---|---|---|---|---|---|
| 118 | 102 | 111 | 97 | 102 | 92 |
| 155 | 142 | 144 | 133 | 142 | 135 |

During the boring of rings 15 to 27 surface monitoring results indicated that heave of over 100 mm and settlement of up to 50 mm was occurring on the surface above the TBM. Initially the source of the problem was not identified as the monitoring results suggested that the heave was occurring approximately five meters behind the TBM cutterhead rather than in the area directly above the cutterhead as would normally be expected. Also, this section of the tunnel alignment was within the boundary of the launch site compound and passed beneath recent excavations that had been carried out to enable re-routing of surface storm drain culverts and services. Heavy plant including cranes and muck shifting trucks were operating over the same area of ground so it was assumed that the movement of this equipment was causing surface ground movement in the area of the backfilled excavations, which was resulting in erroneous monitoring results. Despite this assumption numerous adjustments were made to boring parameters, including TBM advance rate, EPB pressure and cutterhead RPM in an attempt to minimize the excessive heave.

Once the TBM had passed this area and similar monitoring results were still being recorded it became clear that the heave/ground movement was in fact being caused by the TBM, hence further investigation was carried out. This was in the form of continuous monitoring of the surface directly above the TBM during the boring of the following five rings. The results revealed that the heave was occurring immediately above the articulation joint of the TBM. As stated above, at this point the TBM was being articulated in an upwards plane vertically in order to reduce its gradient and with left lead to maintain the right-hand steering around the curve. After detailed analysis and discussion, it was thought that the most probable cause of the ground disturbance was that the articulation was causing the rear section of the TBM to apply forces against the ground in an upward direction, resulting in the heave (see Figure 7). It is worth noting that the results also showed that the pattern of disturbance was similar to that of the bow wave of a boat wherein the greatest amount of heave was recorded on the inside of the curve and subsequent settlement or troughing was greater on the outside of the curve.

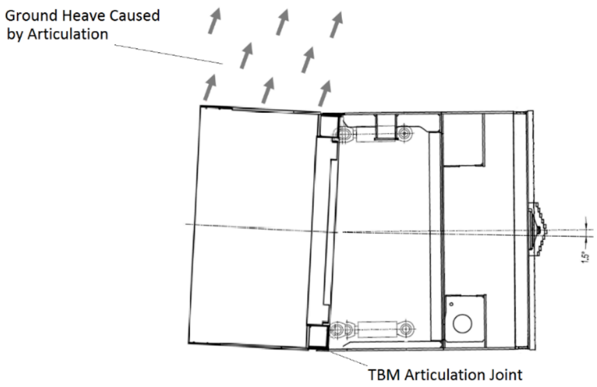


Figure 7. Forces acting on ground due to articulation

To prove this theory the articulation was gradually reduced over the course of the following five rings of boring while continually monitoring surface movement. The results from the monitoring confirmed that as the articulation was reduced the heave on the surface also reduced; however, it became clear that the machine could not be steered effectively without the aid of articulation. The problem now faced was how to steer the machine without utilizing the articulation.

The original methodology for steering the unmodified machines was via the use of copy cutters for over-boring and applying variable thrust forces through the main thrust cylinders. The machines still possessed both capabilities but it had been decided by the contractor that the copy cutters were now redundant due to the addition of the articulation systems; hence, they had been blanked off with steel plates. It was not possible to remove these plates from inside the cutterhead so a small shaft was excavated above the cutterhead, the plates were removed and the copy cutters commissioned.

There now only remained 30 m of boring before the machine stopped to install the backup gantries plus a further 10 m of boring before the machine entered the gate's zone of influence. During this time the operating parameters of the machine had to be refined to the point where boring operations could be carried out while meeting the contractual requirement of no more than 4 mm of surface settlement. The initial 9 m of boring after the restart would not give conclusive results as the whole of the TBM needed to pass through the overbore created by the copy cutters before the effect of the copy cutters would be fully realized.

The TBM was now beneath a busy arterial road, which meant that continuous monitoring of the datum points on the surface could not be carried out. However, due to the short start-up and restricted length of the TBM conveyor only one muck car could be used at a time. Four muck cars were required to complete the excavation of a 1.2 m ring; hence, a regime of monitoring the surface points after every 300 mm of boring was initiated by intermittently holding up traffic. The results of the monitoring were relayed directly to the TBM operator who then adjusted the TBM parameters accordingly. The baseline starting parameters were 1.5 bar of face pressure, cutterhead speed of 1.3 RPM and TBM advance rate of 15mm/minute. The copy cutter was deployed from face positions 10 o' clock to 4 o'clock and set to overcut 50 mm. These parameters were then refined over 30 meters of boring. When the TBM stopped after completion of ring No. 70 to install the gantries the face pressure had been reduced to 1.4 bar, cutterhead speed was 1.2 RPM and TBM advance rate was maintained at 15mm/minute. The copy cutter was being deployed from the 9 o' clock position through to the 5 o' clock position and overcutting 50 mm. Pumping of bentonite through the cutterhead and around the profile of the shields had also been introduced to reduce frictional forces between the TBM shields and ground. The results of the fine tuning of the parameters can be seen in Figure 8. The maximum heave above the machine was 3 mm, and the maximum heave/settlement for the preceding seven rings was restricted to 1 mm.

