Problem and Solutions of Weak Soil In Engineering Application

Ir. Liew Shaw Shong

G&P Geotechnics Sdn Bhd, Kuala Lumpur, Malaysia
Content

- Common Problems in Linear Infrastructure Project
- Site Investigation
  - Planning, Execution & Interpretation
- Forensic Investigation
  - Stability of Piled Supported Retaining Wall
  - Embankment Distress (Strain Incompatibility)
  - Abutment Distress due to Piled Embankment Failure
  - Unreliable Facing Capacity of Soil Nailed Slope
- Design of Stone Columns for Wall Support in Soft Ground
Common Problems of Linear Infrastructure Projects

- Alignment – Cut & Fill Problems over Terrains & Formations
  - Cut: Slope Stability, Excavation in Rocks & Hard Materials
  - Fill: Walls, Embankment Bearing Stability & Settlement
- Bisecting Drainage Catchment & Flow Path: Internal/Scouring Erosion & Bridge Foundation
S.I. vs. Medical Diagnosis

- History
- Symptoms & Signs (Non-specific)
- Physical Examination

Diagnosis

Causes & Triggers

Solution Development

Treatment Decisions

- Differential Diagnosis
- Pattern Recognition
- Diagnostic Criteria
- Decision Support System (Knowledge Database)
- Others (Algorithms/Exhaustive Method)
Site Investigation

- Planning, Execution and Interpretation of Site Investigation (SI)
  - Lack of Geological & Geographical Knowledge (Genesis of ground formation, sequences of geo-processes, alteration with development activities, etc)
  - Inadequate Desktop Study
  - Over-emphasis on sampling & laboratory testing within project site & often ignoring macroscopic view of site
  - Time dependent variation of site condition
  - Validity of empirical calibration between pre and post site disturbance
Site Investigation

• Establish appropriate geological model from desktop study
  – Topographical & terrain maps
  – Geological & hydrogeological maps
  – Pre & post site disturbance survey
  – Historical land use information
  – Adjacent site information

• Minimise investigative resources to validate geological model and characterise the site with engineering properties

• Review the strategy of sampling and testing during drilling by experienced site supervising engineer

• Use of Geophysical exploration tools with good communication on investigating objectives & expectation
Case 1: Lessons Learnt on Stability of a Piled Retaining Wall in Weak Soils
Cross Section of Wall

- **RL48m**

- **50mm Thk Lean Concrete**

- **T12-150**
  - **150mm Weep hole**

- **300mm Free Draining Granular Material**

- **Construction Joint**

- **T16-100**

- **T12-150**

- **T20-100**

- **T12-150**

- **100mm Subsoil Pipe**

- **5 Rows of 200x200 RC piles @ 2m Spacing**
Water Level & Erosion

- Weephole at RL47.5m
- Weephole at RL45m (Water staining)
- Weephole at RL42.5m

Erosion at Wall Base

Erosion by Weephole Discharge
Forensic Boreholes

Undrained Shear Strength, $S_u$ (kPa)

0 2 4 6 8 10 12 14 16 18 20 22 24 26

Depth (m)...

Strength adopted in analysis, $S_u = 25$ kPa

Undrained shear strength profile of normally consolidated fine soils

Previous Stream

Wall

1st Stage BH

2nd Stage BH

Forensic BH

ABH1

ABH2

BH8

BH9

BH10

BH1

BH4

BH3

BH7

BH6

RL42.34m

RL38.34m

(Possible Slip Surface)

Interpretation of Vane Shear Test Results

bullet Peak Strength

bullet Remoulded Strength

$\text{Peak Strength adopted in analysis, } S_u = 25\text{ kPa}$

$\text{Line } = 0.22\sqrt{z}$

Undrained shear strength profile of normally consolidated fine soils

Peak strength and remoulded strength are obtained from vane shear test results

Relationships between points...
Stability Assessments

FOS of External Wall Stability

<table>
<thead>
<tr>
<th>GWT</th>
<th>Over-turning</th>
<th>Sliding</th>
<th>Global Stability</th>
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</thead>
<tbody>
<tr>
<td>RL45m</td>
<td>✓</td>
<td>✗ 0.97&lt;1.0</td>
<td>✗ 1.13/1.17</td>
</tr>
<tr>
<td></td>
<td>2.9&gt;2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL42.5m</td>
<td>✓</td>
<td>✗ 1.34&lt;1.5</td>
<td>✓/✗ 1.16/1.24</td>
</tr>
<tr>
<td></td>
<td>3.7&gt;2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL40.4m</td>
<td>✓</td>
<td>✗ 1.5</td>
<td>✓/✗ 1.19/1.25</td>
</tr>
<tr>
<td></td>
<td>3.8&gt;2.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bearing Capacity is never a concern as pile foundation is designed to take the vertical loading of wall
More prominent in effective stress analysis, but less for total stress analysis.
Pile Integrity Testing

