APPLICATION NOTE

AN-0401 December 2004

INSTRUMENTATION OF UNDERGROUND METRO CORRIDORS

1. Introduction

The mass rapid transit system (MRTS) forms the very backbone of the transportation infrastructure of a bustling metropolitan city anywhere in the world and the underground metro is a vital constituent of (even synonymous to) a MRTS. The benefits of MRTS are many like easing out pressure of vehicular traffic on roads, reduction in air pollution levels caused by automobile emission, quick transit between two points, cheaper and safer travel as compared to moving in a private vehicle etc. All these factors reduce stress on commuters and bring social and environmental benefits to the society at large.

Generally underground metro projects have a comprehensive instrumentation and monitoring program, more so during the construction phases, when there are population, buildings or other structures of interest in the vicinity of the underground construction activities. Instrumentation monitoring in general, is carried out at strategic locations selected along the entire length of the underground metro corridor tunnel alignments and station boxes. Its scope includes: monitoring of the structures under construction together with the ground, buildings and other facilities within the predicted zone of influence.

2. Construction methodology

The underground metro corridor construction work is carried out basically by two methodologies, namely: cut and cover and tunnelling (bored/NATM). The latter method, however expensive than the former, is particularly feasible for the underground track alignments below important buildings and densely populated areas of a city. The bored tunnelling is generally carried out with the help of a shield machine i.e. either tunnel boring machine (TBM) or earth pressure balanced machine (EPBM). The TBM-with a heavy-duty cutter head is deployed for cutting through rocky earth strata and the EPBM is deployed for boring through soft ground. For construction of station boxes, cut and cover method with either top down or bottom-up approach is used. All construction works have to be carried out in a manner, which ensures minimum ground movement.

Early activities in the underground metro project include diverting utilities, establishing traffic diversions where necessary, enclosing the work sites with high hoardings and establishing support facilities such as power generation at the construction sites.

2.1. Cut and cover construction

Construction of underground stations and tunnels in the less congested, open area is done by the cut & cover method. The area near the station is excavated to full depth and the station box is constructed, then it is backfilled. Various earth retaining systems namely diaphragm wall, soldier pile, sheet pile, secant pile and rock bolting are used to support the open cut excavations. The stations are typically built around 15-20 m below the ground level, having a width of 20 m and varying length of 275 m to 300 m (dimensions are typical).

Excavation is done in layers and each layer is supported by steel struts before excavating the next layer. The general method of construction of stations box is "bottom-up" which means the total area of construction is excavated and the slabs are cast from bottom, going upwards. For a few cases where the station are located in a crowded area, “top-down” method is adopted i.e. the top slab is cast first to resume the traffic and construction proceeds from top to bottom with the base slab being cast last.

Station box consist of three levels namely, top slab level, concourse level and platform level, which are connected to each other through stairs and escalators. Concourse level is used for ticketing and other equipment rooms, while platform level caters to rail tracks.

2.1.1. Diaphragm walling

Diaphragm walls (D-walls for short) are structural elements, which are constructed below ground level to prevent the collapse of retained earth due to high lateral pressure induced by nearby structures and self-weight of soil. The permanent stations are constructed using the bottom-up/top down method within the diaphragm walls, which becomes an integral part of the structure.

The slurry trench technique, which was developed in Europe, is generally used for its construction. This technique involved excavating a narrow trench of around 0.8 m width, 6 m long within the guide wall to the required depth, filled with bentonite slurry. The slurry exerts hydraulic pressure against the trench walls and acts as shoring to prevent collapse. Cast in place diaphragm walls are then built in these trenches.

Figure 1: Trenching work for D-wall under progress

Trenching is done using trench cutters, which either have cutting jaws (fig.-1) or have two cutting wheels, which rotate in opposite direction. The muck/cuttings removal is done by mud circulation using the heavy suction mud pump mounted on a frame in between the cutter wheels and sent by pipeline to the bentonite plant. Special attachments are used to cut through rocky strata.

Prefabricated steel reinforcement cage in single unit, fabricated to the required dimension are then placed inside the trench with the help of crane. Threaded bars and couplers are used for the slab connection. In addition to the above, GFRP (glass fibre reinforced plastic) bars are used for the soft eye tunnel entrance locations. These fibre-reinforced bars are used for easy cutting of concrete D-wall by tunnel boring machine. Great care and precision is taken while fabrication, lifting and lowering of these cages due to their fragility.

Two I-stop ends between primary panels and one stop end between secondary panels are used to prevent soil collapse from sides and to have continuity. Concrete is then poured in one continuous operation, through two sets of tremie pipes that extend to the bottom of the trench. The slurry, which is displaced by the concrete, is sent by pipeline to the bentonite plant.

To ensure water tightness between the panels joint water bars were used for the full length of the joint to prevent seepage of water during deep excavation of around 20 m below ground level during construction. When the concrete sets, the I-stop ends were jacked and withdrawn. Similarly, secondary panels were constructed between the primary panels and the process is continued to create a continuous wall.

Figure-2 Soldier pile wall

2.1.2. Soldier pile walling

Soldier piles (fig. 2) are used as temporary support only and are not incorporated into the permanent works. Soldier piles also known as Berlin walls, are constructed of wide flange steel H sections spaced about 2-3 m apart, driven prior to excavation. As the excavation proceeds, horizontal timber sheeting (lagging) is inserted behind the H-pile flanges. The gap behind the lagging and the un-excavated soil is grouted to avoid gaps and the potential for excessive ground movements. The horizontal earth pressures are concentrated on the soldier piles because their relative rigidity compared to the lagging.

2.1.3. Sheet piling

Sheet piling (fig. 3) is used for most shallow temporary excavation support. It is used extensively for support of excavation during construction of station access and egress tunnels.

Figure-3 Sheet pile wall

2.2. Bored tunnel construction

2.2.1. Earth pressure balance tunneling

The earth pressure balance (shield) machine-EPBM in short, with slurry injection is used to drive the tunnels through soft ground. This type of ground along with ground water conditions require its immediate support after each excavation step to stabilize the excavation and control ground movement.

The following parts form the basis of the EPBM:

- Cutter head
- Shield including tail skin
- Cutter head drive
- Erector
- Back-up system

At the Delhi Metro project, India, the cutter head of the Herrenknecht EPBM had a 6460 mm outer diameter. The tunnel lining has an outer diameter of 6260 mm with a grout annulus of 95 mm, which allows a 5 mm over cut to prevent any jamming.

In the above EPBM there were 40 jacks with 2 jacks per jack shoe. The jack shoes are equally spaced at 18 degrees intervals. The maximum thrust force that can be imposed by the jacks was 3960 t. For shield tunnelling in soil, which is not stable, a loss of stability at the working face is prevented by creating a supporting pressure. With the earth pressure shield, in contrast to the other shields which rely on a secondary support medium, the soil loosened by the cutting wheel serves to support the working face.

The shield area in which the cutting wheel rotates is designated as the extraction chamber and is separated from the shield section, which is under atmospheric pressure, by the pressure wall.

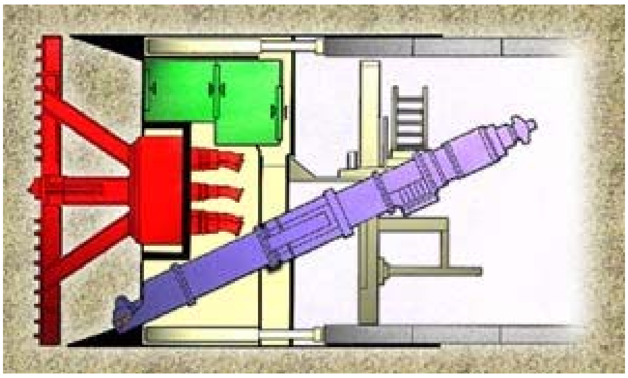


Figure-4 The EPB shield machine (left) and a concrete segment lined bored tunnel

The soil is loosened by the tools of the cutting wheel, drops through the openings in the cutting wheel into the extraction chamber and mixes together with the plastic pulpy soil which is already there. Uncontrolled penetration of the soil from the working face into the extraction chamber is prevented by transferring the power of the tunnelling jacks from the pressure wall to the pulpy soil. At the point when the pulpy soil mixture in the extraction chamber is no longer compressed by the pressure of the earth and water which lies ahead, a state of equilibrium is reached.

The material which has been extracted is removed from the extraction chamber with a screw conveyor. The amount of material conveyed is regulated by the revolutions of the screw and the diameter of the opening of the upper screw valve.

The screw conveyor transfers the extracted material to the first conveyor belt of the conveyor belt cascade. The extracted material reaches the so-called reversing belt via these belts. The transport cars for the extracted material in the backup system in the reversing operation are loaded via this belt.

