Buoyancy Effect on Slightly Sloped Horizontal In-Place Inclinometer

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The 7-Line Extension is a $900 million subway tunnel excavation located in Manhattan, New York. The largest components of the project are 3 shafts, a 1,000 ft (300 m) long station cavern, and two bored tunnels totaling over a mile (1.5 km). The tunnels were excavated from 20th Street north 20 blocks under 11th Avenue in rock at a depth of approximately 100 ft (30 m). They then turned to the east and followed 41st Street 8 blocks, rising to meet the existing 7-Line tracks around 8th Avenue.

The TBM's were to hole through to a receiving chamber excavated beneath the basement of the Port Authority Bus Terminal (PABT), the busiest bus terminal in the world by traffic volume. Due to the proximity of tunnel excavation to the foundations of the PABT – in some cases, within 5 feet (Figure 1) – the instrumentation specification included 10 vertical borehole extensometers (BX) to monitor ground movement during the TBM drive 200 to 500 feet from the receiving chamber.

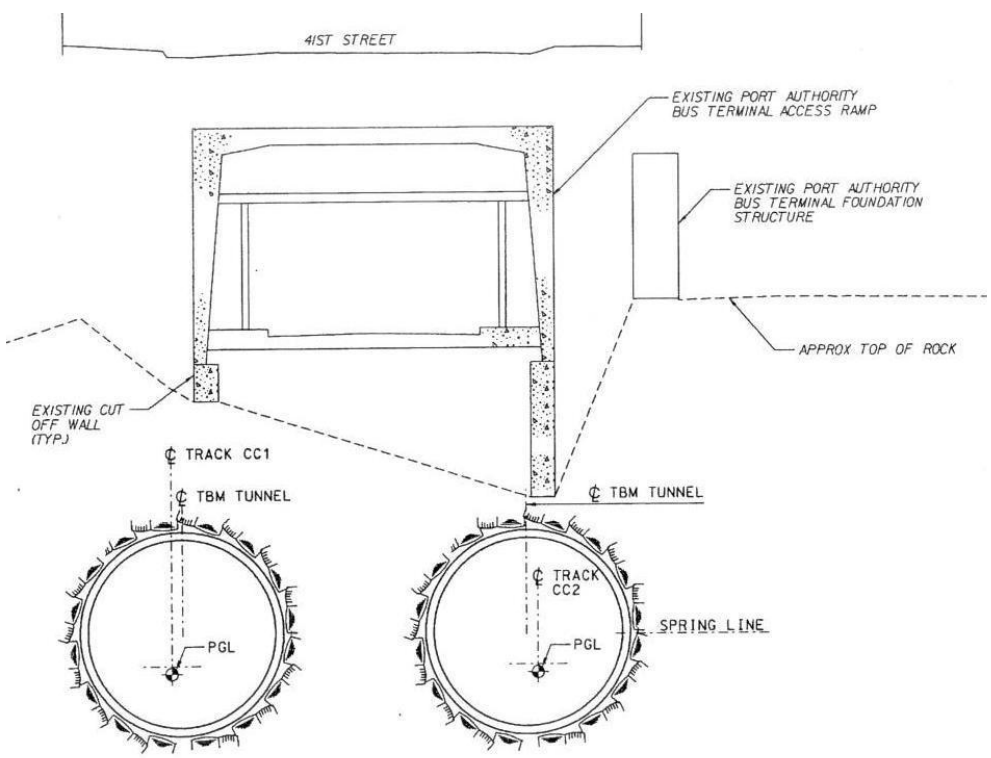

Figure 1. Cross section of final tunnel drive beneath PABT foundations.

The last 200 feet were left open to be monitored by a system designed by the contractor. As the contractor's instrumentation consultant, GZA was instructed to install one horizontal in-place inclinometer (IPI), consisting of 20 individual sensor elements spaced at 10 foot (3 meter) increments.

