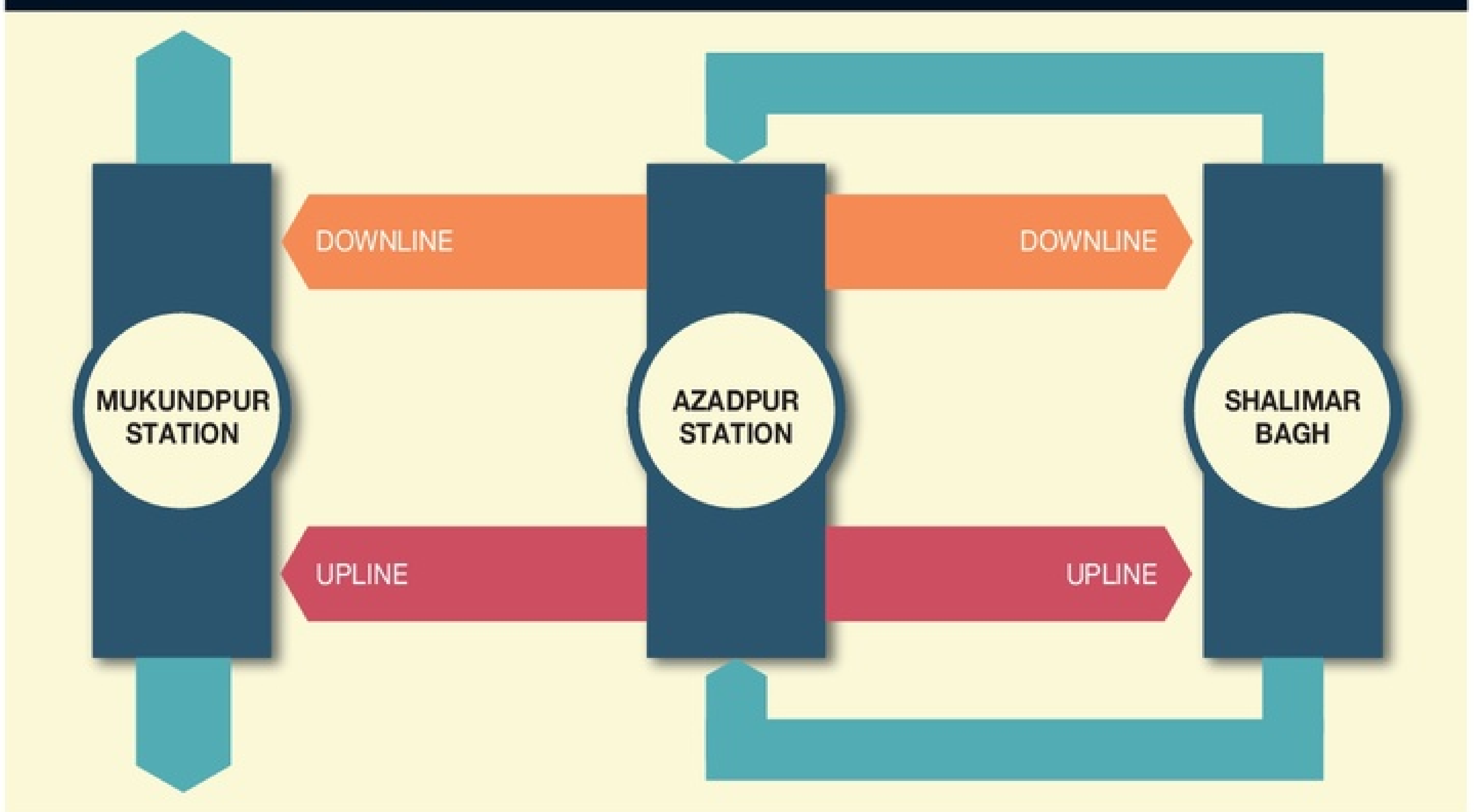
CONDITIONING DELHI METRO PHASE-III

Chris Cooper, Project Leader, CEC-CICI Jv, G.Jagadeswara Rao, Sr.Manager-Survey (TBM),CEC-CICI Jv, and Lars Langmaack, Technical Manager TBM, Normet International Ltd, explore the Soft Ground Tunnelling challenges faced on the Delhi Metro Phase III - CC04 and how the selection of the right soil conditioner and the ratio of mixing were the key factors for success.

CONTRACT CC04 on the Delhi Metro Phase III was constructed between 2013 and 2015 and consisted of a total length of 2602m of twin running tunnels constructed using two 6.56m cut diameter EPBMs. The 1st of the EPBMs was launched from Azadpur Station South Shaft and advanced towards Shalimarbagh Station followed closely by the second EPBM on the twin downline bore. Both machines travelled 1450m each from Azadpur Station to Shalimarbagh Station. After sucessfully breaking through into Shalimarbagh Station they were both dismantled and transported back to Azadpur Station North Shaft where they were deployed to bore the Azadpur to Mukundpur Drives.