The tunnel is usually lined with steel reinforced concrete lining segments, which are positioned and fastened by the erector in the shield area behind the pressure wall under atmospheric pressure conditions. The remaining fissure between the outside of the lining segment and the diameter of the excavation cavity is continuously injected with mortar via the injection openings in the tailskin.

For metro tunnelling, which is situated below the ground water table, the following measures are used against water penetration:

- Triple brush seal - this will seal the un-grouted segmental ring from water ingress.
- Pressure bulkhead - the pressure bulkhead in the front shield separates the excavation chamber from the rest of the tunnel. Muck extraction is by means of the screw conveyor that can be safely cut off in the event of water inflow by closing the discharge gate of the screw conveyor.

2.2.2. Rock tunnel boring machine

The rock TBM's cutter head is designed as a "heavy duty steel" construction. Drag bits are mounted on the cutter head to excavate the rock. The maximum possible speed of the cutter head is around 6 rpm.

2.3. NATM tunnelling

In the ‘New Austrian Tunnelling Method’ (or NATM), the tunnel is supported by rapid application of shotcrete to freshly exposed excavated surface. NATM is particularly suitable for weaker grounds. In this method, the inherent strength of the ground is preserved to a great extent to make it almost self-supporting thus requiring much less artificial support in the form of concrete or steel. Basically the excavation of NATM tunnels is performed by top heading-bench-invert excavation and the ring closure is achieved as soon as possible. In general the following construction sequence is followed:

Figure-5: NATM tunnelling

- Excavation of round
- Application of sealing layer at round and face, if required, and / or installation of rock bolts
- Installation of wire mesh with required overlap in circumferential and longitudinal direction
- Installation of lattice girder
- Application of shotcrete according to the designed thickness
- Installation of rock dowels or self drilling dowels according to support scheme

2.4. Construction de-watering

De-watering of the cut and cover sections is essential for ensuring slush free and dry construction zone. It is substantially dictated by the rules laid down by the concerned government statutory body, which stipulates the maximum groundwater drawdown from the existing averaged groundwater level outside of the construction excavations, maximum depression limits inside the construction excavation zones and the maximum settlement limit of adjacent structures owing to dewatering.

The construction-dewatering schemes are usually finalized during the definitive design stage. The schemes are designed for satisfying both the statuary body's requirements and the design pore pressure profile. The design aims at limiting dewatering locations to within the excavation. Maintenance of the maximum drawdown criteria outside of the walls require the use of recharge wells.

3. Role of instrumentation

The purpose of monitoring using geotechnical instrumentation is as follows:

3.1. Safety of buildings and utilities

To provide early warning through regular or continuous monitoring for any excessive and undue ground movements affecting the adjoining premises, structure and utilities like the railways, power lines, water lines etc. within the zone of influence of the excavations or tunnels. This allows for implementation of preventive remedial actions well within time.

3.2. Design verification

To provide settlement, deflection and deformation data for the verification of initial design of the permanent structures and the temporary works supporting the excavation.

3.3. Construction control

To monitor that the parameters such as total settlement, differential settlement, angular distortions, wall lateral movements, earth pressure, strut load, bottom heave etc. are within allowable limits. If exceeded construction methodology might be changed as a remedial measure. Thus monitoring provides confidence in the construction process. Monitoring of ground water level is done confirming that the dewatering drawdown is in accordance with the statutory body's stipulations.

3.4. Performance monitoring and verification

For monitoring the performance and its verification, generally the same instruments as recommended for the verification of design are used. At times some instruments are added for monitoring of the actual dynamic behaviour of various structures but these require specialists for data analysis.

3.5. Long term monitoring for safety (wherever required)

It is essential to periodically monitor condition of the underground structures to ensure its maintenance. The main factors affecting the performance is steel corrosion, degradation of concrete with age, undue settlement and change in the loading pattern due to increase in passenger traffic with time. Sometimes, natural calamities like flood, earthquake or a cyclone may effect the metro sub and superstructures, In all such cases, the instruments installed for design variation and performance monitoring give very important data on the state of the structures. This is reflected in abnormal changes in strain, inclination and displacement values. Another parameter to be closely monitored is crack, if any, that might be formed at any time during the operation of the metro.

4. Typical instrumentation scheme

4.1. Construction instrumentation and monitoring

4.1.1. Instrumentation and monitoring for cut and cover station boxes and shafts

At cut and cover station boxes and shafts, instruments are installed in monitoring arrays (fig.-6 and 7). Exact number of arrays and the spacing between them depends upon the ground conditions and design of the station box and shaft. However at least there should be a minimum of two arrays in a station box. In general the following types of instruments are used:

- Precise levelling point (PLP) arrays are established to monitor ground movements with distance from the excavation. These arrays are orientated at 90º to the route alignment wherever practicable. However, due to the density of existing buildings in many areas, this may not always possible. In these conditions precise levelling arrays will have to follow the orientation of existing roads and/or walkways. All arrays will extend to the predicted 1 mm settlement contour.

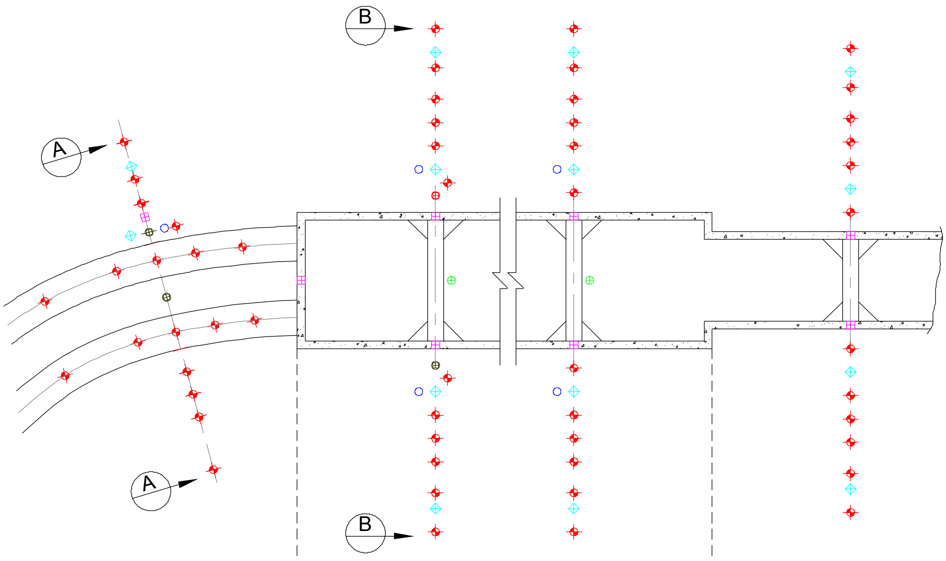


Figure 6: Typical monitoring arrays for bored tunnel, cut & cover station box/tunnel

- Inclinometer cum magnetic extensometers are positioned close to the diaphragm wall on each side of the excavation (typically two no. are located in a monitoring array) to monitor the slurry trenching excavation for the diaphragm walls.
- Inclinometer gage wells are installed in the diaphragm walls to monitor the lateral wall movement.
- Heave extensometers of either electronic type or magnetic type are installed at main monitoring arrays between the excavation support walls, where the excavation formation level is in soil.
- Earth pressure cell below the concrete base slab to measure heave pressure.
- Strain gauges with built-in temperature sensors and load cells are mounted to all levels of temporary struts at monitoring sections to monitor the strut loads. At each I beam of the struts strain gauges are equally spaced around the strut perimeter to get averaged out strain value.
- Additional strain gauges with built-in temperature sensors are attached to the reinforcement cages of two opposing diaphragm wall panels at monitoring test sections. The gauges are located at each strut level on the soil face reinforcement and at maximum moment point between concourse and base slabs on the inner face reinforcement, each mounted on the vertical bars in both diaphragm walls. They will be used to verify bending moments within the diaphragm walls. Jack out pressure cells are also installed in these panels at three elevations for measuring the lateral earth pressure on the soil face.