An in-place inclinometer is an array of tilt sensors installed in a borehole casing. The casing is grooved on the inside, and the sensors have spring-loaded wheels rolling in the grooves, such that the sensors' orientation is maintained throughout the depth or length. Thus, any tilt detected should be attributable to movement in the ground. We used biaxial sensors which detect tilt along the two horizontal planes. In a horizontal IPI, the B-axis corresponds to rotation within the casing, which would be detected if the vertical orientation of a sensor were not maintained throughout the casing (Figure 2). The A-axis is the primary observation, oriented along the borehole in order to detect any ground settlement or movement.

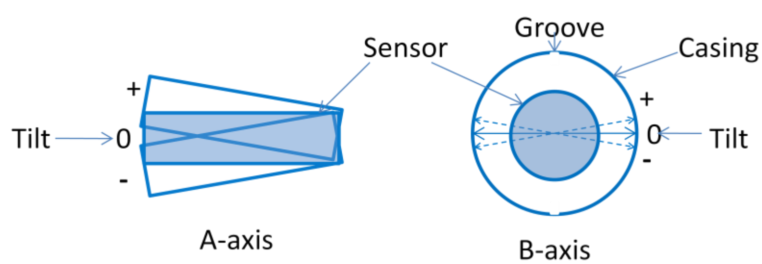

Figure 2. A- and B-axes of sensor detection.

The readings from the tilt sensors are converted to displacement by applying the tilt angle over its 10 foot spacing (Figure 3). The distance thus calculated is summed for each sensor to determine total, cumulative displacement at each location.

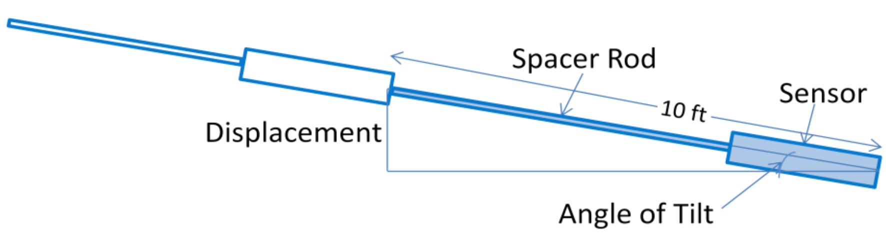

Figure 3. Displacement determined by tilt sensor.

The IPI borehole was drilled into a vertical rock face from the receiving chamber, parallel to the tunnel alignment, 1 meter above its expected path (Figure 4). At this location, the Tunnel Boring Machine (TBM) path slopes up towards the receiving chamber at a 3% grade. The seemingly logical decision to drill parallel to the tunnel drive, dipping slightly down from the borehole opening, was an unfortunate one that created several problems described below.