Figure 1: TBM sequencing of CC04



Geology and Hydrology

The stratigraphy based on earlier soil investigations divided the subsurface into the following geotechnical units: A top layer of manmade fill, silty clay with small kankar inclusions, poorly graded fine to medium sand, silty sand with traces of clay with small inclusions of kankar, silty clay - again with small kankar inclusions, and silty sand with traces of clay with further kankar inclusions.

The geological setting of the TBM tunnel alignment had been investigated via site surveys in 2011 and 2012. During the 2012 survey, 16 core recovery drillings investigated the stratigraphy of the soils. Additional in-situ test (SPT and Lefranc) and laboratory tests have allowed the geotechnical and hydrogeological parameterisation of the different soil units. For the determination of the soil properties, the following geotechnical laboratory tests were carried out - specific gravity, dry and bulk density, natural moisture content, relative density, void ratio, grain size distribution and Atterberg limits. Furthermore, for determining the geomechanical characteristics (resistance and deformability) the following lab tests were carried out - triaxial tests, direct shear tests and consolidation tests in the soil. The soil description and the range of the geotechnical parameters adopted for the different geotechnical units detected along the TBM tunnel area were all shown in the Geological and Geotechnical Interpretative Report

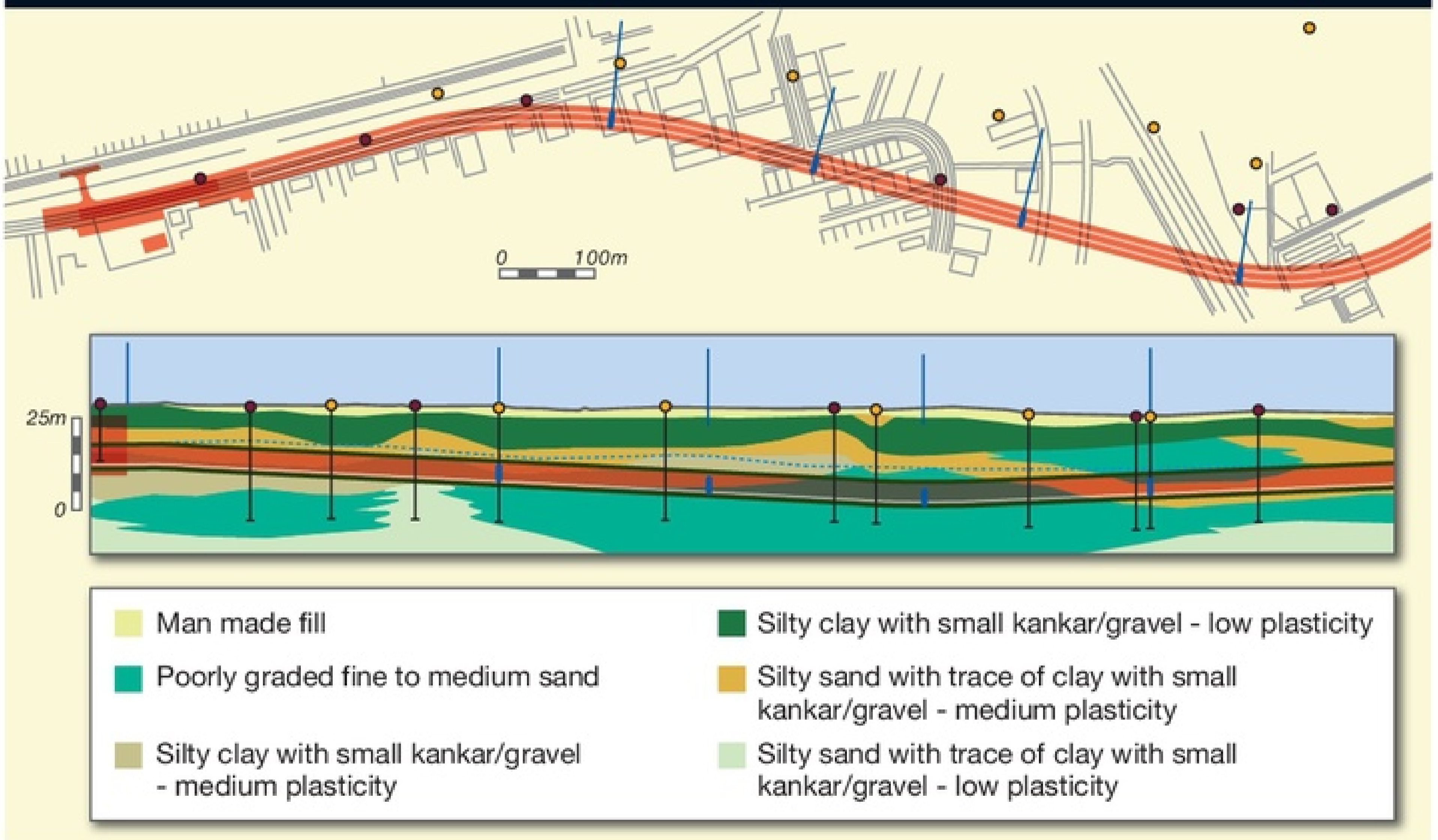
To study the responses of each building in relation to its closest borehole, three zones were established. The final characterization was derived from laboratory and in-situ tests. The boreholes considered for the geotechnical characterization of each zone are shown in Figure 2. A confirmation of the laboratory test results was obtained from SPT in-situ tests which were interpretated using curved strength envelops, as Baligh criterions, and subsequent linearization with Mohr-Coulomb criterion. The Young modulus E was defined on the base of the SPT results.