4.1.2. Instrumentation and monitoring for cut and cover tunnel sections

The cut and cover tunnel sections are monitored extensively in much the same manner as described above for the station boxes. PLP arrays are established to monitor ground movements with distance from the excavation

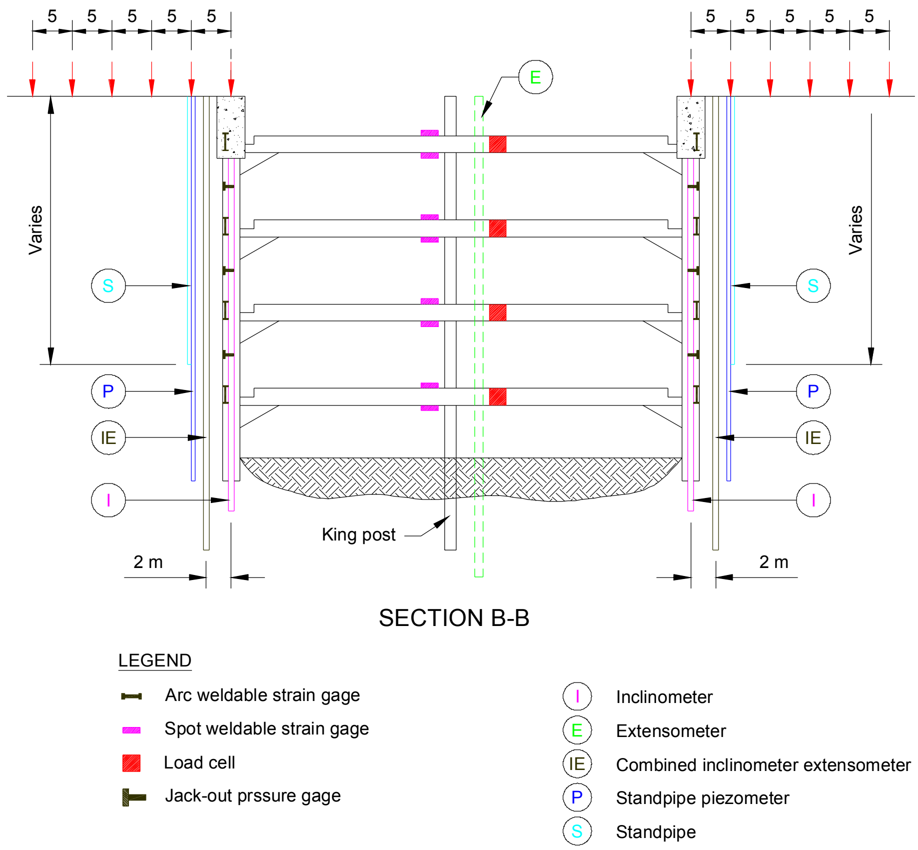


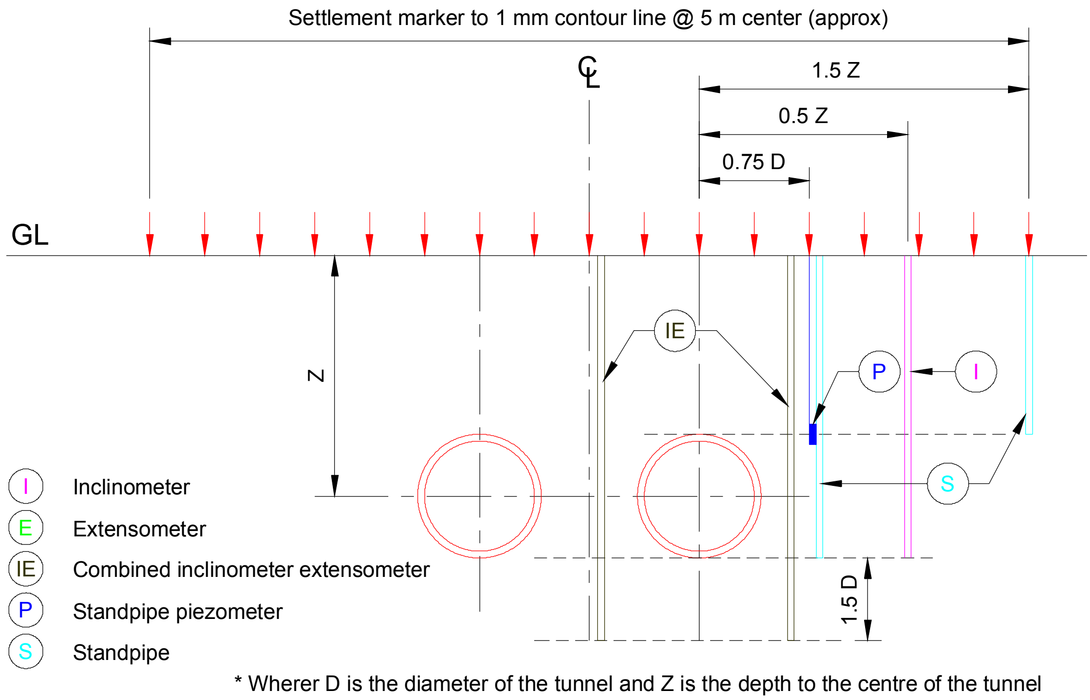
Figure-7: Typical cut and cover station box monitoring section

at approximately every 200 m for each section of cut and cover tunnel. Movement markers are also placed at every 50-100 m on the top of the retaining walls. Inclinometers are positioned in or behind the soldier pile excavation support walls approximately at every 100 m to monitor the lateral wall movements. Strain gages and load cells are mounted on struts typically at location per cut and cover tunnel section to monitor the strut loads.

4.1.3. Instrumentation and monitoring for bored tunnel sections

Monitoring along the alignment of bored tunnel sections (fig.- 8) are undertaken by a combination of inclinometers, magnetic extensometers and precise levelling point arrays. Typically, monitoring locations are identified at a maximum of 400 m spacing and closing to approximately 200 m approaching station boxes.

- PLP arrays are established at ground surface orthogonal to the tunnel alignment, with alternating left and right at approximately 50 m intervals where practicable. Full through width arrays are established at the location of the combined inclinometer and magnetic extensometer casing. All arrays are extended to the predicted 1 mm settlement contour.
- Precise levelling points are also established at ground surface at 10 m interval along each of the bored tunnel alignment for the first 100 m of each drive and at 25 m interval for the remainder of each drive, wherever practicable.
- For the first tunnel boring machine drive of project two monitoring locations are located within 100 to 150 m distance. Monitoring at these arrays will provide early indications of bored tunnelling performance and settlement effects.
- Ground lateral movements and settlement along depth is measured using inclinometers and inclinometers cum magnetic extensometers.
- Convergence measurement is carried out using tape extensometers and precise optical methods between targets attached to the wall and roof at every 25 m intervals.



SECTION A-A

Figure-8: Typical instrumentation scheme for bored tunnel

4.1.4. Monitoring of NATM tunnels

Various monitoring devices are installed in monitoring sections in a NATM tunnel (fig.-9) which can be subdivided according to the instrumentation installed, into: standard monitoring sections, consisting only of targets for underground absolute displacement monitoring and main monitoring sections consisting of instruments like bore hole extensometers, shotcrete pressure cells, strain meters, load cells, measuring anchors, 3D targets etc. These instruments facilitate additionally an assessment of the loading of the primary support and of ground movements outside the excavation. Purpose of installing different instruments is as follows:

- Borehole extensometers are used for determination of ground movements outside of the excavated structure. They allow an assessment of the development of strains in the surrounding ground and stabilization of movements around an excavation. Extensometers are generally of the multiple rod type with anchors connected to the ground by grouting at predefined positions.
- Shotcrete strain meters are used for determination of the stress development in the shotcrete lining by measuring strains. These are always installed pair wise to allow a determination of sectional forces such as normal thrust and bending moments. Based on the measured strains, stresses in the shotcrete lining are calculated by utilization of a non-linear material law. As several input parameters are required for this material law, long-term creep tests on young shotcrete is performed, allowing determination of the required material parameters.
- With radial shotcrete pressure cells the development of ground pressure acting on the primary support structure (shotcrete lining) is measured. Tangential shotcrete pressure cells are used for determination of the shotcrete lining stress. They are generally installed in areas of special interest such as intersections.
- Measuring anchors are used to determine the load development along the anchor. These provide information how load increases from the anchor tip to the anchor plate. Measuring anchors are installed together with rock bolt load cell and extensometers.
- The centre hole load cell installed through a rock bolt at the anchor plate, gives information on the maximum anchor load and the degree of utilization of the anchor.

- Tape extensometers are used for carrying out convergence measurements by measuring distance between fixed targets attached to the walls and roof of the excavation.

