CEE AT ILLINOIS
Department of Civil and Environmental Engineering

GESO

# CEE 595 – Geotechnical Engineering Seminar

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## Monitoring and Controlling Ground Behavior at the Source: Recent Applications to Pressurized Tunneling

*Edward J. Cording, M. NAE*
*Professor Emeritus at University of Illinois at Urbana-Champaign*

**Abstract**

Ground movements monitored at their source are at the heart of the observational method and key to understanding and controlling ground behavior around an advancing tunnel boring machine (TBM). The challenge is to understand the pressures and displacements around the cutterhead and entire body of the tunnel shield to locate and minimize ground loss, and thereby prevent damage to structures.

Pressurized TBM technology has allowed the industry to tunnel deep under waterways and at shallow depth in urban areas. Recent advances in both technology and operational procedures have included the increasing capability to coordinate and control the TBM operation and monitor key machine functions and their impact on the surrounding environment in real time as the TBM advances.

Maintaining and monitoring a continuously pressurized envelope of conditioned muck, bentonite slurry, and grout around the entire face, body and tail of the TBM has resulted in improved control of ground movements throughout the tunnel drive. The records of machine functions are coupled with observations of ground behavior, including reconciliation of excavated weights/volumes and continuous measurements of ground movements and groundwater pressures using instrumentation such as borehole extensometer/piezometer systems and directionally drilled horizontal inclinometers above the tunnel crown.

Clearly, real time ground and machine information and improved feedback systems integrated with TBM advance are key to controlled tunneling. The benefits have been most dramatic in their application to large diameter TBMs and tunnels driven at shallow depth in urban areas.

These key interactions are described for shield tunnels in soft Chicago clay, earth-pressure balance tunneling on recent urban transit tunnel projects in Toronto, Seattle and Los Angeles and on the recently completed Alaskan Way Viaduct Replacement highway tunnel driven with a 17-m-diameter earth pressure balance machine (EPBM) in Seattle where the writer served as the Contractor's chief consultant on ground behavior and settlement control. Throughout the eleven month drive beneath the Viaduct structure, Historic Pioneer Square, and downtown Seattle, the TBM cutterhead and all gaps around the tunnel shield were continuously filled and pressurized preventing ground loss. Essentially, such a tunneling operation achieved the objective described in an 1818 patent application for a tunnel shield by Marc Isambard Brunel of "excavating only the ground that is located within the perimeter of the advancing shield". (Brunel later built the first subaqueous shield-driven tunnel, under the Thames River, London.)

Ground movements and groundwater pressures around the 17-m-diameter TBM were measured with borehole extensometer/piezometer units in boreholes spaced an average of 16 m along the alignment. The precision of the extensometers allowed measurement of the small displacements occurring immediately around the TBM caused not by ground loss into the gaps but by the elastic response due to the differential between overburden pressure and shield face/body pressures. Percentages of ground loss around the TBM ranged from 0 to 0.1%, far below initial estimates based on experience with smaller diameter tunnels. Settlements at the surface 12 to 66 m above the tunnel were zero, or within level survey error. The piezometers showed a different response in sands and clays, allowing identification of the soil types. In the undrained clays, the piezometers acted as stress cells, recording a reduction in ground stress in the clay above the shield due to the differential between overburden pressure and the applied pressure around the TBM. In sands, the piezometers measured the dynamic response of the groundwater which tended to track just below the face pressure and shield body pressures, which have to be consistently maintained above groundwater pressures to prevent ground loss. Groundwater pressures drop further below the face and shield body pressures as a cake of clay or bentonite forms a membrane on the excavated surfaces around the TBM.

One of the major issues faced by designers and contractors in planning and preparing for a tunnel project is the requirement for protecting structures along the tunnel alignment. Ground loss around the tunnel is distributed through the soil mass, resulting in lateral and vertical ground displacements at building foundations, in turn causing angular distortion and lateral ground and bending strains within bays of the structure which can then be correlated with damage criteria. The first priority should be to control building damage, not at the building or in the soil mass, but at the source of the ground loss. Increasingly, ground control is being achieved during tunneling with less reliance on procedures such as ground improvement, compensation grouting or ground reinforcement. Decisions are made to use these additional procedures to reduce risk, for example at start-up where the TBM cannot be fully pressurized or early in the tunnel drive where a history of ground control has not been demonstrated.

Locating the sources of ground movement, making synchronous adjustments in TBM operation and maintaining consistent control throughout the tunnel drive serves as a demonstration to tunnel project participants and third parties alike that structures along the tunnel alignment will be protected. The benefits to tunneling world-wide will be highlighted and discussed.