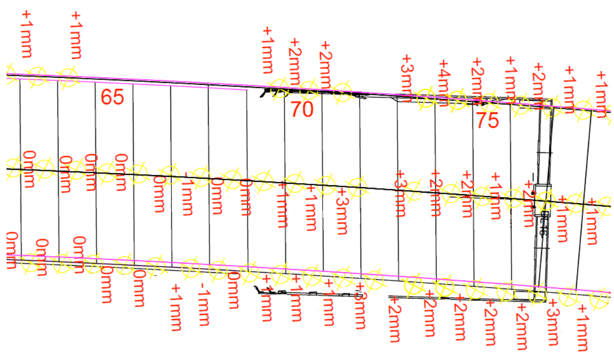


Figure 8. Surface monitoring points

## 5.1 *Boring beneath Chandpole gate*

The key to boring beneath the gate without any adverse effects had always relied on refining the TBM operating parameters before the TBM reached the zone of influence. As this had been achieved, these parameters were maintained after the restart and similar results were achieved up until ring No. 75 where surface heave increased slightly. Due to the increase in heave the EPB pressure was reduced to 1.2 bar and cutterhead speed to 1.1 RPM. These changes reduced the heave to within tolerance. Although vibrations levels were minimal, as the TBM approached the gate the cutterhead speed was further reduced to 1.0 RPM to reduce the risk of damage by vibration. The machine passed beneath the gate and through the zone of influence without incident using these parameters. The maximum recorded settlement in the vicinity of the gate was 2 mm and absolutely no adverse effects were sustained to the gate. The lessons learned on the first drive were applied to the second drive and TBM II also passed beneath the gate with minimal settlement and no damage to the gate.

## 6 CONCLUSIONS

Relying on the latest available technology may not necessarily be the best option for all underground projects. The lessons learned on the Jaipur Metro project showed that active articulation, which is considered to be the most up to date and effective technique for steering a TBM, actually caused excessive ground disturbance due to the extremely low overburden and non-plastic nature of the soil. In this case the older methodology of steering the TBM by means of utilizing copy cutters and differential forces on the main thrust cylinders proved not only to be the most effective, but the only viable option. These points should be considered during TBM selection for future projects with low overburden in non-plastic soils.

## REFERENCES

Jaipur Metro Rail Project, Phase 1B. 2013. *Environmental Impact Assessment.*

Government of Rajasthan, 1961. *Rajasthan monuments archeological sites and antiquities act*.

