Study of Nail-soil Interaction by Numerical Shear Box Test Simulations

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Preface

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Y.C. Chan
Head, Geotechnical Engineering Office
March 2012
Foreword

This study forms a part of a series of nail-soil interaction studies. Numerical simulations of direct shear box and zone shear box tests have been carried out to examine the soil-interaction of soil nails in respect of lateral soil pressure, and the mobilisation of axial force, shear force and bending moment in the soil nails. The findings of the study lay out a framework for examining the feasibility of using new material other than steel for soil-nail reinforcement.

The study was carried out by Dr R.W.M. Cheung and Dr G.W.K. Chang of the Standards and Testing Division. Many other colleagues provided constructive comments on a draft of this report. Their contributions are gratefully acknowledged.

W.K. Pun
Chief Geotechnical Engineer/Standards & Testing
Abstract

Soil nailing has been commonly used as a structural support to enhance stability of existing and newly formed slopes. Its performance is generally satisfactory, however, the current design approach has made little account for the nail-ground interaction in particular if new materials other than steel are used for soil-nail reinforcement. A study using simulated direct shear box and zone shear box has been carried out to investigate the behaviour of steel soil-nail reinforcement subject to shearing with and without contrast in soil stiffness between the two shear zones.

The results indicate that axial force, shear force and bending moment were mobilised when the soil nail was subject to shearing. The distributions of axial force, shear force and bending moment generally resemble those determined theoretically. The degree of mobilisation increases as the width of shear zone decreases, and as the contrast in soil stiffness increases. Among the mobilisation of axial force, shear force and bending moment, the latter is the highest irrespective of the width of shear zone and the contrast in soil stiffness.

This report presents the details and findings of the study.
Contents

Title Page 1
Preface 3
Foreword 4
Abstract 5
Contents 6
List of Tables 7
List of Figures 8

1 Introduction 10

2 Effect of Shearing and Bending on Soil-nail Reinforcement 10
  2.1 Past Experimental and Theoretical Studies 10
  2.2 Numerical Simulations 12
    2.2.1 General 12
    2.2.2 Assumptions 12
    2.2.3 Modelling of Shear Plane 15
      2.2.3.1 Numerical Model - Direct Shear Box Test 15
      2.2.3.2 Results and Discussions 15
    2.2.4 Modelling of Shear Zone 20
      2.2.4.1 Numerical Model - Zone Shear Box Test 20
      2.2.4.2 Results and Discussions 26
    2.2.5 Modelling of Ground with Contrast Stiffness 26
      2.2.5.1 Results and Discussions 26
  2.3 Technical Implications 41

3 Conclusions 41

4 References 42
## List of Tables

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Summary of Results on Numerical Direct Shear Box Test and Zone Shear Box Test Simulation</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Summary of Results on Numerical Direct Shear Box Test Simulations with Soils of Contrast in Stiffness</td>
<td>27</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Distribution of (a) Bending Moment ($M/M_p$), (b) Shear Force ($P_s/P_p$) and (c) Lateral Stress ($\sigma'/\sigma'_b$) at a Shear Displacement of 60 mm (after Pedley, 1990)</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Simplified Distributions of Net Lateral Soil Pressure on a Soil-nail for Different Failure Modes (Modified Tan et al, 2000)</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Shear Patterns Generated by Different Types of Shear Box Test Simulations</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Details of Numerical Direct Shear Box Test Simulation</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Net Lateral Soil Pressure Distribution along the Soil Nail in Numerical Direct Shear Box Test Simulation</td>
<td>18</td>
</tr>
<tr>
<td>2.6</td>
<td>Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta$ = 5 mm</td>
<td>21</td>
</tr>
<tr>
<td>2.7</td>
<td>Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta$ = 10 mm</td>
<td>22</td>
</tr>
<tr>
<td>2.8</td>
<td>Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta$ = 25 mm</td>
<td>23</td>
</tr>
<tr>
<td>2.9</td>
<td>Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta$ = 50 mm</td>
<td>24</td>
</tr>
<tr>
<td>2.10</td>
<td>Details of Numerical Zone Shear Box Test Simulation</td>
<td>25</td>
</tr>
<tr>
<td>2.11</td>
<td>Net Lateral Soil Pressure Distribution along the Soil Nail in 100 mm Numerical Zone Shear Box Test Simulation</td>
<td>28</td>
</tr>
<tr>
<td>2.12</td>
<td>Net Lateral Soil Pressure Distribution along the Soil Nail in 200 mm Numerical Zone Shear Box Test Simulation</td>
<td>30</td>
</tr>
<tr>
<td>2.13</td>
<td>Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta$ = 5 mm</td>
<td>32</td>
</tr>
</tbody>
</table>
Figure No. | Description | Page No.
--- | --- | ---
2.14 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 10$ mm | 33
2.15 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 25$ mm | 34
2.16 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 50$ mm | 35
2.17 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 5$ mm | 36
2.18 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 10$ mm | 37
2.19 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 25$ mm | 38
2.20 | Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 50$ mm | 39
2.21 | Details of Numerical Direct Shear Box Test Simulation with Soils of Contrast in Stiffness | 40
1 Introduction