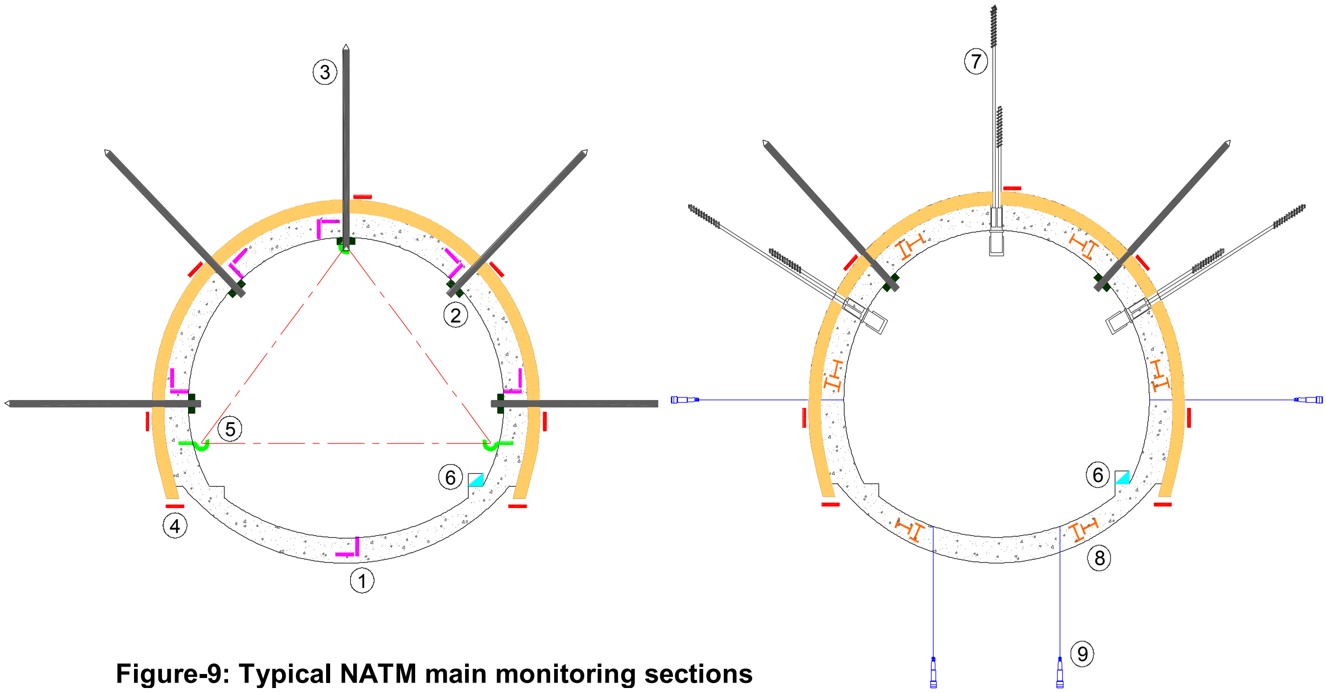


Figure-9: Typical NATM main monitoring sections

4.2 Groundwater monitoring

For carrying out groundwater monitoring, standpipe and Casagrande piezometers are installed in the ground at strategic locations along the route. In most cases stand pipe and Casagrande piezometers are located at the same instrumentation monitoring sections, described earlier. Standpipes, installed during the site investigation in initial stages of the project, are also utilized in monitoring during the construction phase.

For permanent diaphragm walls in stations Casagrande piezometers are used to measure porewater pressures at the lower elevations behind diaphragm walls. Standpipes at the same offset from the wall are installed for measuring groundwater levels. For cut and cover tunnels only standpipes are installed.

Electronic piezometers are installed at sections where on-line monitoring is done.

4.3 Existing building and utility monitoring

An assessment is made of the existing buildings with particular attention paid to heritage structures, monuments and other important structures before the actual construction commences.

All buildings that fall within the predicted 5 mm settlement contour line are monitored by precise levelling survey and crack gauges. Precise levelling points are installed at the corners of each block of buildings. Subject to structural arrangements, these are also established in the order of 5 m centres along the facade of the buildings and are located as close to ground level as practicable without causing a trip or other hazard.

Crack gauges are installed at existing structural cracks, as identified by the building condition survey reports provided with the project’s tender documents, in each structure that falls within the 10 mm settlement contour line.

Utility pipes and conduits predicted to experience significant movement and those that are likely to be sensitive to such movement are, where possible, monitored by precise levelling and visual inspection.

Tiltmeters and electrolytic level beams sensors are used on structures requiring protective measures against settlement-induced damage.

Table-1 Bill of material for one monitoring array in a station box, one in a bored tunnel section and one in a cut and cover section

#	Description	Qty. for C&C tunnel	Qty. for bored tunnel	Qty. for C&C station	Qty. for bldg.
1.	EPP-10SP standpipe typically for 20 m borehole	2 no.	2 no.	4 no	-
2.	EPP-10 Casagrande piezometer typically for 24 m borehole	-	1 no.	2 no.	-
3.	EPP-10/6 water level sounder	1 no.	1 no.	1 no.	-
4.	Vibrating wire piezometer model EPP-30V-020. Range: 0-20 kg/cm^2 (for sections where on-line monitoring is done)	-	1 no.	2 no.	-
5.	EAN-20/1.8A inclinometer ABS access tubes typically 36 m per borehole, also suitable for combined inclinometer cum extensometers	72 m	108 m	144 m	-
6.	EDS-91/3.3 spider magnet suitable for EAN-20/1.8A inclinometer ABS access tube	-	36 no.	36 no.	-
7.	EAN-20/2-inclinometer torpedo, EAN-20/3.2-3 cable lowering fixture, EAN-20/4-datalogger, EAN-20/3.1-cable reel, calibration check frame (components of inclinometer readout system)	1 set	1 set	1 set	-
8.	EDS-91 magnetic extensometer system	-	-	1 no.	-
9.	EDS-91/2.1 signal receiver and probe	-	1 no.	1 no.	-
10.	ELC-210S electronic strain gage based load cell with top and bottom mounting plates, 200t capacity NOTE: For conducting slope stability tests and tension pile pull out tests, wherever required, one no. ELC-210S load cell, 350 tf capacity is required extra	10 no.	-	10 no.	-
11.	ELC-30S strain gage based center hole load cell	As required	-	As required	-
12.	EDS-64V mutipoint borehole extensometer with leaf spring type anchors and vibrating wire displacement sensors of 50 mm range (for installation in vertically downwards position over tunnels/cross passages)	-	As required	-	-
13.	ESMP-10 soil settlement markers	As required	As required	As required	-
14.	EPS-10 concrete pavement settlement markers	As required	As required	As required	-
15.	EBS-14 vertical settlement gages with removable reference locator	-	-	-	As required
16.	EBS-16 vertical settlement gages with fixed reference locator	-	-	-	As required
17.	EDJ-40C crackmeter	-	-	-	As required
18.	EAN-10 (± 1^{o}) strain gage based tiltmeter	-	-	-	As required

#	Description	Qty. for C&C tunnel	Qty. for bored tunnel	Qty. for C&C station	Qty. for bldg.
19.	EAN-30-EL electrolytic beam tilt meter (where greater sensitivity in tilt measurement is required)	-	-	-	As required
20.	EDS-80 tape extensometer	-	1 no.	-	-
21.	EDS-20V-SW spot weldable/epoxy bondable strain gage for struts	40 no.	-	40 no.	-
22.	EDS-20V-A arc weldable strain gage for rebars	-	-	20 no.	-
23.	EPS-31V-J-150 jackout pressure cell (10 kg/cm^2)	-	-	06 no.	-
24.	EPS-33V earth pressure cell (35 kg/cm^2)	-	-	02 no.	-
25.	ESB-13-1 junction cum switch box suitable for input from 10 sensors, output through 4 core cable to indicator and 40-core cable to DAS	07 no.	-	07 no.	-
26.	EDI-53L microprocessor based digital portable readout unit for strain gage based sensors: tilt meter EAN-10 and load cell ELC-210S	1 no.	-	1 no.	1 no.
27.	EDI-51V microprocessor based digital portable readout unit for vibrating wire sensors: spot weldable strain gage, arc weldable strain gage, jackout pressure cell, earth pressure cell, and piezometer	1 no.	-	1 no.	-
28.	EDI-53EL microprocessor based digital portable readout unit for electrolytic level tiltmeter	-	-	-	1 no.
29.	CS0401-4 four core cable from sensors to junction boxes	As required	As required	As required	-
30.	CS0407-20 twenty core cable from sensors to junction boxes	As required	As required	As required	-
31.	CS0407-40 forty core jelly filled cable from junction boxes to DAS	As required	As required	As required	-
32.	EDAS-10 automatic data acquisition system suitable for 76 channels consisting of: CR-10X control and measurement module-1 no. ESP-216 surge protector-10 no. EAM416 16 channel multiplexer-5 no. AVW100 V/W interface-1 no. Multilogger software -1 no. EBP-127Ah datalogger power supply -1 no. 500 VA UPS with 20 minutes battery back up-1 no. (user's scope) IBM compatible PC-1 no. (user's scope) Colour ink jet printer-1 no. (user's scope)	-	-	1 syst.	-

Table-2 Bill of material for one main monitoring section of a NATM tunnel (refer to figure 9)