6 PIT: Discontinuity detected at depths from 1m to 4m below pile top
Probable Causes of Wall Distress

- Potential perched water regime in natural valley terrain after raining
- Rise of groundwater increases the lateral force on wall
- Inadequate lateral pile resistance
  - Fixed Head : 32kN/pile (Likely the case)
  - Free Head : 20kN/pile
- Ultimate lateral pile capacity reached when RL42.5m < GWT < RL45m
- Reduction of effective soil strength due to reduction of vertical stress as wall loading carried by piles
Remedial Solution

- **3m Soil Replacement below RL39.3m**
- **Disconnected piles by over cutting below cut-off level**
- **Collector Pipe Drain**
- **Drainage Blanket**
- **Stabilising Berm**

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**Diagram Note:**
- Horizontal arrows indicate the direction of drainage flow.
Case 2: Extendible Basal Reinforcement for Embankment Construction Over Soft Soils

- **Problem Statements**
  - Embankment Fill over Soft Deposits
  - PVD Treatment with Staged Fill Construction
  - Basal Reinforcement for Temporary Embankment Stability
  - BS8006
  - Strain Incompatibility

- **Distresses**
  - Longitudinal flexural cracks on embankment surface
Embankment Distresses

Cracks locations of distressed embankment

Crack line observed.
Embankment Distresses

1m surcharge removal after distresses observed
Embankment Distresses

Excavation on cracks found after 1m surcharge removal
Instrumentation Layout

Plan at Distresses area
Instrumentation Results

Fill Thickness and Settlement of Embankment with time monitoring by **SG580**

Inclinometer I6 Monitoring Results
Finite Element Model (Back Analyses)

Case 1: Ultimate strength (600kN/m) mobilized at 10%
Case 2: Ultimate strength (140kN/m) mobilized at 1%
Finite Element Model

Comparison of Back Analysed Settlement Trend With Actual Measurement (Case 1)

Comparison of Lateral Displacement Profile (Case 1)
## Summary of Back Analyses

<table>
<thead>
<tr>
<th>Stage</th>
<th>Tensile Stiffness</th>
<th>Mobilised Tensile Load / Tensile Strain</th>
<th>Maximum Lateral Deflection at Edge of Embankment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Case 1</td>
<td>40.6kN/m / 0.68%</td>
<td>267 (173)</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>65.9kN/m / 0.47%</td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>Case 1</td>
<td>41.8kN/m / 0.70%</td>
<td>295 (180)</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>67.4kN/m / 0.48%</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Case 1</td>
<td>64.6kN/m / 1.08%</td>
<td>400 (253)</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>106.8kN/m / 0.76%</td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>Case 1</td>
<td>67.4kN/m / 1.12%</td>
<td>425 (265)</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>110.3kN/m / 0.79%</td>
<td></td>
</tr>
</tbody>
</table>
Probable Mechanism

- Tension Crack
- Settlement
- Potential Slip Surface
- Horizontal Displacement
Conclusions

- Back-analysis result ➔ indicated mobilised tensile strength and strain << conventional assumed values for LEA stability analysis.

- Strain incompatibility (Strain level): Weak Alluvial Soil (Plastic Straining) ➔ Basal Reinforcement (Extendible) ➔ Compacted Fill (Brittle) ➔ Longitudinal cracks.

- Review on current design practice by arbitrarily adopting unrealistic high mobilised strength is needed.

- Wishful high tensile strain assumed in LEA can lead to misrepresentation on safety margin of embankment.
Recommendations

- Counterweight berm was proposed to solve the strain incompatibility between basal reinforcement and the subsoil.