Challenges from Azadpur to Shalimarbagh

Up until advance (Ring) No.455, the TBM steered well while within the mixed face ground conditions. Advance No. 456 took the machine into the silty sand within a high water table zone. Nobody noticed this change in geology, and the machine started sinking – but thankfully within the limit of tolerances.

The TBM Operators recognised that the

Figure 2: Geological long section of CC04



machine was responding by modifying the thrust pressures applied to the Bottom Group C to 340bar and to 85 pressure to the Top Group A.

Up to advance No.490 (35 rings) the TBM was driven in the same way, with low pressures applied to Top Group A, and high pressures to the Bottom Group B. Still the TBM sunk, finally by 131mm/ring which was now out of the project tolerances.

As the Geological Interpretation Report says, the machine sunk in poorly graded fine to medium sand under a high water table with the top band of stiff clay positioned above the Cutterwheel. Every effort to put the TBM back on track failed.

Finally it was decided to use the copy cutter above the TBM's 9 O' clock to 3 O' clock axis and inject a bentonite slurry to avoid settlement caused by to over excavation.

Figure 3: Grain Size distributions

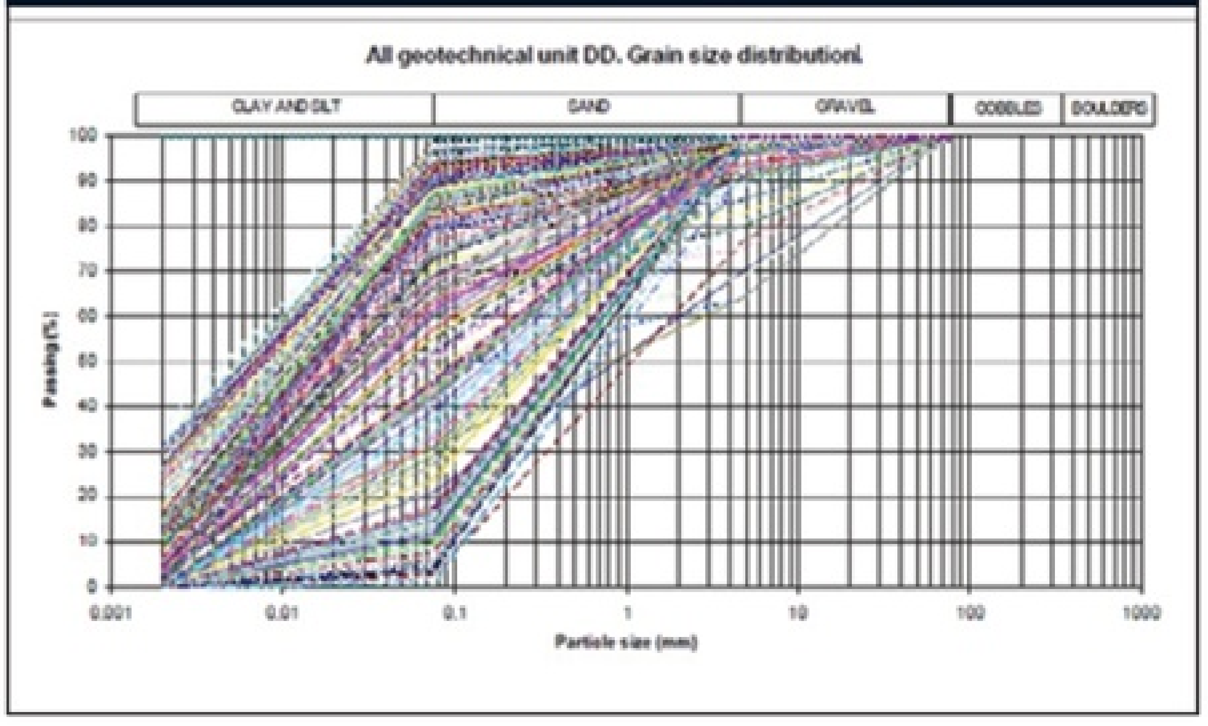


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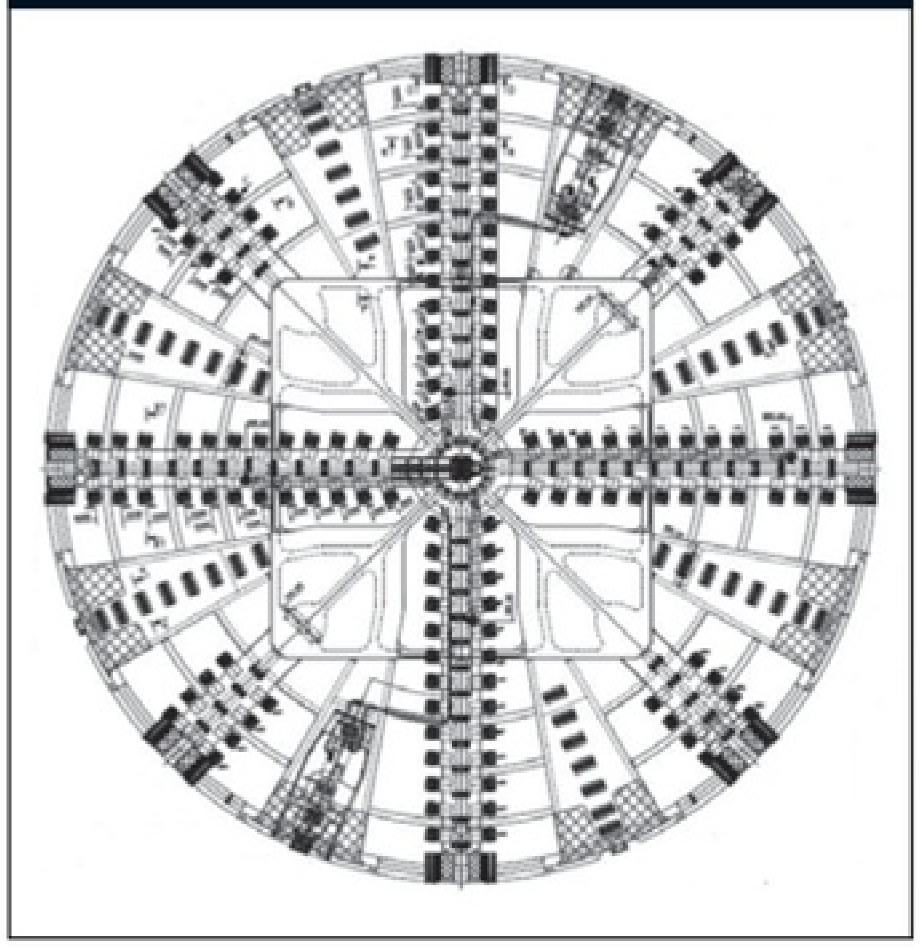
Table 1: TBM Specification

Item	Name	Parameter
Design Condition	Minimum Curve Radius	250m
	Maximum Gradient	3%
	Lining Out Diameter	6.350m
	Lining Inner Diameter	5.900m
	Lining Length	1.200m
	Type	5+1
Main Shield	Total length	8.000m
	Total weight	400Ton
	Excavation diameter	6.560m
	Front shield diameter	6.540m
	Middle shield diameter	6.530m
	Tail skin diameter	6.520m
	Shield thickness	45mm
	Tail clearance	45mm
	Maximum excavation speed	80mm/min
	Main Thrust Cylinders	30
	Thrust force	350bar
	Soil pressure cells	6
Cutter head drive system	Copy cutter	2
	Overcut	75mm
Shield Articulation	Non-Articulated	

Figure 4: TBM cutterhead design

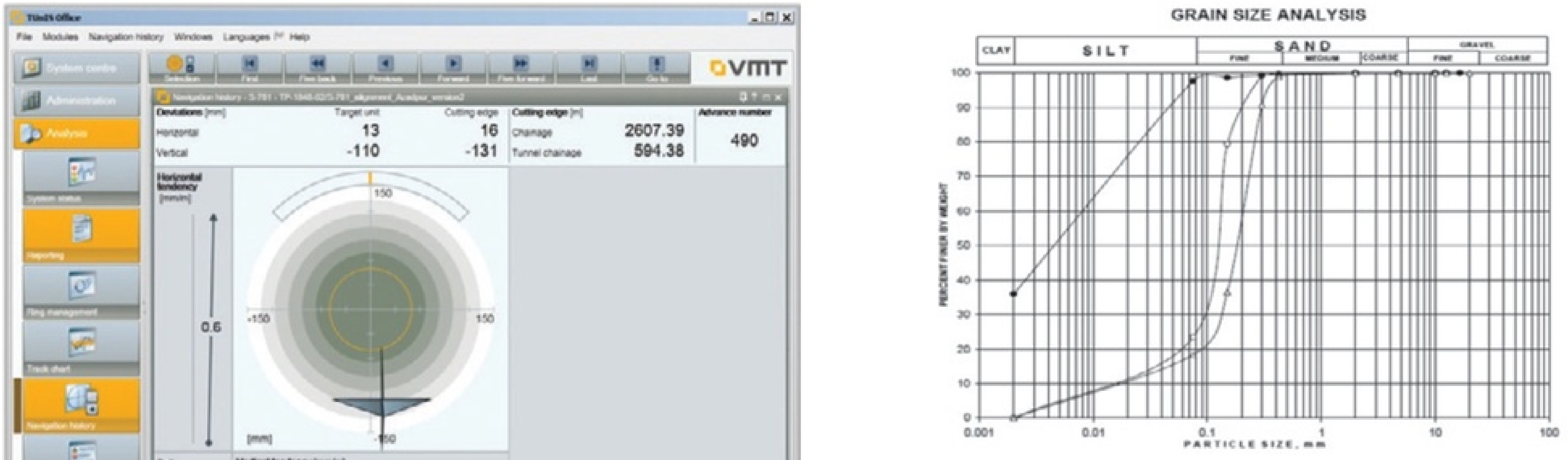


From advance No.491 to advance No. 517, the copy cutter was used above the TBM axis, but still the TBM continued to sink to 648mm below the designed alignment. The magnitude (pitch) of the machine increased from -3 to -4mm (advance No.456 to 490) to -4 to -10.6mm (advance No.491 to advance No.517).

