Reinforced Soil Projects: Bringing Research to Applications

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• RSW for mining project (D+C)
• Reinforced embankment on very soft clay
Introduction

• Reinforced Soil = RS
• = Mechanically Stabilised Soil (MSS)
• = Reinforcement + soil
• Reinforcement = Inclusions
Forms of RSS

- Fill structure:
  - dominantly sustained loading under normal conditions
Forms of RSS

- Cut slope:
- Transient loading: pavement structure
Forms of RSS

- Combined system-1:
- Geosynthetic encased stone columns: The geosynthetic reinforced the stones which in turn reinforced the surrounding soft soil.
Forms of RSS

- Combined system-2:
- Bored pile wall with soil nails (or passive anchors)
Stabilising Effects

- Provision of stabilising force(s) for O/A stability
Stabilising Effects

- Closely spaced reinforcement changing or controlling the strain state, thus stress state, of soil in its vicinity.
  - Metallic reinforcement: near K0 condition.
  - Geosynthetic reinforcement: limit lateral strain and hence prevent development of collapse mechanism. Soil around reinforcement likely to be at or near-failure state but RSS is safe.
Reinforced Soil Wall

- Wall configuration:

Active / Yielding Zone

Passive/Resistant Zone: soil holding reinforcement back

"Thin" Front panel: panels or continuous

Select fill

General Fill

Reinforced Zone / Block

$T_c$ $T_{\text{max}}$
Design Considerations

- Highly redundant system.
- Design Vs collapse based on simplified mechanisms.
- Internal stability: reinforcements of “adequate strength” that “bind” the soil into an integral (coherent) mass.
- Overall stability as an integral gravity RW
Internal Stability

• Reinforcement tension not excessive: normally check $T_{\text{max}}$ and $T_c$. Well “codified” in most cases.

• Adequate interaction between reinforcement and soil: pullout resistance.

Range of reinforcement + soil combinations presents opportunities.
Overall Stability

- Check as equivalent gravity RW.
- $\delta$ along virtual back depends on reinforcement stiffness because it affects the “overall stiffness” of the reinforced zone.
Overall Slip

- Weak foundation
- Hybrid failure modes:
  Often overlooked outside HK
Movement

• Rule of thumb and precedence.
• Finite element or FLAC analysis is very powerful and useful but need great care ….
• Particular issues for geosynthetic RSW.
  – A proper and consistent FE or FLAC analysis will give you considerable movement for most cases, and this is REAL.
  – We can usually rely on “smart” construction sequence to “built out” the movement. This means the reinforced zone has to be near-drained condition at end of construction. From a specification point of view, the select fill ….
• Also relate to construction sequence / details.
Model wall

- Paper as reinforcement
Steel straps
Ladder strap

- Ladder strap
Terramesh
Terramesh wall

- Lean back wall: Great Ocean Road
Soil nails

- VW strain gauging
Polyester Strap

Short term strength per strap:
20 to 100kN.
Pullout design issue to be discussed later.
Geogrid

- Flexible: from small polyester straps
- Stiff: Drawn from HDPE
Design sections

- Tall wall

Abutment wall
Pullout resistance

\[ R_p(i) = [\sigma_o(i)f(i)] \]
\[ A_p(i) = [\sigma_o(i)f(i)](\text{perimeter})L_p(i) \]

- Pullout Check: \( R_p(i) \) is “adequately large relative to” \( T_{\text{max}}(i) \).
- \( R_p(i) \) is a 2D design eqn.
- \( f = “\text{friction factor}” = “\text{apparent friction coefficient}” = \mu^* = \tan \delta^* \)
- \( f = \alpha F \).
  Where \( \alpha \leq 1 \) is a scaling factor to take into account progressive failure for extensible reinf.
- A few challenges (opportunities) presented by \( f \) or \( F \).
Friction Factor for straps

• Ribbed steel strap, $\alpha = 1$
• For well graded granular soils with $< 15\%$ fines:
  – How can we have $f > \tan \phi$?
  – Reduction of $\phi$ with overburden stress cannot explain the very high $f$-value at shallow depth.
  – How about other types of straps and select fill? (Textured surface polyester straps)
Constrained Dilatancy

- 3D interaction

\[ \tau_f = (\sigma_o + \sigma_y) \tan \delta \]
\[ = \sigma_o \left[ (1 + \frac{\sigma_y}{\sigma_o}) \tan \delta \right] \]
\[ = \sigma_o F \]
Pullout Testing