#	Description	Qty.
1.	ESC31/37V vibrating wire shotcrete pressure cell (radial and tangential)	12 no.
2.	ELC-30S center hole load cell (strain gage type)	5 no.
3.	EMA-12M measuring anchor	5 no.
4.	EPS-33V concrete pressure cell	7 no.
5.	Convergence studs for EDS-80 tape extensometer	3 no.
6.	ESB-13 10 position junction cum switch box	As reqd.
7.	EDS-64V-2 multipoint bore hole extensometer	3 no.
8.	EPP-30V vibrating wire pore pressure meter	4 no.
9.	EDS-11 shotcrete strain meter	12 no.
10.	EDI-51V readout unit	1 no.
11.	EDI-53L readout unit	1 no.
12.	CS0401-4 four core cable from sensors to junction boxes	As required
13.	CS0401-6 six core cable from sensors to junction boxes	As required
14.	CS0407-10 six core cable from sensors to junction boxes	As required
15.	CS0407-40 forty-core jelly filled cable from junction boxes to DAS	As required

5. Case study: Instrumentation and monitoring at Delhi Metro Rail project

Instrumentation and monitoring of 11.1 km long underground metro corridors MC1A and MC1B was done using Encardio-rite's range of geotechnical instruments. The route has 10 underground stations of approximately 0.3 km length each, with 7.6 km (3.8 km x2) of bored tunnels and 4.3 km of cut and cover tunnels. The owners of the project, Delhi Metro Rail Corporation (DMRC) had awarded the fixed lump sum price design build turnkey contract in two parts: MC1A (4.5 km long 4 stations) and MC1B (6.6 km long, 6 stations) corridors. The former was awarded to KSHI (Kumagai-Skanska-HCC-Itochu) JV and the latter was awarded to IMCC (Dywidag-L&T, Samsung, Ircon-Shimizu) JV. The total cost of the project was INR 25500 million (INR 9000 million for MC1A and INR 16500 million for MC1B). MC1A has been commissioned since December 19, 2004. MC1B shall be commissioned from June-2005.

Safety first and environment friendly work methods are a unique feature of this mammoth project. The noise level, track & passenger safety have been taken highest care of and incorporated in the project. Uninterrupted traffic flow, across construction areas was maintained over the steel decking. All utilities like pipelines; cables were carefully diverted or supported

The following types of instruments were used:

5.1. Ground water monitoring

Following instruments were used for groundwater monitoring depending upon the requirement:

- Standpipe
- Casagrande piezometer
- Electrical piezometer

Purpose of installing Casagrande piezometers and standpipes was to measure the pore water pressure of the soil and ground water level in general, respectively. Standpipes were basically used for monitoring the lowering of groundwater level during the dewatering process. The observed data was fed in groundwater modeling software like MODFLOW to determine the groundwater profile around the station box to check the effectiveness of dewatering scheme implemented.

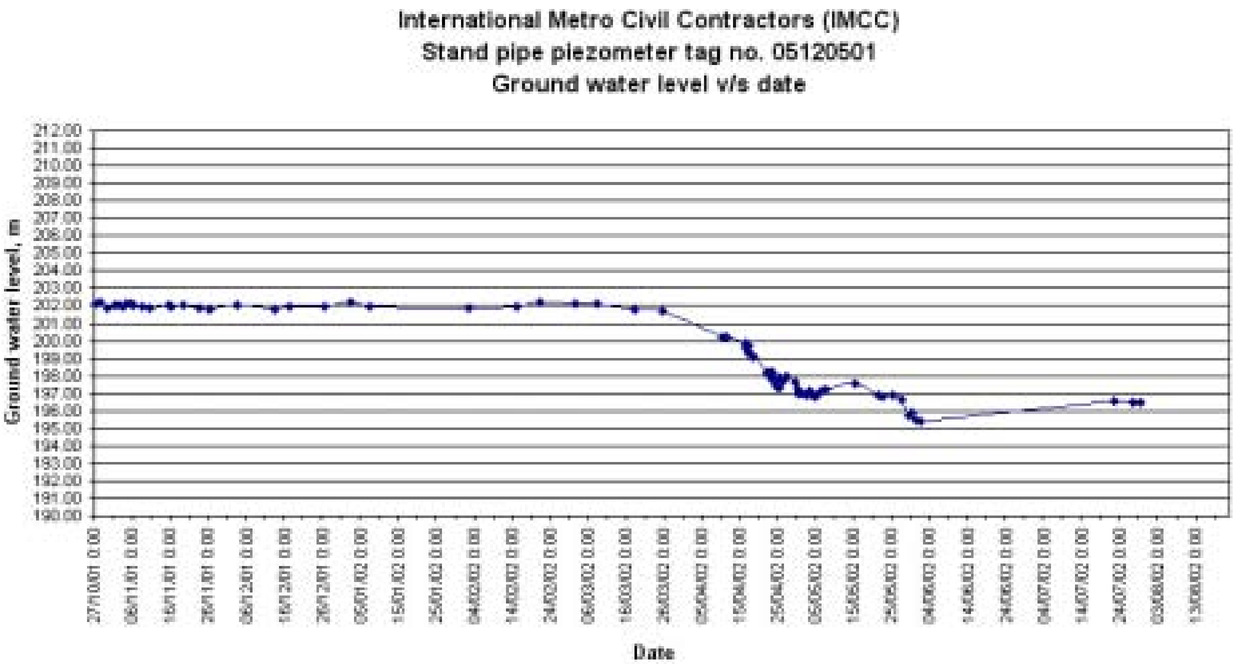


Figure-10 Ground water level v/s time as measured from a standpipe near a cut and cover station box (level falling after 26.03.02 as a result of construction dewatering)

Standpipes model EPP-10SP were installed in monitoring arrays across cut and cover station box/tunnel and bored tunnel sections for monitoring the general ground water level. These are constructed from heavy duty 50 mm nominal diameter PVC pipes jointed together by push fit couplings, using PVC solvent cement. The bottom 1 m section, known as the filter, is perforated by drilled holes and is covered by brass wire mesh. Lockable, steel manhole covers were provided at the top for protection against moving traffic and vandalism. For each installation standpipe top elevation was determined by surveying to present results in terms of reduce level (RL).

Casagrande piezometers model EPP-10 featuring a 600 mm long carborundum tip and 20 mm dia PVC standpipes were installed behind the diaphragm wall to determine the pore water pressures in the soil strata around the tip. For taking readings of both standpipes and Casagrande piezometers model EPP-10/6 water level sounder with non-stretch flat tape, featuring Kevlar straining member was used. This is a simple but rugged battery operated device, very much suitable for field use under harsh conditions. Readings could either be noted down or fed in a palm top computer at the site itself.

Model EPP-30V vibrating wire type piezometers were used in monitoring sections for which ground water data had to be collected on-line using an automatic data acquisition system. These piezometers are of stainless steel construction, featuring a hermatically sealed sensor and are suitable for installation in 100 mm dia. bore hole. Slim type vibrating wire piezometers model EPP-40V are suitable for installation in the standpipe model EPP-10SP mentioned above. Theses could be retrieved from the standpipe after the monitoring is over.

5.2. Measurement of lateral movement of ground / retaining walls

Inclinometers were installed for determining the lateral movement of ground and retaining walls due to nearby excavation and tunnelling activities. At Delhi metro these were extensively used for various applications like:

- To study the lateral movement of the diaphragm wall as the excavation progresses, under various phases such as preloading of struts, excavation, de-stressing of struts and removal of struts.
- To study the movement of soil and to gauge the effectiveness of sheet pile wall, when installed at around 0.5 m behind the sheet pile.
- To study the lateral movement of the soil due to slurry trenching work, when installed around 0.5 m behind the diaphragm wall.
- To monitor the soil deformation due to tunnelling work undertaken by means of TBM, EPBM or NATM when installed in the vicinity of the tunnels constructed by the above methods.

The data obtained from the inclinometer system was used to check excessive lateral movement by comparing the same with the trigger/thresholds values. Also the borehole profile is matched with the theoretical profile under the given conditions such as soil parameters, excavation level etc., generated by modelling package like PLAXIS. Based on the results of the above exercise sometimes, certain assumed coefficients related to soil properties were modified to bring them close to the actual values. These modified coefficients are used further in designing/modifying design of the retaining structure and other calculations.