At that point it had become clear that every mechanical method used to get the

Figures 5a and 5b – TBM position at Ring No.455, and 456

Figures 6a and 6b - TBM position at ring No.490 and related geology (grain size distribution of excavated soil)



Symbol	BH No.	Depth, m	Soil Description	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
○	13B	18.00	Silty Sand (SM)	0.00	77.00	23.00	0.00
●	13B	21.00	Silty Clay of high plasticity (CH)	0.00	2.00	62.00	36.00
△	13B	24.00	Silty Sand (SM)	0.00	82.00	18.00	0.00

TBM back on track had failed. Furthermore, the point of no return was dramatically approaching.

The only two remaining options were to:

1. Massively modify and adapt the soil conditioning system, or
2. Stop the TBM and pre-grout respectively to stabilise the running sand in front of the TBM (which would be very costly and time consuming).

The decision was made to try to rectify the situation using an immediate soil conditioning modification.

The soil conditioning system

The soil conditioning system used for the clayey sands was a standard Tunnel-Foam TamSoil 200CF. No clay clogging or adhesion problems had been reported so there was no need to use anti-clay polymers.

The Normet soil conditioning foam TamSoil 200CF is a clear liquid already containing a natural polymer to increase its efficiency and is to be used in silty sand conditions with moderate groundwater pressures.

Figure 7: Tunnelfoam TamSoil 200CF creating foam and reacting with the soil particles