The soil nailing technique was introduced to Hong Kong in the 1980s. Since the early 1990s, the technique has been popular in enhancing the stability of existing and newly formed slopes. Experience gained over the years of application has led to the publication of the Geoguide 7: Guide to Soil Nail Design and Construction (GEO, 2008), which summarised the standard of good practice for the design, construction, monitoring and maintenance of soil-nailed systems.

As steel reinforcement has high shear ductility, which renders the failure mode of a soil-nailed system likely to be ductile, it is generally not necessary to check against bending and shear failure of steel reinforcement in design. With the advancement of material technology, the potential of using new materials as an alternative to steel bars for soil-nail reinforcement will increase. Among those factors listed in Geoguide 7, the susceptibility to bending or shear failure should be considered if an alternative material other than steel is used as soil-nail reinforcement.

Numerical modelling provides a tool to investigate the behaviour of a soil-nail reinforcement subject to shearing. In this study, the element behaviour of a soil-nail reinforcement under shearing was studied by means of numerical shear box test simulation using the finite element programme, PLAXIS (Version 8). The reinforcement was placed normal to the shear plane. This is to examine the behaviour of the reinforcement under the worst scenario in respect of maximum bending and shear force. The bending moments and forces obtained from the numerical simulations were also compared with theoretical values.

2 Effect of Shearing and Bending on Soil-nail Reinforcement

2.1 Past Experimental and Theoretical Studies

When a soil nail is being sheared, lateral soil pressures will be developed on both sides of the soil-nail reinforcement, and hence the development of axial force (tension or compression), bending moment and shear force. Figure 2.1 reproduces some experimental results showing the distributions of bending moment, shear force and lateral soil stress in shear box tests obtained by Pedley (1990). A key finding of his study is that the maximum mobilised shear forces are well below their ultimate values even though the corresponding bending moments are close to their plastic values.

On the basis of the experimental and theoretical work by Pedley (1990) and Jewell & Pedley (1992), Tan et al (2000) proposed the following simplified failure modes to describe the nail-soil lateral interaction when a soil-nail reinforcement is subjected to shearing:

(a) Mode A1: Plastic soil-elastic nail failure mode.
(b) Mode A2: Plastic soil-plastic nail failure mode.
(c) Mode B: Plastic nail-elastic soil failure mode.
(d) Mode C: Plastic soil-nail failure mode.
### Legend:

- **M**: Bending moment of nail
- **$M_P$**: Fully plastic bending moment of nail
- **$P_s$**: Nail shear force
- **$T_P$**: Fully plastic axial force in nail
- **$\sigma'_l$**: Lateral stress on nail
- **$\sigma'_b$**: Limiting bearing stress
- **$L$**: Total length of nail
- **$z$**: Distance measured from origin in the Z direction
- **$\theta$**: Angle made between nail and the normal to the shear plane

### Note:
The plastic shear force, $P_p \approx \frac{T_P}{2}$

---

**Figure 2.1** Distribution of (a) Bending Moment ($M/M_P$), (b) Shear Force ($P_s/T_p$) and (c) Lateral Stress ($\sigma'_l/\sigma'_b$) at a Shear Displacement of 60 mm (after Pedley, 1990)
Mode A1 failure will occur if a soil nail is relatively stiffer and stronger than the surrounding soil. Mode A2 failure is a further development of Mode A1 when the relative displacement between the soil and soil nail increases. Mode B failure will occur if the soil is relatively stiffer and stronger than the soil nail, whereas Mode C failure will occur when the soil nail and the soil have compatible stiffness and they reach their plastic stages simultaneously. The distributions of net lateral soil pressure for failure modes A1, A2 and B are shown in Figure 2.2. Failure mode C is a special case of mode A1 and therefore has a similar distribution of lateral soil pressure as shown in Figure 2.2, except that the point of maximum bending moment is replaced by the point of moment capacity of the soil nail.