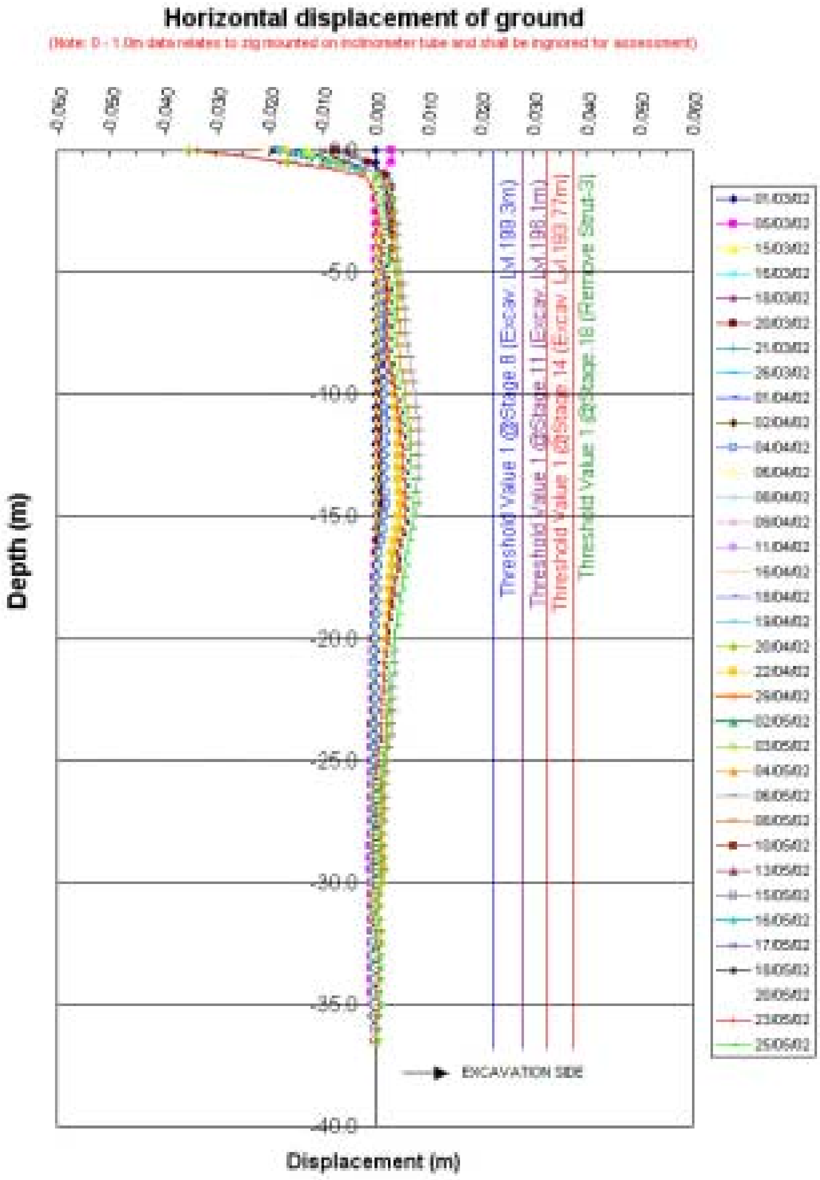


Figure-11: Lateral movement of soil near to 20 m deep excavation as measured from an inclinometer

Encardio-rite model EAN-20/1.8 self-aligning PVC grooved tubings were successfully used for all the above applications. However we now provide a better solution in the form of ABS grooved tubings model EAN-20/1.8A that are imported. These tubings are easier to install, more rigid, lighter and have negligible groove spiralling.

The tubings were installed in 125 mm boreholes of the required depth. Tubes were jointed by means of PVC cement and riveting. The joints were made waterproof by applying sufficient rounds of BOPP tape over it. As the boreholes were waterlogged, clean water was pored inside the tubing while lowering into these to overcome buoyancy. In case of installation inside the diaphragm wall the tubes were lowered in 150 mm diameter GI pipes, pre installed in the D-wall by welding these to the wall reinforcement cage. The annular space between the tube and borehole/GI pipe was filled with grout to ensure that the tube doesn't hangs loose.

For monitoring Encardio-rite model EAN-20/2 biaxial servo accelerometer based probe of 0.5 m gage length was used in conjugation with model EAN-20/3.1 cable reel and model EAN-20/4 datalogger. All the necessary accessories like cable lowering pulley, extension jig, calibration check frame, carrying case etc. were also provided with the system. The data collected at every 0.5 m length throughout the tube depth and stored in the datalogger was downloaded to a PC and the current tube profile (cumulative deviation) along the full depth was compared with the initial tube profile (base reading), which was determined by using the same measuring system when there were no influencing factors.

To get meaningful data it is very essential that for a given borehole only one set of measuring system is used throughout the project. It is also recommended that the same monitoring team should take the reading of this borehole everytime, as far as possible. However if any of the components of the measuring system is required to be replaced with a new one, necessary corrections are to be made in the data to maintain continuity with the original set of readings.

For installations in diaphragm wall it is essential that the heat of hydration of the mass concrete has dissipated before the tubings are installed. Otherwise warping of the tubes might occur leading to unstable and incorrect data. For ensuring that the temperature is within safe limits of 30ºC temperature probe ETT-10TH was lowered in the GI pipe for measuring temperature.

5.3. Sub surface and surface ground settlement and heave measurement

The following instruments were used for measuring ground settlement profile measured over a certain depth, ground surface settlement and ground heave at the centre of excavation:

- Magnetic probe extensometers
- Combined inclinometer cum extensometer
- Potentiometric / vibrating wire type bore hole extensometers
- Soil settlement markers
- Pavement settlement points

Magnetic extensometers model EDS-91 consisting of 34 mm o.d. PVC pipe, joined either with rigid or telescopic couplings and featuring spider magnets model EDS-91/3.2 were used for monitoring sub-surface settlement of the strata near a cut and cover excavation or a bored tunnel. It was also used for measuring heave at the center of excavation, which might occur due to ground water pressure acting at the base of the excavated box.

Where feasible, a combined inclinometer cum extensometer was used for the measurement of sub-surface settlement along with ground lateral movement. In this combined device, 76 mm i.d. spider magnets were installed at either 2 m or 3 m intervals over the PVC, grooved from inside, 75.5 mm o.d. inclinometer tubings model EDS-20/1.8. Lateral movement was measured with the same device using EAN-20/2 biaxial servo accelerometer based probe along with other monitoring devices described above in section 5.2.

For both of the above devices the position of magnets, which were in the contact of the surrounding ground were determined using model EDS-91/2.1 signal receiver and probe with 30 m length steel tape with markings at every 1 mm. Elevation of the pipe top was also determined by surveying from time to time to measure any settlement for correct interpretation of the monitoring results.

Multipoint (4-point) bore hole extensometer (MPBX) model EDS-64P with potentiometric displacement transducers EDE-P50 of 50 mm range, were used for measuring sub surface settlement at different soil strata over the cross passage tunnels. For this application special leaf spring anchors were used for anchoring connecting rods in the soil strata. Vibrating wire type displacement transducer model EDE-V50 is also available which is particularly suitable for waterlogged applications and long distance data transmission.

For monitoring of the above MPBX portable digital readout unit model EDI-53P was used. For MPBX with vibrating wire displacement transducers the suitable readout unit shall be model EDI-51V.

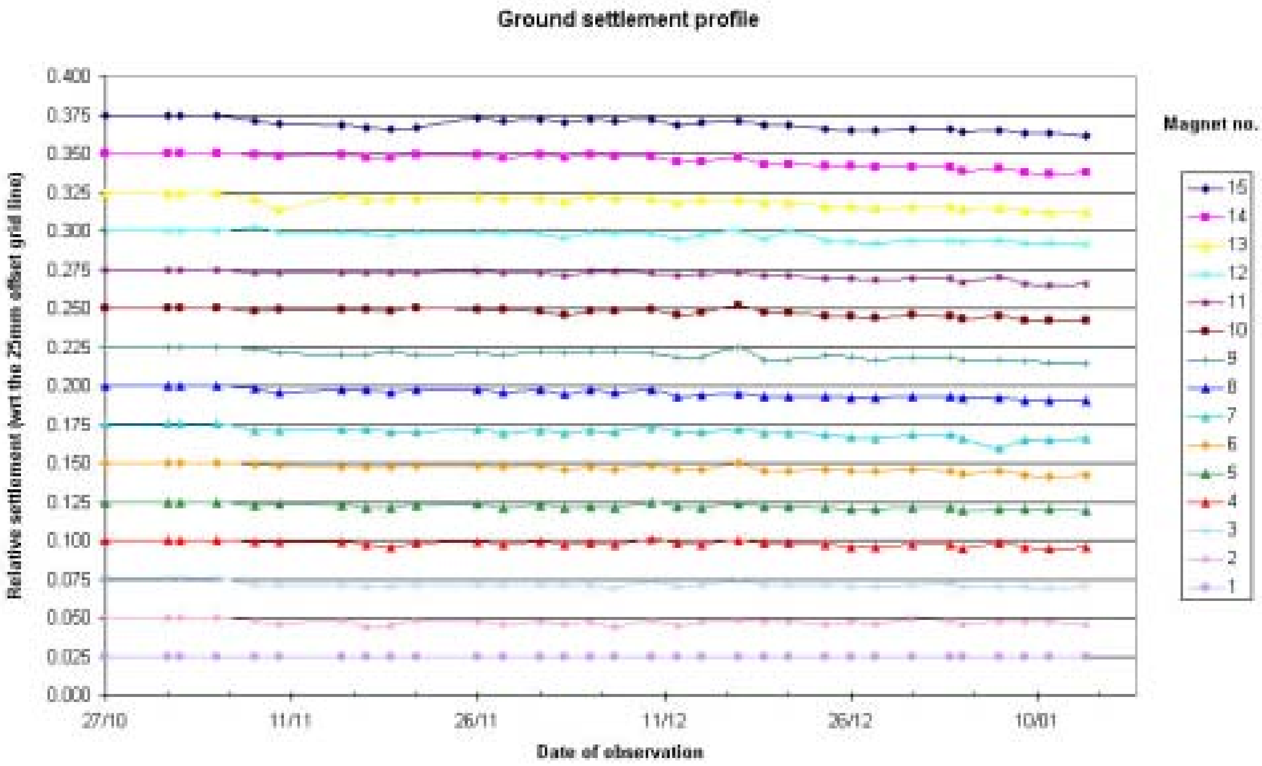


Figure-12: Ground settlement profile near a 24 m deep excavation, measured using magnetic extensometer