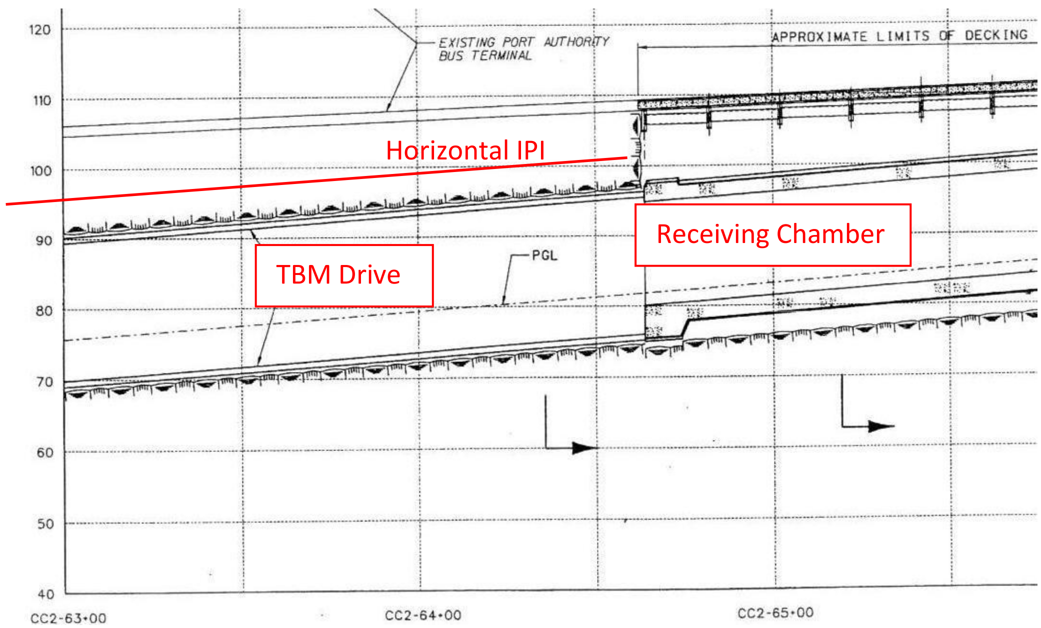

Figure 4. Location of IPI above tunnel, drilled from receiving chamber.

The Geokon inclinometer casing was installed in the borehole with a length of cable inside attached to a pulley fixed to the end-cap (Figure 5). The instrument itself (also made by Geokon) was attached to the cable and inserted into the casing by simultaneously pushing the instrument and pulling it in with the other end of the cable. The difficulty of installing the casing was increased by having the wire cable strung through it. However, the wire and pulley system proved necessary, given the difficulty of inserting the instrument to a depth of 200 feet, horizontally.

Figure 5. IPI casing end cap with pulley and cable attached.

Because we used biaxial sensors, each element of the IPI could be monitored for rotation during installation. This was necessary to assure the wheels stayed in the grooves of the casing, and that the casing and grooves remained vertical for the length of the borehole. This caution was warranted because during the first attempt at installation, a piece of casing was found to have rotated out of its slot, creating a discontinuity in the interior grooves. This allowed the IPI elements to rotate freely beyond that location and we lost control of their orientation. We believe the casing misalignment was caused during insertion of the casing into the borehole, which required substantial effort.

The instrument and casing were removed and reinstalled correctly, with documented tolerance of less than 5% rotation at any point along the borehole (Figure 6). The casing was then grouted into place via a tremmie pipe that had been installed together with the casing.

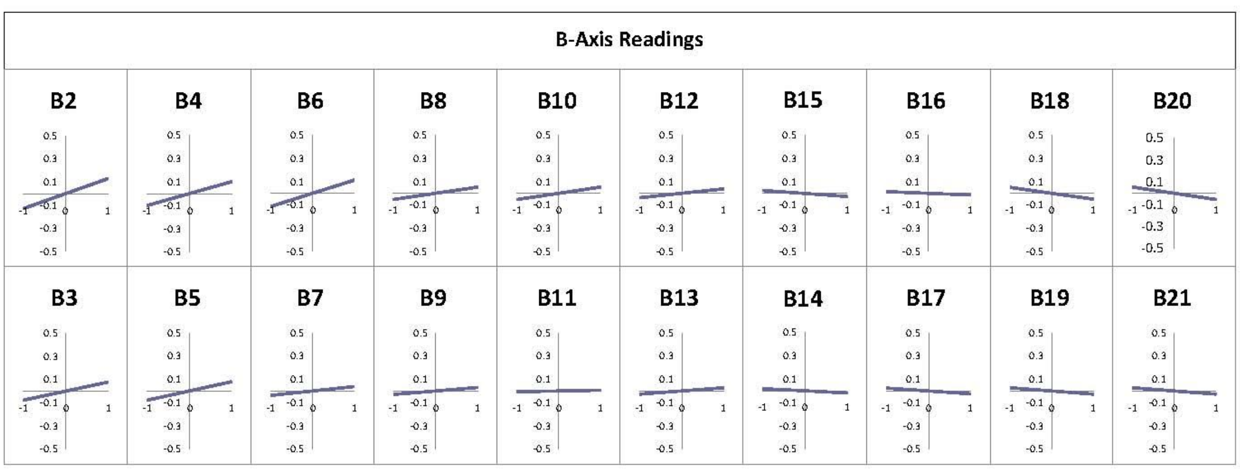

Figure 6. B-axis tilt, verifying sensor orientation within 5% tolerance.