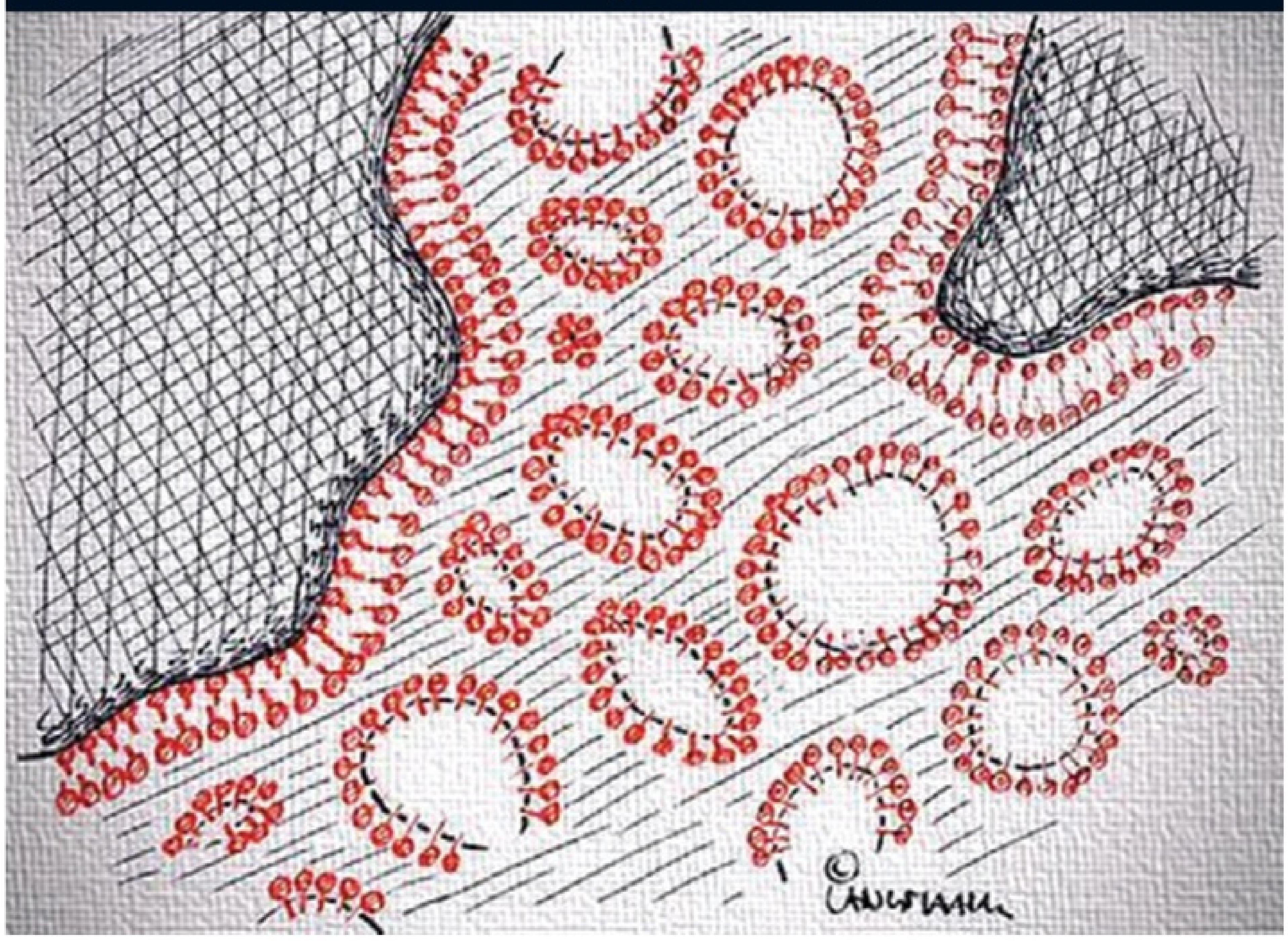
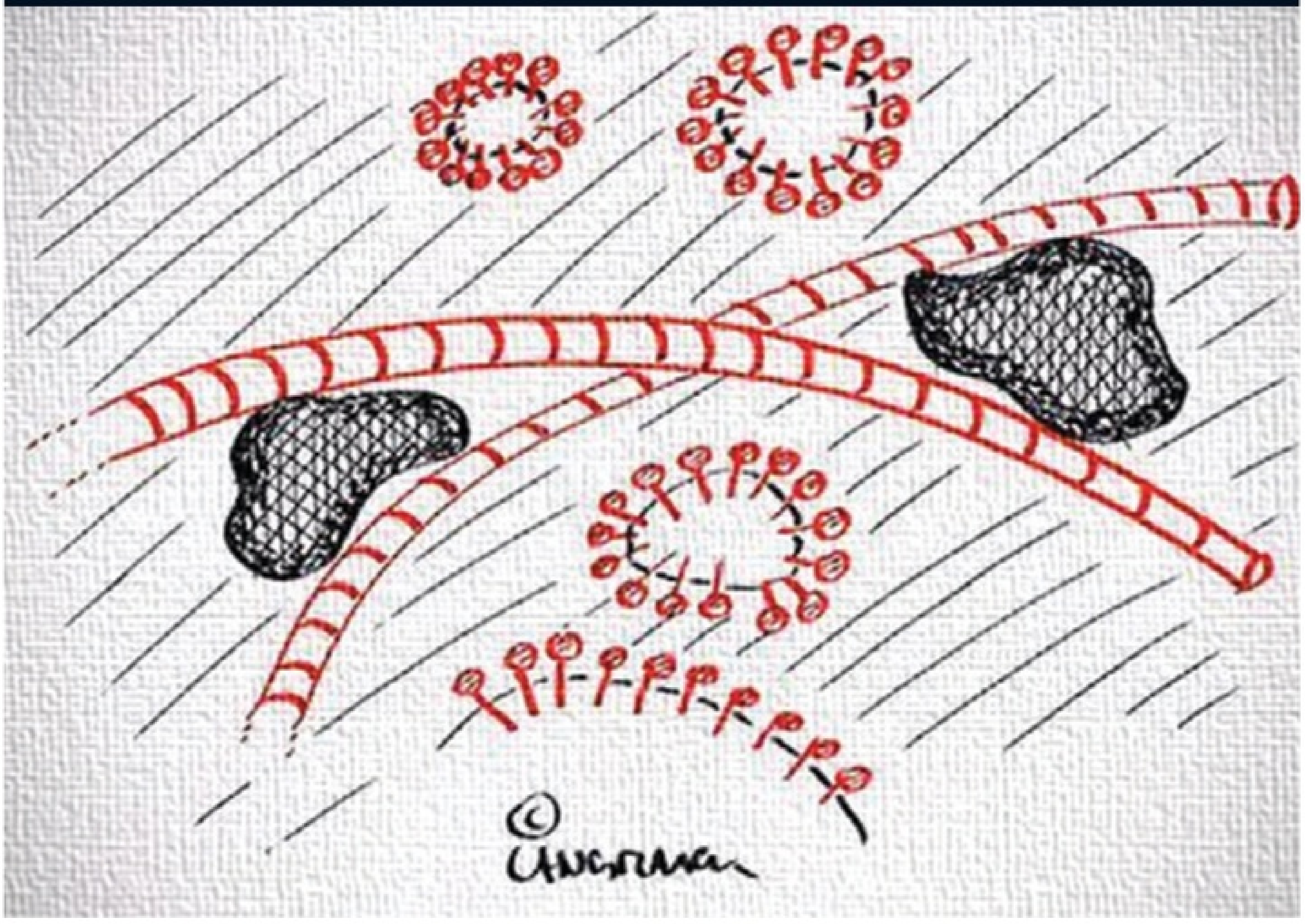


Figure 8: Long chain Polymers interacting with soil particles and excess of water



TamSoil 200CF was used to create a temporary cohesion of the soil as well as to reduce the cutter head torque.

The average consumption reached only 18.2 litres per ring during advance No. 456 to 490, increasing to 25.3 litres per ring from advance No. 490 to 517

When TamSoil 200CF was used in mixed face conditions with running sand up to the shoulder of the machine with stiff clay in the crown - pushing the TBM downwards - the Machine sunk as described above. It was not in control, nor responding to the operational parameters.