Soil settlement markers model ESMP-10 were used for measurement of soil surface settlement measurement. The instrument comprises of a 250 mm long x 15 mm Ø SS-304 surveying pin having a semi-spherical top, with a red colored cross mark engraved in it and a 1 m long x 50 mm Ø GI pipe with lockable cap. The GI pipe is fixed with the help of concrete inside a pit of 1 m x 1m x 1m size, in soil and the pin is grout fixed inside it with its top protruding some 25 mm above the top of the GI pipe. Readings can be taken with suitable surveying equipment.

Pavement settlement points model EPS-10, which are basically tapered cross section steel disks with a center hole, were fixed to the concrete pavement using a suitable steel expandable anchor. The settlement of the concrete pavement due to adjacent excavation or underneath tunnelling activities was monitored at these points, using suitable surveying equipment.

5.4. Strut load measurement

For measuring load on the steel struts, which were used for externally supporting the excavations of cut and cover station boxes and tunnels, vibrating wire type strain gages model EDS-20V-SW were extensively used. The strut load was monitored while preloading the struts and also during the course of excavation when the strut-load is likely to vary due to surrounding soil pressure.

The strain gages were installed almost in the center of the strut span at a distance equal to 4 times of the height of the strut I-beam, away from the support of the strut span at the king post, towards the strut end where the pre-loading jack is placed. This was done to ensure that the end-effects i.e. uneven distribution of stresses in the I-beam at and near the point of support, are minimized. One strain gage each was fixed at the inner surfaces of the I-beam flanges. Special epoxy was used for fixing the strain gages on to the grinded and prepared steel strut surfaces. White coloured (to reflect the sunlight) protective boxes were mounted over the strain gages for preventing damage due to construction activities.

Readings from strain gages mounted at struts at various levels were taken at the junction cum switch box model ESB-13-1 mounted at suitable location at the ground level with the help of readout unit model EDI-51V.

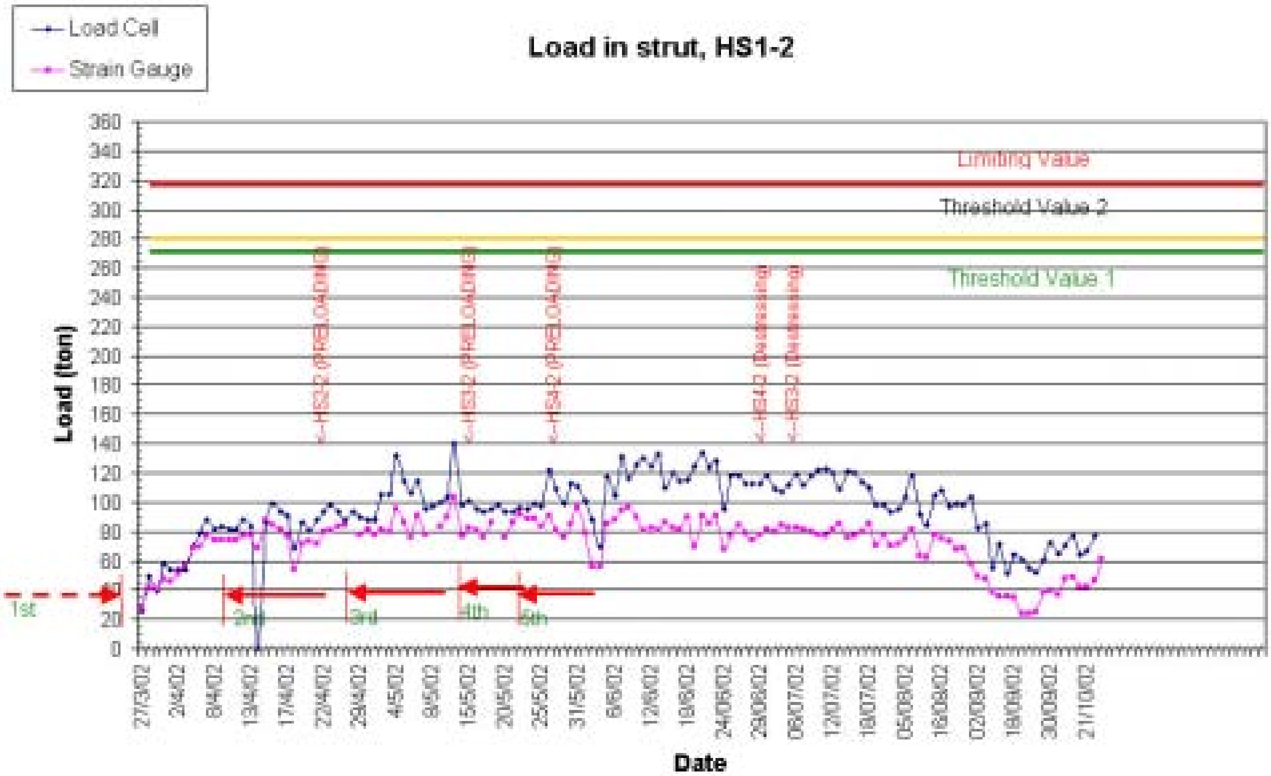


Figure-13: Strut load as measured with the help of strain gages and load cells

Junction box (5 inputs-1 output) model EJB-10 and 20-core jelly filled armoured cable model CS-0407-20 were used for carrying out the cabling work.

Similar strain gauges were also installed a few TBM/EPBM reaction-frames to determine the load experienced by them due to the thrust of jacks of the machine for pushing it forward, during the initial drive.

Besides the strain gages model ELC-210A compression type, resistance strain gage based electronic load cells were also used at certain locations to measure the strut load. For mounting these load cells special brackets were fabricated at site to which the load distribution plates were tightened by nut-bolts. The load cell in turn was tightened one of the load distribution plates using an allen bolt. Before loading the retaining plates are removed from the load cell assembly. Model EDI-53L portable indicator was used for monitoring the load cells.

While monitoring the strut load it should be noted that the time of monitoring should be preferably in the morning hours when the strut temperature is in equilibrium with the atmospheric temperature and temperature induced stresses are absent.

5.5. Load in tie back anchors

To support the retaining walls multi strand tieback anchors were used where required (excavation internally supported). For measuring the load on these tieback anchors while prestressing and in long term, model ELC-30S resistance strain gage based center hole load cells were used. Necessary mounting arrangements were provided at the wailer beam along the periphery of the walls. The center hole load cell is mounted between the bottom load bearing plate and the top load distribution plate, which are supplied with the load cell. These plates are precision ground for perfect contact with the load cell for total load transfer. The anchor loading plate comes over the top of the load distribution plate mentioned above. The whole arrangement sits over the chair, which is having its face perpendicular to the direction of tieback anchor.

5.6. Building instrumentation

5.6.1. Vertical settlement gages

For the measurement settlement of buildings model EBS-16 vertical settlement gages were installed around the external façade of the building, as close to the ground as practical without causing a trip hazard. The installation of these points featuring a spherical head and a plated body were installed in such away that damage to the building façade is minimum. Special two part quick setting epoxies were used for fixing these points in 12 mm dia x 65 mm deep-drilled holes. Battery operated drill machine was particularly suitable for installation of these points as it was not practical to get a mains supply everywhere along the metro route where these points were installed. Model EBS-14 settlement points with detachable reference locators were practical to install at locations where the EBS-16 with permanently installed reference locator posed a trip hazard or was likely to get damaged due to traffic.

Precise levelling was used for monitoring building settlements with the help of the vertical settlement gages.