- Instrument on basal reinforcement to reveal the distribution profile and performance of installed basal reinforcement.
Case 3: Piled Supported Embankment Failure

- Abutment A
- Pier P1
- Pier P2
- Abutment B
- Piled Embankment
- PVD + EVD Area

Filled Working Platform
Upper Weak Soil
\( S_u = 13\sim18\text{kPa} \)

Lower Firm Stratum

\( S_u = 7\sim12\text{kPa} \)

\( S_u = 10\sim15\text{kPa} \)

5.4m
Site Inspection Findings

- Piled Embankment 30m from Abutment B shown structural distress
Site Inspections Findings

- Piles of Piled Embankment has shown flexural cracks
Site Inspections Findings

- Damaged piled embankment slab damaged & 100mm gap at slab joint
Site Inspections Findings

- Settlement of 0.4 to 1.0m under the Piled Embankment
Site Inspections Findings

- Bearing distortion at Pier P1
Site Inspections Findings

- Bearing distortion at Pier P2
Settlement Markers (LDC) : 28 May - 31 Jul 2005
Displacement Markers (by LDC) : 02 Mar – 18 Jun 2006

- $P_A$: Active Earth Pressure
- $P_1$: Action/Reaction Force between Piled Embankment Slab & Abutment
- $P_2$: Ultimate Lateral Pile Group Capacity of Embankment Piles
- $P_3$: Mobilised Thrust on Stability Soil Mass with Corresponding FOS

**FOS \approx 1.0**
Conclusions

- Weak post-treatment soil strength unable to support embankment
- Creep movement of weak subsoil beneath embankment coupled with embankment instability due to low FOS
- Monitored bridge displacement confirmed pattern of lateral movement of entire bridge & piled embankment
- Further consolidation of weak overburden soil beneath working fill platform resulting in free standing pile conditions
- Structural damage on free standing embankment piles was expected as structural threshold has been reached
Case 4: Unreliable Facing Capacity of Soil Nailed Slope

- With intention of minimized earthwork cutting forming any platform, soil nailed slope profile is normally steep.
- Facing capacity has remarkable effect on Internal Stability of steep soil nailed slope.
- Volumetric swelling & shrinkage of soils with moisture variation are realistic observation.
- Moisture depletion after covering with shotcrete surface results in volumetric shrinkage of slope soil face leaving air gap with separation of contact with shotcrete.
- Mobilisation of face capacity in uncontacted slope surface is unrealistic, thus giving incorrect safety margin of slope stability.
Volumetric Shrinkage of Exposed Soil
Gap below Shotcrete Surface with Depleting Moisture
Nail Force Diagram & Stability

With Nail Head Capacity

Without Nail Head Capacity

\( f_{s,p} \)

\( f_{s,a} \)

FOS \( \uparrow S_2 \)

\( \downarrow S_1 \)

Soil Nail

Slip Surface

T_N

T_H
Case Study 5: Performance of Stone Columns Supported RS Wall

- Original Topography
- Subsurface Information
- Adopted Foundation System for RS Wall
- Design Consideration
- QA/QC During Construction
- Design Verification
- Conclusion
Original Topography of Site

- Original ground is hilly
- Surface runoff towards natural valley area
- Within proximity of previous water stream

⇒ Weak deposits
Piled Embankment

RS Wall Elevation Profile
SUBSURFACE INFORMATION

- Residual Soil
- Granitic Formation
- Intermediate Boulders
S.I. Layout Along RS Wall
Subsurface Profile Along RS Wall

Soft Compressible Layer
Implications

Soft compressible subsoil
ADOPTED FOUNDATION DESIGN SYSTEM FOR RS WALL

- 10m high reinforced soil wall on up to 12m thick soft compressible subsoil

- Stone column
  - 1m diameter
  - 2m centre to centre spacing
ADOPTED FOUNDATION DESIGN SYSTEM FOR RS WALL

Reasons

- Reinforcement of weak subsoil
- Drainage for dissipation of excess pore pressure generation
- Improving strength and deformation properties of soil
DESIGN CONSIDERATIONS

- **Bulging** of individual stone column
- **General shear** of stone column
- **Stress distribution** between stone columns and subsoil
DESIGN CONSIDERATIONS

- Bearing capacity of subsoil and stone column
- Global stability of RS wall
- Overall ground settlement after improvement
QA / QC DURING CONSTRUCTION

