The Use of Permanent Tiedown Anchors for Underground Structures

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Background

- Urban transit project, Multiple underground stations
  - Limited ROW
  - Slurry walls, temp & permanent earth support
- Rock at or below invert
- Shallow groundwater
- Historic flooding
- Stations: Water tight
Options For Uplift Resistance

- Additional deadweight concrete
  - Thicken walls
  - Thicken interior & roof slabs
  - Thicken invert slab
  \[\text{Limited ROW}\]
  \[\text{Limited interior space, cover}\]
  \[\text{Requires 12 – 30 ft thick slab}\]
- Heavy weight concrete
  - Magnetite or iron aggregate
  - Limited precedence
    - Local availability?
    - Corrosion – ASR, stray currents
Options For Uplift Resistance (Continued)

- Skin Friction on Slurry Walls
  - Use for temp support
    - Deflection during excavation
    - Reduced normal force - ??
    - Bentonite slurry impacts - ??
  - Extend walls into rock
    - Significant embedment (tens of feet)
    - Add’l installation time & cost, feasibility
Options for Uplift Resistance (Continued)

- Passive structural elements in rock
  - Drilled shafts
    - Equipment impractical within excavation
    - Install from street level prior to excavation
      - Staging
      - Construction & demolition of shaft
  - Micropiles
    - Compact equipment, work inside excavation
    - Passive – require movement
    - Corrosion protection?
- Tie-down anchors
  - Active elements – locked off in tension
  - Design for corrosion protection
  - Overall more favorable, but need to manage risks

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- Bond in rock (rock anchors)
- Limited precedence for underground public works
- Transit agencies
  - Many do not address
  - Some prohibit (NYCTA, WMATA)
  - Limited precedence
    - North Shore Connector in Pittsburgh
      - Use for service load conditions
    - Berlin, Germany
    - Malmo, Sweden
    - Thessaloniki, Greece
    - All projects recent (< 10 years)
      - Long term performance??

(From Sabatini et al., 2004)

(From Zick, 2008)
Tiedown Anchors for Underground Structures (continued)

- Other underground structures
  - Sewer shafts
  - WWTP, pumping stations

- Concrete dam stabilization
  - Dates to 1930s, more common since 1970s
  - Corrosion protection has evolved
  - Design standards – USACE, PTI, etc.
  - High or significant hazard dams
    - Likely loss of human life
    - Underground structures: critical infrastructure, high cost to repair

(From Dywidag, 2013)
(From Eberling et al., 2013)
Tiedown Anchors
Risks & Mitigation Measures

- Anchors cast into invert slab
  - Cannot test/inspect anchors in the future
  - Cannot install anchors in the future
    - Too restrictive in station
    - Penetration of slab & waterproofing
- Incorporate additional reliability into design
Tiedown Anchors
Risks & Mitigation Measures (continued)

• Tiedown Anchor Design
  \[ \sum \eta_i \gamma_i Q_i \leq \sum \phi_i R_{ni} \]
  – Geotechnical uncertainties: address w/ resistance factors, \( \phi_i \)
    • Grout-rock bond stress
    • Dead weight of rock
Geotechnical Failure Mechanism Considerations

- Grout-bond interface (anchor pullout)
  - Standard practice:
    - Presumptive values (empirical)
    - Resistance factor, $\phi_r = 0.5$
      - $(FS = 2 \text{ in ASD})$
      - All anchors tested (proof or perf.)
    - Inherent risks?
        - Presumptive values vs. measured values, 100 case histories
        - $FS = 2.3$ proposed $(\phi_r = 0.43)$
      - Use $\phi_r = 0.40$
        - 100 year life, full load for service case
Geotechnical Failure Mechanism Considerations (continued)

- Cone Breakout (failure through rock)
  - Factored cone mass > uplift force
    - Deadweight of rock
      - (strength & friction neglected)
    - Design:
      - AASHTO, $\phi_r = 0.90$ for concrete
      - More variability for rock
      - Use $\phi_r = 0.70 - 0.80$ for rock
      - Minimum factored rock wt. = overburden soil

(From Sabatini et al., 2004)
Corrosion Risks

- Previous failures
  - Inadequate corrosion protection
    - Older case histories: similar to Class II, temporary anchors (grout only)
  - Leakage through anchor head
    - Exposed heads

(From Eberling et al., 2013)

Figure 1. Rock Anchor Components (PCI, 1974).
(Note the lack of protection to the steel other than grout.)
(From Bruce and Wolfhope, 2007)
Corrosion Mitigation Measures

- Tendon – threaded bar
  - Large section
  - More anchors, greater redundancy compared to multi-strand

- Head and Hardware
  - All hardware galvanized
  - Bitumen impregnated polyurethane gasket
  - Additional sealants
  - Recessed head w/ non-shrink grout

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Corrosion Mitigation Measures

• Additional Corrosion Considerations
  – Tendon material
    • Considered stainless steel or epoxy coated - lack of widespread precedence
    • Use ASTM Grade 150 black steel
      – Industry standard
      – Reliable, avoid unforeseen issues
  – Grout mix
    • Type II – some high chloride readings
    • 8% silica fume to decrease permeability
  – Electrical resistance integrity testing of plastic sheath
  – Long-term monitoring considered
    • Not used
    • Sensor life < design life, degradation leads to “false positives”
**Construction Staging Considerations**

- Water proofing membrane under invert slab
- Risk: anchors do not achieve capacity
  - Cannot install add’l anchors through membrane
- Developed detailed construction sequence:
  - Excavate to subgrade, pour mud slab
  - Install & test anchors on mud slab
  - Install waterproofing membrane & invert slab
  - Final testing & lock-off
  - Install hardware, grout recesses
Summary

• Detailed review of anchor design & performance risks
  – Geotechnical risks
  – Corrosion potential
  – Waterproofing
  – Construction sequencing

• Careful consideration of risks:
  – Anchors incorporated into underground structure design
Questions are welcome.
Thank you for your interest.

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