2.2 Numerical Simulations

2.2.1 General

The nail-soil interaction under direct shearing was investigated using numerical shear box test simulation with different boundary conditions. Figure 2.3 shows schematically the shear patterns generated by the two types of shear box test simulations. They are (a) the direct shear box test and (b) the zone shear box test. The direct shear box test simulation allows a designated failure plane to develop, whilst the zone shear box test simulates a designated uniform shearing zone across the nail.

Numerical shear box test simulations were conducted using the finite element computer programme PLAXIS. The following scenarios were considered in the numerical simulations:

(a) Shearing plane.

(b) Shearing zone with thickness of 100 mm and 200 mm.

(c) Contrast in soil stiffness between the two halves of the shear box.

2.2.2 Assumptions

A 25 mm diameter steel bar was modelled in the present study. The following assumptions were made in the numerical simulations:

(a) The effect of soil pressure re-distribution in the direction normal to the paper (z-direction) was ignored in the 2-dimensional (plane-strain) model.

(b) The results including the axial force, the shear force and the bending moment for a single steel bar were simply taken by dividing the results per metre run by the total equivalent number of bars in the 2-dimensional analysis, i.e. 40.

(c) The effect of reinforcement ribs on the nail-soil interaction was ignored.
Figure 2.2 Simplified Distributions of Net Lateral Soil Pressure on a Soil-nail for Different Failure Modes (Modified Tan et al, 2000)

Legend:

- $\sigma_b$: Soil limit bearing pressure
- $\sigma$: Soil pressure on soil nail
- $T_c$: Nail-soil lateral resistance
- $l_s$: Width of shear band
- $l_b$: The minimum soil-nail length required beyond the point of maximum bending moment
Figure 2.3  Shear Patterns Generated by Different Types of Shear Box Test Simulations

(a) Direct Shear Box Test

(b) Zone Shear Box Test
(d) Interface elements were used to model the interface between soil and the nail. The reduction factor in shear strength, $R_{\text{inter}}$, for the interface between the nail and the soil was taken as 0.66 in this comparative study as recommended by the PLAXIS.

(e) A Mohr-Coulomb elastic-perfectly-plastic model was employed.

(f) The effect of soil contraction/dilation during shearing was ignored.

### 2.2.3 Modelling of Shear Plane

#### 2.2.3.1 Numerical Model - Direct Shear Box Test

The simulated shear box has dimensions of 1 m wide x 3 m deep and a length of 6 m split into two halves. A 1 m wide steel plate equivalent to 40 no. of 25 mm diameter and 3 m long steel bars was inserted in the middle of the box across the vertical slip surface. The box was filled with homogeneous sand. The details of the model shear box, and the soil and steel parameters are given in Figure 2.4.

A 2-dimensional (plane strain) Mohr-Coulomb model was used for the soil. The shear box was initially restrained to move horizontally at both the right-hand and the left-hand sides, and restrained to move vertically at the bottom. A pressure of 80 kN/m$^2$ was applied on the top of the box to model a 5 m high overburden pressure. An imposed uniform boundary shear displacement $\delta$ of 5 mm, 10 mm, 25 mm and 50 mm was then applied in sequence in the downward direction $y$ along the top and bottom of the right half of the box, simulating the uniform downward movement of the right half of the shear box. The lateral soil bearing pressure would be generated as a function of the relative displacement between the soil and the plate, and the interaction between them was then investigated.

#### 2.2.3.2 Results and Discussions

For each imposed boundary shear displacement $\delta$, the net lateral soil pressures $\sigma_l$ obtained from the numerical simulations are shown in Figure 2.5. The theoretical net lateral soil pressure distributions for failure modes A1 and A2 as described in Section 2.1 are also plotted in the figures for comparison.