• Material control

• Appropriate termination criteria of stone column installation

• Verification test (plate load test)
Material Control

- Clean, hard, durable
- Chemically inert natural materials

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Criteria</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing Value</td>
<td>BS 882:1992</td>
<td>&lt;30%</td>
<td>1 test per 30,000 tonnes of aggregate</td>
</tr>
<tr>
<td>Los Angeles Abrasion</td>
<td>ASTM C131</td>
<td>Max loss of 40% at 500 revolutions</td>
<td></td>
</tr>
<tr>
<td>Flakiness Index</td>
<td>BS 882:1992</td>
<td>&lt;30%</td>
<td></td>
</tr>
<tr>
<td>Sulphate Soundness</td>
<td>ASTM C88</td>
<td>&lt;12%</td>
<td></td>
</tr>
</tbody>
</table>
Material Control
(Allowable grading of stone aggregates)

Range of Soils suitable for Vibro Compaction Methods
(Baumann and Bauer, 1974)
Termination Criteria

- Hydraulic pressure in the vibratory probe = 190 bars

TO BE VERIFIED BY PLATE LOAD TEST DURING FIRST COLUMN INSTALLATION
Termination Criteria

~190 bars
Verification Test (Plate Load Test)
Verification Test (Plate Load Test)
Verification Test

Load Settlement Curve for 1000mm diameter stone column

< 250mm :: OK
DESIGN VERIFICATION

• Finite element method (FEM) analyses using PLAXIS

• Monitoring instrumentation scheme
PLAXIS Model & Analyses

- Compacted Backfill 1
- Compacted Backfill 2
- Pavement
- RS Wall
- Soft Clay 1
- Soft Clay 2
- Bedrock
- Medium Stiff Soil
- Stone Column
Instrumentation Monitoring Scheme
Instrumentation Monitoring Scheme

Inclinometer with Magnetic Extensometers

Details of Displacement Markers
Instrumentation Results

E-Wall Profile and Settlement Displacement Markers Along E-Wall With Time

Settlement (mm)

E-Wall Profile and Settlement Profile

Piled Foundation to protect existing pipe culvert beneath RS Wall

Chainage

Settlement Profile

~120mm
Instrumentation Results

E-Wall Profile and Settlement Displacement Markers Along E-Wall With Time

Settlement (mm)

Piled Foundation to protect existing pipe culvert beneath RS Wall

Maximum Rotation = 1: 265

Maximum Rotation = 1: 178

Maximum Rotation = 1: 184

Maximum Rotation = 1: 214

< 1:100 ➔ OK
Instrumentation Monitoring Scheme

Revised location

Legend:
- REMOVAL & SOIL REPLACEMENT (UP TO THICKNESS OF 1m)
- REMOVAL & SOIL REPLACEMENT (UP TO THICKNESS OF 2m)
- STONE COLUMN DESIGNED BY GUE & PARTNERS SDN BHD
- STONE COLUMN DESIGNED BY SPECIALIST CONTRACTOR SDN. BHD.
- DISPLACEMENT MARKER - SDM (36 NOS.)
- INCLINOMETER AND EXTENSOMETER - IN (1 NO.)
Instrumentation Results

Inclinometer at CH84.6m (A-A) @SDM18

Displacement (mm)

Depth (m)

Design Limit
Instrumentation Results

Lateral Displacement Profile

Inclinometer

Lateral Displacement Profile
Instrumentation Results

Graph showing settlement vs. depth with dates from 7/29/2004 to 11/30/2004. The design limit is indicated on the graph.
Instrumentation Results

Vertical Displacement Profile

Inclinometer

Vertical Displacement Profile
(δ/ρt) Diagram with Factor of Safety (After Matsuo et al, 1977)

Legend

- Current
- Predicted

Instrumentation Results
CONCLUSIONS

• Successful installation of stone columns within economical means

• To consider
  ➔ Design Aspects
  ➔ Quality Assurance and Quality Control during construction
CONCLUSIONS

- Use Observational Method and Finite Element Analysis

- Matsuo plot can also be applied to verify the FOS of RS wall
Conclusions

- Site investigation practices vs. medical diagnosis
- Five case studies
  - Erroneous external wall stability of pile supported wall
  - Incompatible straining of basal reinforcement with brittle compacted fill and plastic supporting soft clay
  - Unstable piled embankment due to free standing pile support from consolidation of piling platform fill
  - Unreliable face capacity of soil nailed slope due to volumetric soil shrinkage by depleting moisture content
  - Stone Columns in Soft Clay for Wall Support
Thank You for Your Attention