- Pullout testing is NOT an element test.
- It’s a model test that needs to be interpreted.
- At Det “X”: we need a sleeve because ….
Pullout Testing

• Influence of wall friction and box geometry
  – Section:

\[ \sigma_0 \ll \text{applied pressure} \]
\[ \sigma_0 \sim \text{applied pressure} \]

\( \sigma_0 \) wall friction

Low pullout resistance NOT representative
Pullout Testing Apparatus
Pullout box – pressure bag
Friction factor from pullout testing

- SW-Project (geosynthetic strap)
- PR-project (geosynthetic strap)
Modelling of Constrained dilatancy

- Key question: $\sigma_y = ??$
- Simple eqn to represent $(\tau/\sigma_n) - \gamma$ relationship in SS.
- Elasto-plastic decomposition of shear strain.
- Rowe’s Stress dilatancy eqn (in generalisd form) to model dilatancy in SS

$$\frac{F}{\tan \delta} = 1 + \left( 1 + \frac{\sigma_y}{\sigma_o} \right) = 1 + \left[ \frac{S_y(k_o)^n}{\left( \frac{\sigma_o}{P_a} \right)^{1-n}} \right] \left( \int_{\text{RP}}^{\infty} L.d\gamma^p \right) \tan \psi$$

(Note “C” and “RP” state as limit of integration)

$$\tan \psi = - \left( \frac{d\varepsilon_y}{d\gamma} \right)^p = \frac{\tau_f}{\sigma_n} \frac{K_{cv}}{K_{cv}}$$

$$\frac{f}{f_{100}} = \left( \frac{F}{F_{100}} \right) = \left( \frac{\frac{F}{\tan \delta}}{\frac{F}{\tan \delta}_{100}} \right) \left( \frac{\tan \delta}{\tan \delta_{100}} \right)$$

M2 toll road project
M2 Abutment
M2 Construction
Modelling of Constrained dilatancy

- M2 road project: we have the input parameters for making a real prediction (which tend to be lower than the measured values).
Not so happy story

- Abutment wall
- Severe reinforcement pullout issue.
- Do not want to spoil your appetite
TBB wall

• Dutton Park rail abutment: somewhere between Brisbane and Gold Coast.

• Tied back-to-back subject to high partial UDL.
TBB wall

Issues:
- Constructability
- Considerably higher $T_{\text{max}}$ (due to self weight of fill) been reported.
- Heavy setback surcharge.
TBB wall

• Construction:
TBB wall: Issues

• Nonlinear FE analysis.
• Results relevant to the design issues not sensitive to assume soil models.
• Conventional design eqns can be used for calculating $T$ due to self weight of fill and UDL.
• Use FEA results to develop simplified method for calculation $\Delta T$ due to setback surcharge.

Barnes Point Abutment

30 to 45 min drive from Gold Coast
Barnes Point Abutment

• Initial design based on both LE & FLAC analysis ….
• Wall instrumented with EPC, strain gauges, load bolts, HPG, settlement markers, inclinometers.
• Both vertical and horizontal movements (upon completion of wall) are somewhat unexpectedly high and of a pattern that leads to some concern about overall stability.
• Pre-construction (design stage) numerical analysis predict movements that are considerably & significantly lower than observed. With wisdom of hindsight, ….
• Whats wrong? Do we need to strengthen the wall?
Barnes Point Abutment

- Settlement at foundation level
  (note ~ 1000 day movement)
Barnes Point Abutment

- Wall settlement as measure by HPG

- Lateral movement: by inclinometer

![Graph showing wall settlement and lateral movement](image)
Barnes Point Abutment

• Higher than expected movements at service state (working condition)
  – Can be accommodated by bridge articulation (MJ etc)
  – may or may not infer a safety (ULS) issue.

• Initial limit equilibrium analysis indicated adequate FOS, but ……

• Therefore, need to address the two separate limit states with the “same” calculation model (in our case the same numerical model).
Barnes Point Abutment

Challenges:

• **Not** to predict the known movements at working condition. *Well, one can …*

• But to have a “single” analysis that can
  – Give conservative prediction (hopefully not too conservative) relative to the known movements.
  – continue to collapse (without the need of ad-hoc procedures to handle numerical ill-conditioning) so as to assess the safety margin of the wall.

• This means that our observations of higher than expected movements can be “fed” into the calculation of safety margin
Barnes Point Abutment

- Strategy:

  Develop numerical model

  Estimate design parameters

  Perform analysis to working condition

  Computed movement ≥ observed?