The maximum shear force $P_{s\text{max}}$, maximum bending moment $M_{\text{max}}$ and maximum axial force $T_{\text{max}}$ of nail reinforcement corresponding to boundary shear displacement $\delta$ of 5 mm, 10 mm, 25 mm and 50 mm, together with those for zone shear box test simulations (see Section 2.2.4) are shown in Table 2.1. The distributions of shear force, bending moment and axial force along the soil nail corresponding to boundary shear displacement $\delta$ of 5 mm, 10 mm, 25 mm and 50 mm are shown in Figures 2.6 to 2.9 respectively.

Figure 2.5 indicates that as the boundary shear displacement $\delta$ increases, the net lateral
### Table 2.1  Summary of Results on Numerical Direct Shear Box Test and Zone Shear Box Test Simulation

<table>
<thead>
<tr>
<th>$\delta$ (mm)</th>
<th>$T_{\text{max}}$ (kN/nail)</th>
<th>$M_{\text{max}}$ (kNm/nail)</th>
<th>$P_{s\text{max}}$ (kN/nail)</th>
<th>$\sigma_b$ (kN/m$^2$)</th>
<th>$l_s$ (mm)</th>
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<tr>
<td>$z = 0$ mm</td>
<td>$z = 100$ mm</td>
<td>$z = 200$ mm</td>
<td>$z = 0$ mm</td>
<td>$z = 100$ mm</td>
<td>$z = 200$ mm</td>
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<td>0.28 (0.1%)</td>
<td>0.08 (6.7%)</td>
<td>0.70 (0.6%)</td>
<td>350</td>
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<td>0.26 (0.1%)</td>
<td>0.06 (5.0%)</td>
<td>0.06 (5.0%)</td>
<td>0.59 (0.5%)</td>
<td>400</td>
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<td>0.08 (6.7%)</td>
<td>0.06 (5.0%)</td>
<td>1.11 (1.0%)</td>
<td>0.96 (0.8%)</td>
<td>300</td>
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<td>1.15 (12.5%)</td>
<td>0.11 (9.2%)</td>
<td>1.58 (1.4%)</td>
<td>1.55 (1.4%)</td>
<td>400</td>
</tr>
<tr>
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<td>0.24 (20.0%)</td>
<td>2.11 (1.9%)</td>
<td>1.55 (1.4%)</td>
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<td>1.36 (1.2%)</td>
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<td>10</td>
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<td>0.42 (35.0%)</td>
<td>2.15 (1.9%)</td>
<td>1.85 (1.4%)</td>
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<td>0.44 (36.7%)</td>
<td>0.42 (35.0%)</td>
<td>2.81 (2.5%)</td>
<td>1.85 (1.4%)</td>
<td>740</td>
</tr>
</tbody>
</table>

Legend:
- $T_{\text{max}}$: Maximum axial force
- $M_{\text{max}}$: Maximum bending moment
- $P_{s\text{max}}$: Maximum shear force
- $l_s$: Shear band width
- $\delta$: Boundary shear displacement
- $\sigma_b$: Lateral soil pressure near the shear plane

Notes:
1. Capacity of the soil nail:
   - Axial capacity, $T_p = 226$ kN/nail.
   - Shear capacity, $P_s = 113$ kN/nail.
   - Moment capacity, $M_p = 1.2$ kNm/nail.
2. The figures in the brackets are the numerical results compared with the corresponding capacities.
Figure 2.4 Details of Numerical Direct Shear Box Test Simulation

Steel plate size: Equivalent to 40 no. x 25 mm diameter steel bar x 3 m (length)

Steel plate parameters
\[ \sigma_y = 460 \text{ N/mm}^2 \]
\[ E_{\text{steel}} = 205 \text{ kN/mm}^2 \]

Soil sample size: 6 m (length) x 1 m (width) x 3 m (depth)

Soil parameters:
\[ c' = 0 \text{ kN/m}^2 \]
\[ \phi' = 40^\circ \]
\[ \gamma = 16 \text{ kN/m}^3 \]
\[ E_{\text{soil}} = 60 \text{ MN/m}^2 \]
\[ \nu = 0.4 \]

Prescribed downward boundary shear displacement \( \delta \) along y-axis = 0, 5, 25, 50 mm at the RHS of the shear box
Figure 2.5  Net Lateral Soil Pressure Distribution along the Soil Nail in Numerical Direct Shear Box Test Simulation (Sheet 1 of 2)
(c) Boundary Shear Displacement, $\delta = 25$ mm

(d) Boundary Shear Displacement, $\delta = 50$ mm

Figure 2.5  Net Lateral Soil Pressure Distribution along the Soil Nail in Numerical Direct Shear Box Test Simulation (Sheet 2 of 2)
soil pressure increases. Although the distributions of the net lateral soil pressure generally resemble those of the theoretical values, there are high fluctuations of the distribution when the boundary shear displacement increases, in particular when \( \delta \) was increased to 25 mm or 50 mm.