Baseline readings were obtained for each sensor's A-axis orientation (Figure 7).

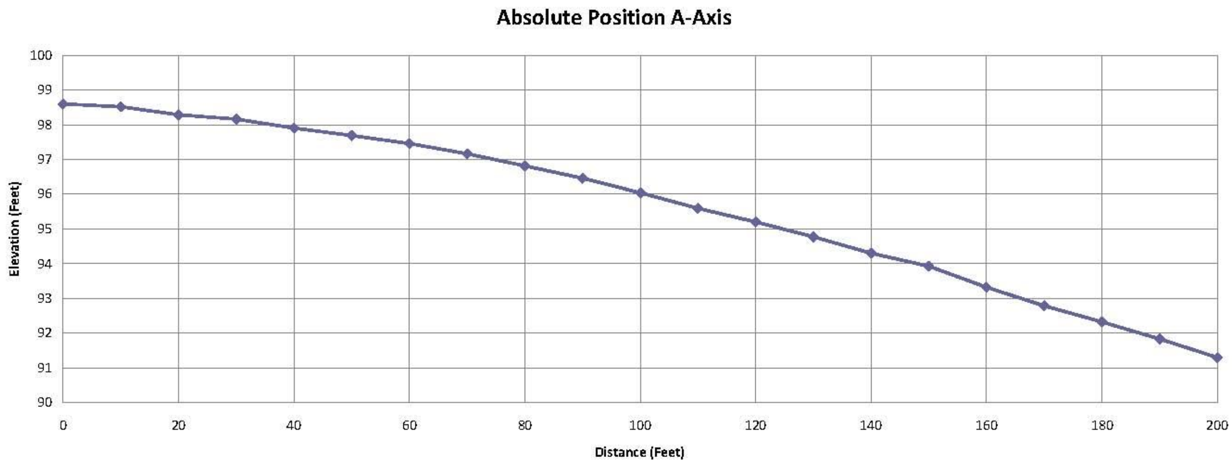

Figure 7. Baseline position shown in absolute elevation. The instrument is designed to detect displacement from the baseline configuration.

No movement was expected before tunnel excavation beneath the instrument and low thresholds were set for movement alarms. However, over a period of several weeks, long before excavation reached the instrument, apparent displacement began to register in each element, one at a time from the deepest to the shallowest (Figure 8).