5.6.2. Crackmeter

For monitoring already existing cracks in buildings as well as for new crack appearing due to differential ground settlements, crackmeter model EDJ-40C were used. These were simple but effective devices comprising of a graduated steel scale and a transparent plastic cursor with a red hairline mark. These instruments were installed across the crack with the help of impact anchors to read its opening/closing with a 0.5 mm precision.

5.6.3. Tiltmeter

To monitor tilt of certain critical buildings which may be caused due to differential ground settlements occurring due to dewatering and/or nearby excavation, model EAN-10S strain gage based tiltmeters with a range of ±1° were used. Electrolytic sensor type tiltmeters model EAN-30EL were also installed. The former was read using portable readout unit model EDI-53L and the latter with model EDI-53EL. The latter tiltmeter model features a better resolution of 0.001 degrees while the former has a resolution of 0.01 degrees but has a lesser effect of ambient temperature on its output. However both types should ideally be installed at an indoor location or in shade to prevent effect of large temperature fluctuations on the monitored results. Reading should possible be taken in the morning hours when temperature induced stresses in the buildings are minimum. Also location of the tiltmeters should be as remote as practically possible, so as to avoid any kind of impact because even a little impact may result in a shift in readings.

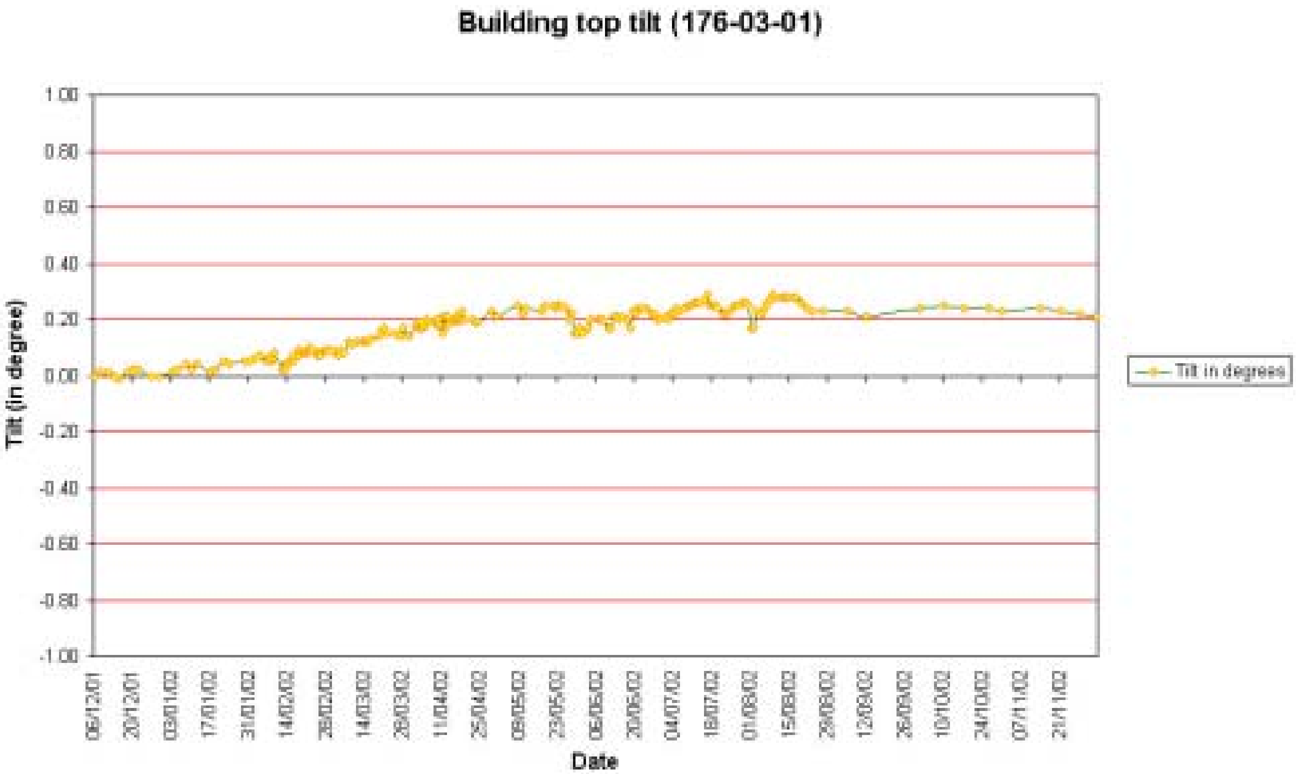


Figure-14 Tilt of a building top near Chawri bazaar cut and cover station box site, measured from EAN-30

5.7 Diaphragm-wall stress and concrete soil interface pressure measurement

For measuring stresses and verifying bending moments within the diaphragm walls, arc weldable strain gages model EDS-20V-AW were welded on the vertical rebars of the reinforcement cage of the diaphragm wall. These were installed at each strut level on the soil face reinforcement and at the point of maximum moment between the concourse and base slabs on the excavation face reinforcements.

For measurement of concrete soil interface pressure measurement jackout pressure cell model EPS-31V-J-150 were installed in the reinforcement cage of the diaphragm wall. To ensure contact of the pressure sensing plate with the ground, a 2 t hydraulic jack between the reaction plate and pressure sensing plate was activated by using a manual pump at the ground level, which was connected to the jack with the help of high pressure hose.

For both arc weldable strain gages and jackout pressure cells, signal cables were protected using 20-mm dia PVC conduit. Readings were taken at the ground level at the junction cum switch box model ESB-13 using vibrating wire indicator model EDI-51V.

5.8 Concrete temperature measurement

For measurement of temperature of mass concrete model ETT-10TH thermistor based temperature probes with a range of 0-80ºC were ideally suited due to its low heat capacitance and quick response time. These probes are suitable for embedment applications and the cable protection was carried out using a 20 mm dia. PVC conduit. Temperatures of up to 50ºC could be measured with the help of digital indicator model EDI-51V but for measurement of temperatures above that a digital multimeter has to be used. The resistance measured with the help of the latter is fed to the logarithmic relationship between the temperature and resistance for the thermistor to get the value of temperature.

5.9 Pile load testing

For verification of the designed and ultimate load bearing capacity of the cast-insitu concrete piles a complete range of instrumentation available from Encardio-rite was used for pile testing: both for the measurement of the applied test load and pile deformation/settlement.

Model ELC-210S, electronic load cells were used for the measuring the applied load on the test pile. Compatible top and bottom load bearing plates are provided for total load transfer. The load cell could be remotely read with the help of digital indicator model EDI-53L.

Arc weldable strain gages model EDS-20V AW are attachable to the reinforcement cage rebars for measurement of stresses developed in the piles as a result of load application. Jackout pressure cell model EPS-31V-J were installed for measuring the concrete soil interface pressure. Inclinometer system model EAN-20 with the tubing installed while casing the pile are used for measuring pile deformation pattern along the length. Tell tale extensometer which is a mechanical device read with the help of a depth micrometer is deployed for measuring the settlement of the pile as a result of load application.

6. Instrumentation monitoring

6.1. Base readings

Base readings of instrumentation were taken in advance of all construction activities within the area of influence. Base readings were scheduled as per the following guidelines:

- Wherever practicable, piezometers should have base readings taken for a minimum of three months prior to any construction activity within the affected zone.
- Inclinometers shall be initialised in advance of any downstage excavation, or tunnelling within the affected zone.
- Strain gauges/load cells on temporary struts shall be initialised prior to any pre-stressing within the affected zone.

- Crack gauges should have base readings taken for a desirable period of one month prior to any significant construction activity.
- At least four sets of readings are taken to confirm a base reading.

6.2. Frequency of readings

The frequency of monitoring was dependent on the instrumentation type, location of instruments and the construction programme. It was also linked to the predicted movements and rate of construction.

Frequency of readings was increased following any breach of the threshold review level for any particular instrument. Frequency was reduced following completion of specific construction activities, if no further movement is evident for at least one month following activity completion.

7. Conclusions

The data observed from the geotechnical instrumentation describe above plays a vital role in providing verification of design assumptions, manage the construction in a safe and controlled manner, safeguarding existing adjacent buildings and other facilities and monitoring long term behaviour of sub and super structures.

During the earlier design stages, specific instrumentation requirements was assessed and incorporated into the design. Specific ground and groundwater conditions, construction methodology and the location and sensitivity of adjacent existing structures have to be given due consideration in selecting a suitable instrumentation and monitoring system. The programme for implementation of instrumentation requires advance planning. The procurement, installation and initialization of instrumentation require sufficient time to enable base readings to be taken, in most cases, before any construction activities commence within the zone of influence. There is no substitute or shortcuts for getting reliable and meaningful data from the instruments, so both the instruments and the manpower deployed for installation, monitoring and maintenance of instruments have to be topnotch.

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