Table 2.1 shows that as the boundary shear displacement increases, the maximum values of shear force, bending moment and axial forces increase. However, the maximum axial force and shear force that were mobilised in the nail reinforcement when \( \delta = 50 \) mm were only 0.7% and 2.5% of their respective capacity, compared with 36.7% of bending moment. This suggests that the bending capacity would be reached prior to the reaching of shear or tensile capacity as the shearing process continues. In other words, bending failure mechanism is the critical failure mode if a steel soil nail is subjected to plane shearing. This finding is consistent with the observations in the mode of failure of the nail reinforcement in landslides. In the previous cases of temporary soil-nailed slope failures, some steel nail bars were bent; no shear rupture of the reinforcement was seen.

One should caution that in order to examine the element behaviour of the nail reinforcement under shearing, the reinforcement was purposely placed normal to the shear plane in the numerical simulation. As a result, the reinforcement was orientated away from the direction of the principle tensile strain in the soil. This represents the worst scenario in respect of maximum bending moment and shear force, and only small axial force would be mobilised. Where soil nails are orientated close to the direction of principle tensile strain in the soil, previous study by Jewell & Pedley (1992) shows that mobilisation of shear stresses and bending moments of soil nails are small under service load conditions. One may also notice from Figures 2.6 to 2.9 that the zone of bending increases when the boundary shear displacement increases, and it is about half metre each from the shearing plane.

As the axial force, bending moment and shear force of the nail reinforcement were obtained from 2-dimensional analysis, the values are likely on the high side when compared with those from 3-dimensional analysis. It is because in 2-dimensional analysis, the nail reinforcement is forced to resist the movement of soil in the shear box during shearing, whereas in 3-dimensional analysis, soil is allowed to “flow” between reinforcement bars.

### 2.2.4 Modelling of Shear Zone

#### 2.2.4.1 Numerical Model - Zone Shear Box Test

To model the effect of shear zone on the nail-soil interaction, the numerical direct shear box model described in Section 2.2.3.1 was modified to a zone shear box as shown in Figure 2.10. Shear zones of width, \( z \), 100 mm and 200 mm, were investigated in the study. In the loading process, a linearly varying downward displacement was applied across the shear zone width spanning symmetrically across the two halves of the box, whilst an imposed uniform boundary shear displacement, \( \delta \), of 5 mm, 10 mm, 25 mm and 50 mm was applied in sequence in the downward direction \( y \) beyond the shear zone along the top and bottom of the right half of the box.
(a) Shear Force
Maximum Shear Force = 1.11 kN

(b) Bending Moment
Maximum Bending Moment = 0.08 kNm

(c) Axial Force
Maximum Axial Force = 0.18 kN

Figure 2.6 Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta = 5$ mm
(a) Shear Force
Maximum Shear Force = 1.58 kN

(b) Bending Moment
Maximum Bending Moment = 0.15 kNm

(c) Axial Force
Maximum Axial Force = 0.42 kN

Figure 2.7 Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta = 10$ mm
Figure 2.8 Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta = 25$ mm
(a) Shear Force
Maximum Shear Force = 2.81 kN

(b) Bending Moment
Maximum Bending Moment = 0.44 kNm

(c) Axial Force
Maximum Axial Force = 1.50 kN

Figure 2.9  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the Numerical Direct Shear Box Test Simulation When $\delta = 50$ mm
Steel plate size: Equivalent to 40 no. x 25 mm diameter steel bar x 3 m (length)

Steel plate parameters
\[ \sigma_y = 460 \text{ N/mm}^2 \]
\[ E_{steel} = 205 \text{ kN/mm}^2 \]

Soil sample size: 6 m (length) x 1 m (width) x 3 m (depth)

Soil parameters:
\[ c' = 0 \text{ kN/m}^2 \]
\[ \phi' = 40^\circ \]
\[ \gamma = 16 \text{ kN/m}^3 \]
\[ E_{soil} = 60 \text{ MN/m}^2 \]
\[ \nu = 0.4 \]

Prescribed downward boundary shear displacement \( \delta \) along \( y \)-axis = 0, 5, 25, 50 mm at the RHS of the shear box

Figure 2.10  Details of Numerical Zone Shear Box Test Simulation
2.2.4.2 Results and Discussions

For each width of shear zone and for each imposed boundary shear displacement $\delta$, the net lateral soil pressures $\sigma_l$ obtained from the numerical simulations are shown in Figures 2.11 and 2.12. The theoretical net lateral soil pressure distributions for failure modes A1 and A2 are also plotted in the figures for comparison.