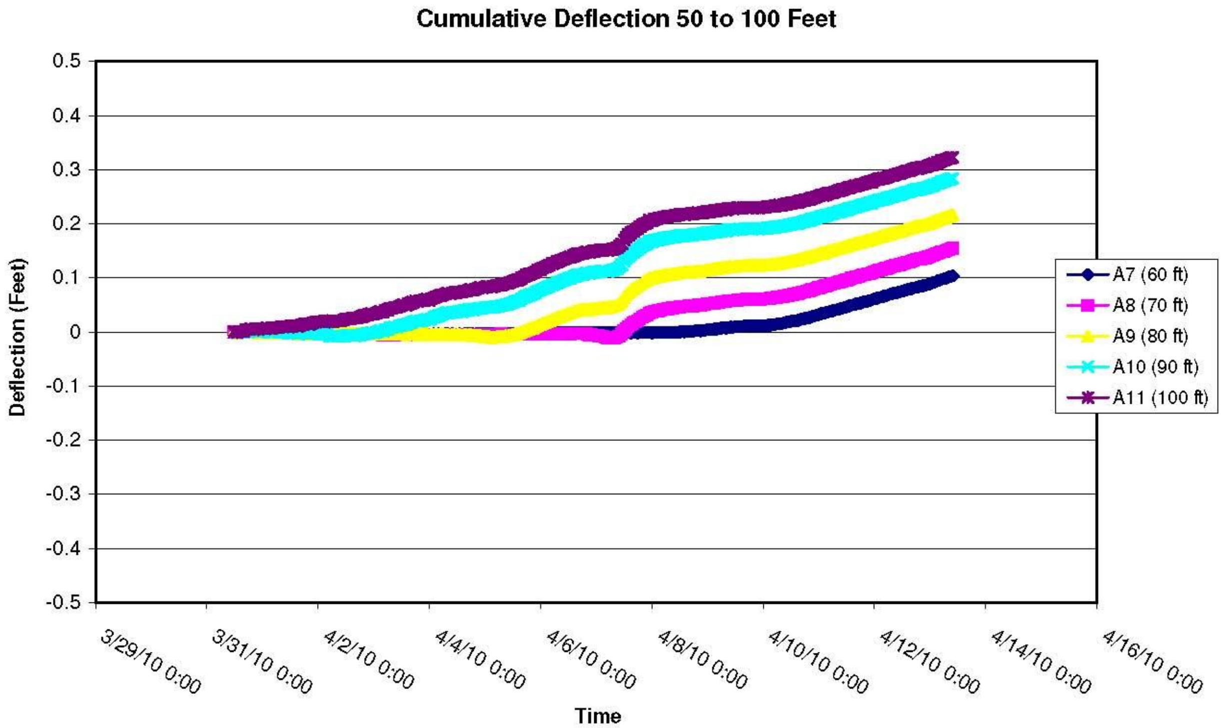

Figure 8. Plot showing apparent movement in sensors progressively along the borehole.

No actual settlement had occurred, and it was ascertained that the apparent displacement was caused by the casing slowly filling with water due to small leaks through the grout and casing joints. Due to the downward slope, the far end of the borehole filled first. As each element was progressively submerged, the buoyancy of the hollow, air-filled spacer rod caused very small bending and tilt of the sensors in precisely the orientation they were designed to detect (Figure 9). This tilt was automatically converted to displacement according the assumptions of the data processing described in Figure 3. Less than half of one degree of tilt is sufficient to produce the apparent displacements, which were over 1 foot (0.3 meters) when added together over the entire length of the instrument.

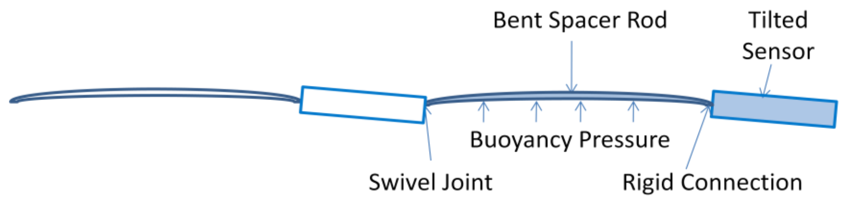

Figure 9. Instrument tilt caused not by ground movement, but buoyant bending of spacer rod. No actual ground displacement occurred.

After the casing had filled entirely with water, a new baseline was established under the new, buoyant condition, and the movement thresholds reset. Alas, when the TBM excavation did reach the area of interest beneath the instrument, the surrounding rock was drained of groundwater, and the water within the casing was rapidly drained along with it. The buoyancy force was removed, and the spacer rods and sensor elements returned to their original orientation, once again triggering the appearance of movement where none had occurred (Figure 10). Finally, after the TBM had passed, the excavation was lined and waterproofed, allowing the groundwater to return to its original level and the instrument to fill with water. The cycle of wet-dry-wet was repeated when the second TBM drove through.