# APPENDIX

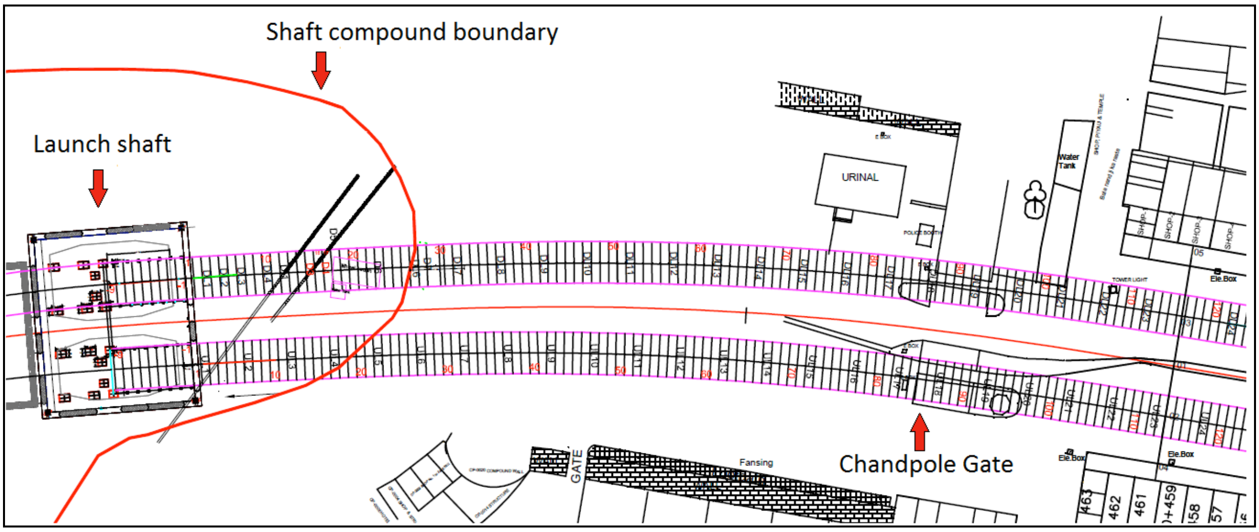


Figure 1. Tunnel alignment to Chandpole gate

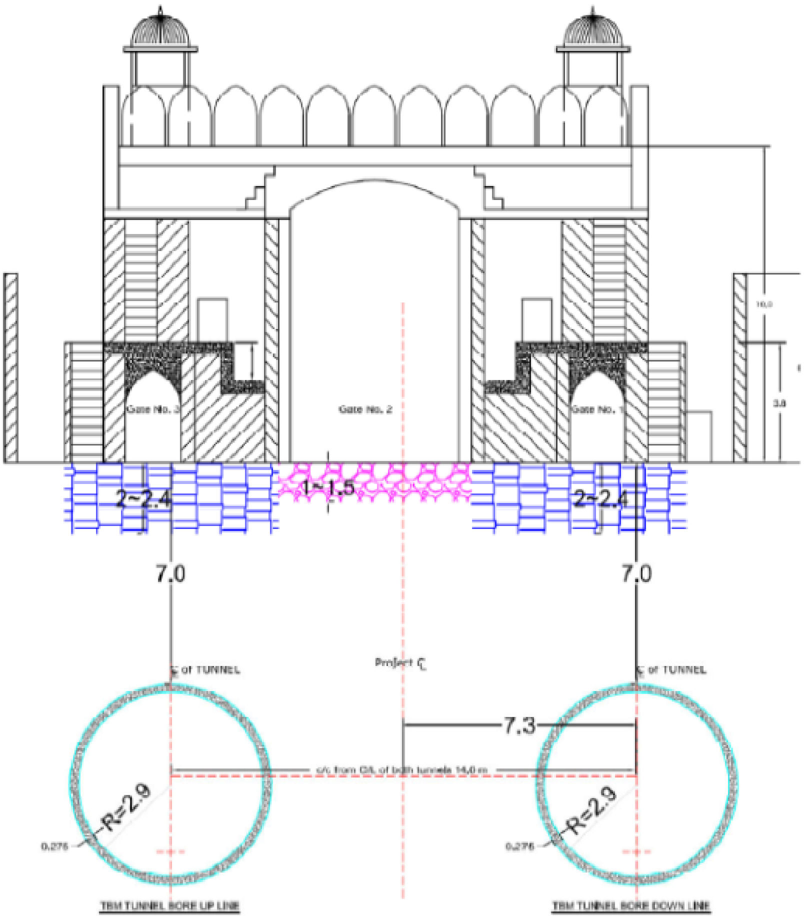


Figure 4. Overburden at Chandpole gate section

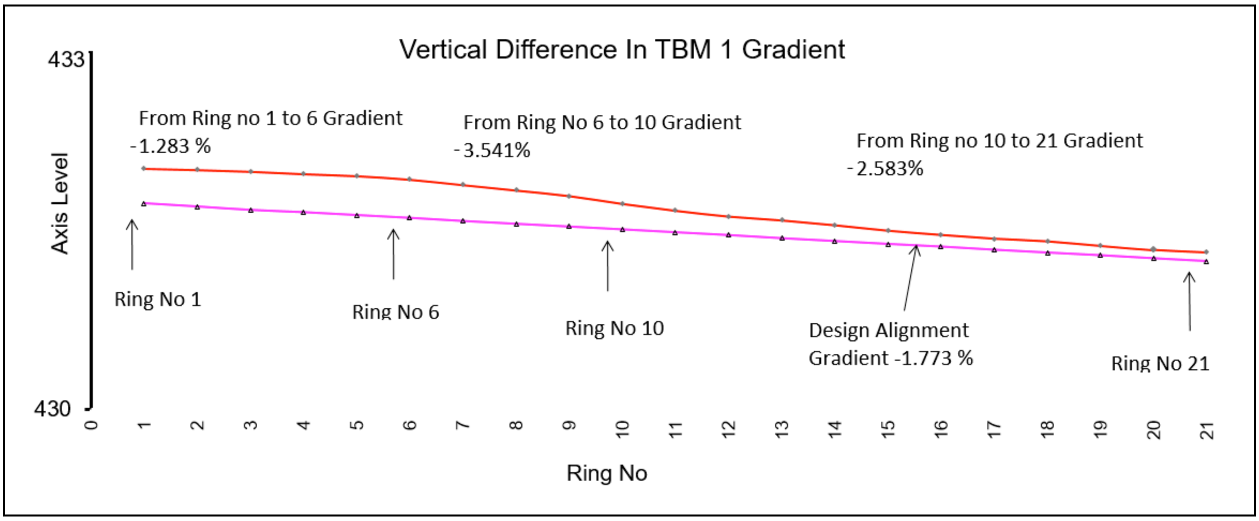


Figure 6. Vertical difference in gradients