The proposed solution was to increase the stability of the running sand by increasing its cohesion. After brainstorming with a dedicated team (contractor and supplier) and finally understanding the behaviour of the ground, it was decided to introduce a long chain Polymer to decrease the water content in the sand and increase its cohesion which should enable the machine to stop the over excavation of the sand and make it respond to standard steering actions. Consequently, the long chain polymer Tamsoil 600CP was chosen to be used together with the soil conditioning foam Tamsoil 200CF.

The basic advantage of the TamSoil 600CP is to increase the links between the sand particles thereby increasing cohesion, and make it less permeable to the groundwater and change the soil behaviour from free flowing to plastic.

Effects of the modified soil conditioning system

Figures 9a and 9b are two pictures of the tunnel muck before using TamSoil 600CP.

Figures 10a and 10b are pictures showing the Tunnel Muck after applying TamSoil 600CP.

Effects of the modified system to TBM steering

On the Azadpur to Shalimar Bagh drive the actions taken during advance No. 517 were:

- Soil conditioning with a polymer/foam Mix with a 80:60 Ratio (concentrations: 2%:1.5%) and injected total volume of 115 litres
- Only used push rams 5-14 until advance No. 526, the injection

Figure 9a and 9b: Running sand through the tail skin (below left), running sand through segment grouthole (below right)

Figure 10a and 10b: The result show drastically improved cohesion

volume of the foam/polymer mixture was increased to 130litres.

Finally, the machine reacted well and the teams managed to get the TBM back under control and the pitch down to -8.0mm/m.

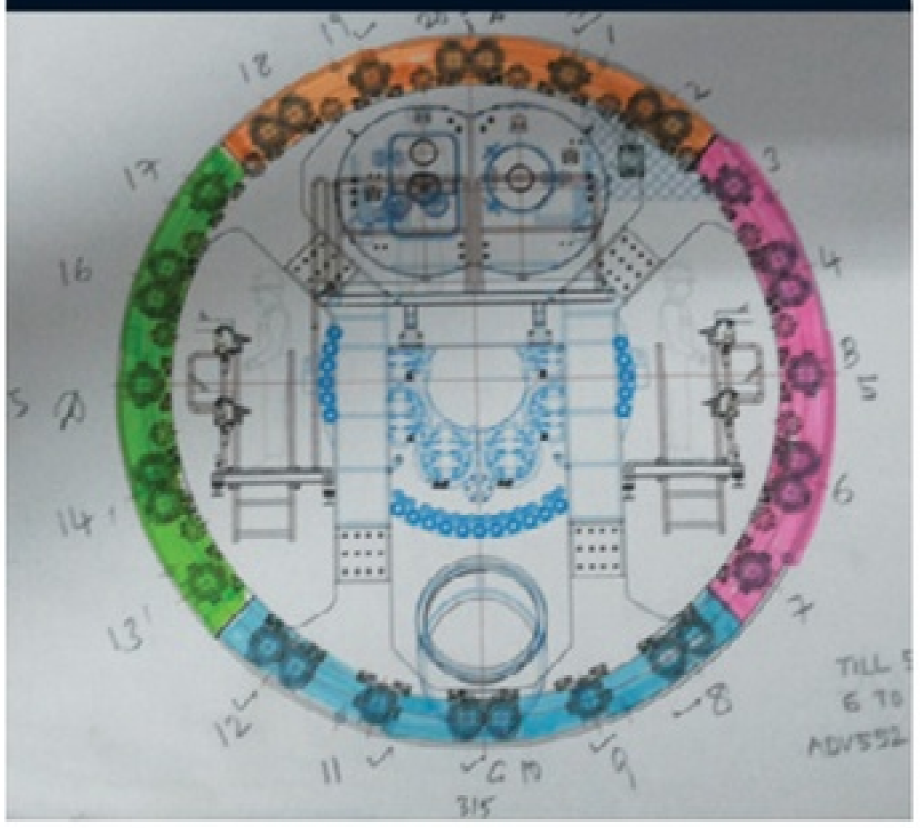
During the following 11 rings (up until advance No.537, chainage 2664) the machine responded positively and finally tilted upwards, reaching a pitch of +0.3mm/m. But, the TBM position was still located 1106mm below the foreseen alignment.

Calculating a maximum allowable tunnel gradient of 3% in order to reach the next planned station, the point of no return for this TBM would have been a level of 2000mm below the planned axis at chainage 2690.

The team realigned the designed tunnel axis in order to meet the original axis.

Finally, the crews managed to bring the machine under complete control within this mixed face geology, and whilst struggling somewhat, finally met the original alignment at advance no.612.

Figure 11: Push ram location



Azadpur to Mukundpur Drive

As experienced and learned on the Azadpur – Shalimarbagh drive through running sand, the teams always kept the TBM 50mm above axis in order to avoid a sudden sinking into the running sand.