  Continue analysis to collapse

  Adequate FOS?

  OK

  Additional investigation to refine parameters

  Refine model and/or parameters?

  Needs strengthening

Barnes Point Abutment

- Computed vertical settlement.

Contour interval = 20mm
Maximum settlement = 140 mm
Great Western Hwy: near Katoomba

- Use ribbed steel straps

Issues

• All “near by” borrow areas gave select fill with high fines content. (Although very low clay content).
• Significant contractual implications if we need to hauled select fuil in (say from >100 km away).
• $f = ?$ Should we jump into pullout box testing?
• One need dilatant soil to get high $f$.
• First study stress-dilatancy behaviour in Tx testing …. 
• Stress-dilatancy plot:
  very dilatant behaviour

- Pullout testing:

\[ D = 1 - \frac{d\varepsilon_{\text{vol}}}{d\varepsilon_1} \]
Pullout Box: Test Assembly (2)

Top half of box installed

Soil in top $\frac{1}{2}$ of box compacted
OB Mine

• For mining project in Qld.
  – in the middle of nowhere.
  – an challenging project.

• Working load:
  Front = 50kN/m
  Rear = 25 kN/m

OB Mine

• Simplified eqns for calculating $T_{\text{max}}$ and $L_p$ problematic.
• FLAC analyses conducted
• At working load: $T = 11.1\text{kN/m}$. Lateral movement due to application of LL is $\sim 20\text{mm}$.
• What is $T^*$ for reinforcement rupture and pullout resistance check.
• Continue FLAC analysis beyond working load and proceed to factored load.
• What should be the factored soil parameters
  – $\phi \rightarrow \phi^*$
  – What should be the factored interface strength?
OB Mine

- Factored interface strength:

<table>
<thead>
<tr>
<th>Partial factor on f</th>
<th>T* (kN/m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>11.1</td>
<td>Extensive interface yielding</td>
</tr>
<tr>
<td>1.0</td>
<td>12.4</td>
<td>Reduced interface yielding</td>
</tr>
<tr>
<td>2.0</td>
<td>14.5</td>
<td>No interface yielding</td>
</tr>
</tbody>
</table>

** Issue of multiple failure modes **
Reinforced embankment

- Road embankment at L-Swamp:
  - 45 min north of Sydney
  - on the way to Central Coast
Reinforced embankment

• X-section

![Diagram of reinforced embankment with X-section details and instrumentation locations.]}
Reinforced embankment

- Reinforcement embankment on very soft clay.
- Basal reinforcement with flexible geogrid (short term strength 200kN/m)
- PVD for ground improvement
Reinforced embankment

- Extensive instrumentation with 9 years of data.
- Contribution of reinforcement to enhancing stability and reducing settlement is slight.
- However, it constrained lateral movement at foundation level and thus prevent “lateral spreading” of embankment fill.

**The embankment fill is not an elastic material. Its strength & stiffness depends on confining stress.**
Do you want me to go thro’ the 9 years of data ??
Thank You
Findings

- Realistic & detailed modelling.
- Movement prediction higher than observed.
- Probable due to over-conservative interpretation of foundation condition.
- Displacement pattern do not show the initiation of a failure mechanism.
- Continue the analysis by progressively reduce foundation strength parameters until collapse is detected. This can be achieved “objectively” in FLAC.
  - FOS on tan$\phi'$ of foundation $\geq 1.5$.
  - Reinforcement tension remaining less than the rupture strength.
Numerical model

- Computed horizontal settlement.

Contour interval = 20mm

Maximum lateral movement = 175 mm
Pullout Testing: strain gauging

- Polyester strap
Progressive Pullout failure

• Progressive failure
  – Due to reinf extensibility
  – Lead to scaling factor $\alpha$
  \[ R_p = (f).\sigma_v.(\text{perimeter}).L_p = (\alpha F).\sigma_v.(\text{perimeter}).L_p \]
Top and Bottom half of split box
Pullout Testing

- **Flexible** sleeve to
  - Remove shear stress transfer
  - Avoid interference with settlement of soil
Bottom half + strap in place
SELECT FILL ISSUES

REMINDER:
- Select fill used in reinforced zone
- Walls are 99% select fill and ~1% reinf
- If the fill is not compatible with design or performance requirement, the wall will be problematic
RS Wall: stresses and Interactions