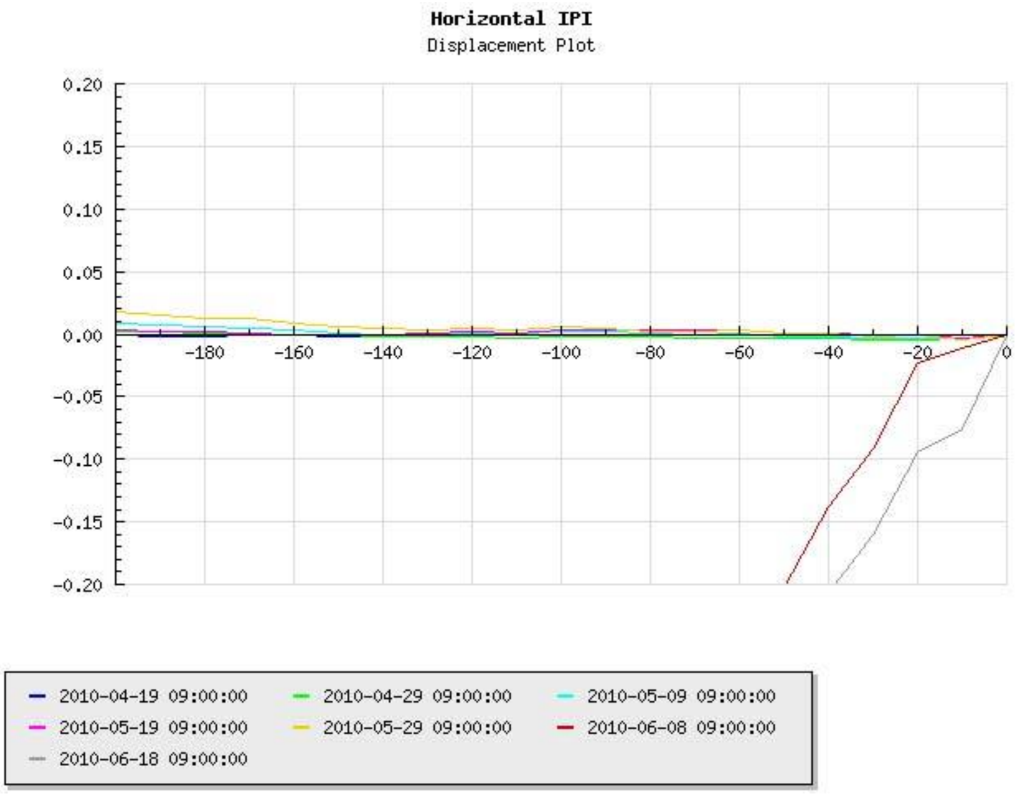

Figure 10. Output of automated online system (ARGUS), showing sudden displacement between 5/29/10 and 6/8/10, well beyond the magnitude of anticipated ground movement. The displacement was not real, but rather caused by draining the casing of water, which released the buoyant pressure bending the spacer rods.

The cause of these false movement fluctuations was found, but it took time and the apparent displacement had to be investigated and discounted in the field. The data was corrected to provide a continuous record, but this could only be produced well after the fact.

These headaches might be avoided in future horizontal IPI installations by preventing or neutralizing the effects of water in the casing. The borehole should be drilled with no slope or slight uphill slope, in order to allow any infiltrating water to drain out the open end. Alternatively, small holes may be drilled in each spacer rod before installation, in order to allow water in and out of them when the rest of the casing and instrument is submerged or drained. In our installation, each casing joint was sealed with primer, PVC glue and electrical tape. However, it is unrealistic to expect such a cumbersome instrument to remain water-tight in field conditions. It should be noted that the electronics of the instrument operated normally, and so must have remained waterproof after the tortuous installation process.

Another logical solution, grouting the instrument inside the casing in order to arrest any movement due to buoyancy, would not be constructible. With approximately 4-cm diameter sensors centered in the 7-cm inner-diameter casing, there would be no room to fit a tremmie pipe, and therefore no means by which to convey grout to the far end.

The final result proves the effectiveness of the instrument for this novel application, with one horizontal IPI taking the place of 4 to 6 vertical borehole extensometers. However care must be taken to avoid the buoyancy effect, which produced false movement alarms and created a delay in generating accurate results. Also, a shorter IPI would be much easier to install, given the difficulties of installing both casing and instrument to a horizontal depth of 200 feet. As with any inclinometer casing, care should be taken to avoid rotating the individual sections out of their sockets, with internal grooves aligned. This is more difficult to achieve in a horizontal installation, because substantial force may be required to insert the casing into the borehole without the aid of gravity as in a vertical borehole.

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