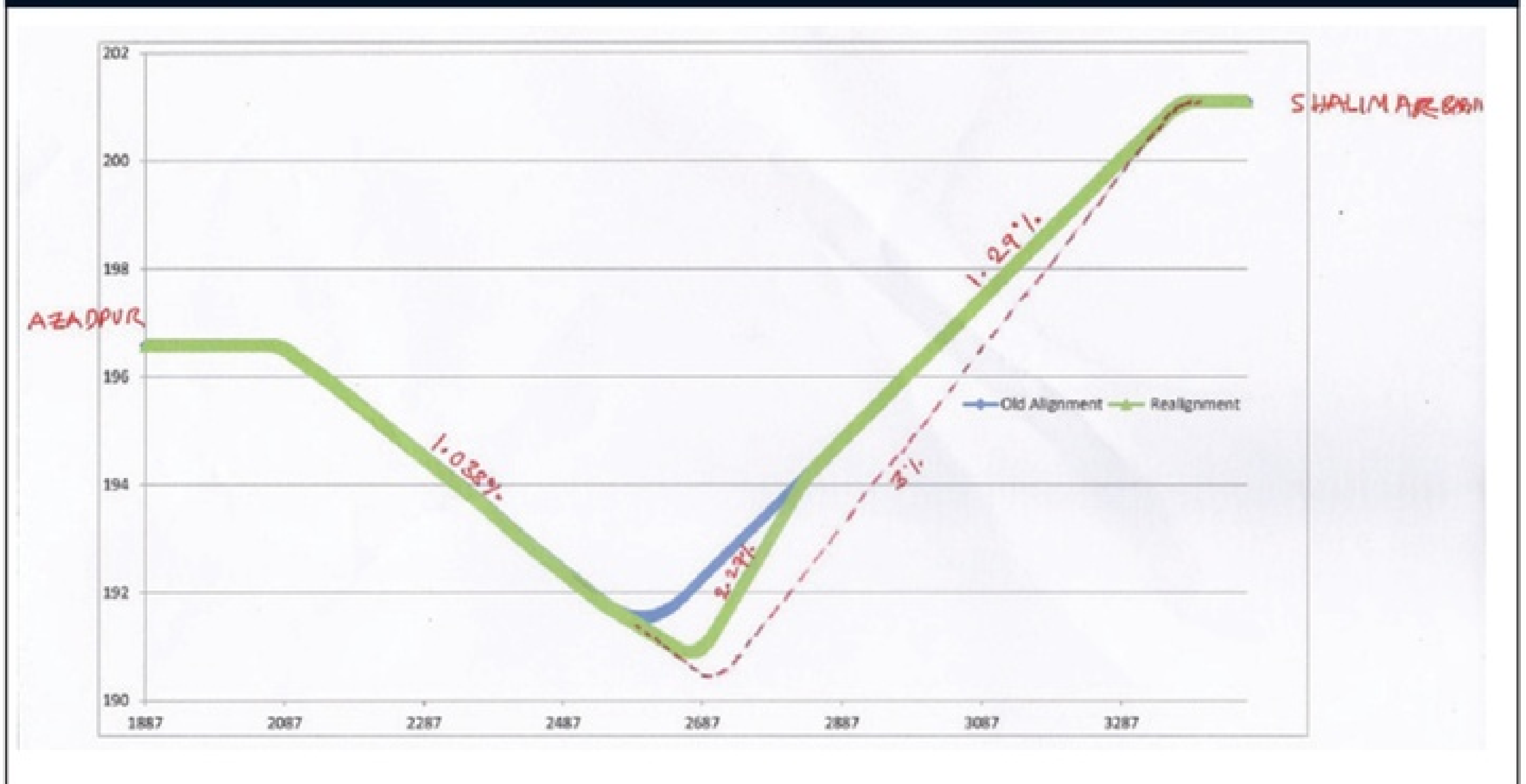
At advance No.357 the TBM was located +50mm above the axis with a pitch of -19mm, on a gradient of 2% and smooth steering - when it was noticed that the machine had started slowly sinking some millimetres per ring, reaching a level +29mm at advance No.384.

The team decided to immediately change the soil conditioning system (using a foam/polymer mixture as before) and reduce the top thrust (by not using top push thrust cylinders no. 16, 18, 20, 2 and 4).

The foam and polymer mix was adapted from a 1:0.7 ratio to a 1:2.2 ratio using trial and error, and finally the machine came back under full control at advance no.409 with a vertical TBM position of +8mm. During this running sand zone the TBM advance speed was less than 20mm/min with a cutterhead RPM of less than 1. The FIR was kept low at 25-30% with an FER of 2-12%.

In the end, the machine was brought back on track at advance no.424 with a position of 40mm above axis and all thrust cylinders once again used for the mining process.

Figure 12: Original alignment, point of no return and final realignment



Conclusion

This paper presents the challenges faced during mixed face soft ground tunnelling to make tunnel engineers aware of the importance of the interaction of the TBM design, the encountered geology as well as the soil conditioning system used.

Apart from correctly defining the TBM design, a well adapted approach to soil conditioning could decide the success or failure of a project. It can definitely save a contractor a lot of money.

It is definitely not sufficient to simply add soil conditioners which may generally work – it is essential to use these readily available conditioners in a way thay allows them to work – combined with employing the correct TBM driving parameters.

Figures 13a and 13b – Back on track at Ring No.424