The maximum shear force $P_{s,max}$, maximum bending moment $M_{max}$ and maximum axial force $T_{max}$ of nail reinforcement corresponding to boundary shear displacement $\delta$ of 5 mm, 10 mm, 25 mm and 50 mm for each shear zone width are shown in Table 2.1. The distributions of shear force, bending moment and axial force along the soil nail corresponding to boundary shear displacement $\delta$ of 5 mm, 10 mm, 25 mm and 50 mm for each shear zone width are shown in Figures 2.13 to 2.20 respectively.

Figures 2.11 and 2.12 indicate that as the boundary shear displacement $\delta$ increases, the net lateral soil pressure increases. Similar to those of numerical direct shear box test simulations, the distributions of the net lateral soil pressure at small displacements generally resemble those of the theoretical values, and there are high fluctuations of the distribution when the boundary shear displacement increases, in particular when $\delta$ was increased to 25 mm or 50 mm. In addition, for a given boundary shear displacement, the net lateral soil pressure increases as the width of shear zone decreases. Similar observations are made for the maximum values of shear force, bending moment and axial forces as summarised in Table 2.1.

Table 2.1 shows that irrespective of the width of shear zone, as the boundary shear displacement increases, the maximum values of shear force, bending moment and axial forces increase. However, the maximum axial force and shear force that were mobilised in the nail reinforcement when $\delta = 50$ mm were only 0.7% and 2.5% of their respective capacity, compared with 36.7% of bending moment. This suggests that the bending capacity would be reached prior to the reaching of shear or tensile capacity as the shearing process continues. In other words, bending failure mechanism is the critical failure mode if a steel soil nail is subjected to plane shearing.

2.2.5 Modelling of Ground with Contrast in Stiffness

In order to understand the nail-soil interaction in the case of a soil nail passing through two soil materials with different soil stiffness, further numerical simulations using the direct shear box model as described in Section 2.2.3.1 were conducted. Two cases were examined. In both cases, the original soil stiffness of 60 MN/m$^2$ was kept unchanged in the right half of the box. In the left half, the stiffness of the soil was increased to 120 MN/m$^2$ and 600 MN/m$^2$ respectively. The details of the model shear box, and the soil and steel parameters are given in Figure 2.21.

2.2.5.1 Results and Discussions

The results are summarised in Table 2.2. In general, the maximum shear force, bending moment and axial force, and the net lateral soil pressure near the shear plane increase as the contrast in soil stiffness increases as well as the boundary shear displacement increases.
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<th>δ (mm)</th>
<th>$T_{\text{max}}$ (kN/nail)</th>
<th>$M_{\text{max}}$ (kNm/nail)</th>
<th>$P_{S_{\text{max}}}$ (kN/nail)</th>
<th>$\sigma_b$ (kN/m$^2$)</th>
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<td>$E_{\text{soil}} = 60$ MN/m$^2$</td>
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Legend:
- $T_{\text{max}}$: Maximum axial force
- $E_{\text{soil}}$: Soil stiffness in the left-half of the shear box
- $\sigma_b$: Lateral soil pressure near the shear plane
- $\delta$: Boundary shear displacement
- $M_{\text{max}}$: Maximum bending moment
- $P_{S_{\text{max}}}$: Maximum shear force
- NC: Non-convergent

Notes:
1. Results of numerical direct shear box test simulations without contrast in soil stiffness.
2. The capacity of the soil nail:
   - Axial capacity, $T_p = 226$ kN/nail.
   - Shear capacity, $P_s = 113$ kN/nail.
   - Moment capacity, $M_p = 1.2$ kNm/nail.
3. The figures in the brackets are the numerical results compared with the corresponding capacities.
(a) Boundary Shear Displacement, \( \delta = 5 \text{ mm} \)

(b) Boundary Shear Displacement, \( \delta = 10 \text{ mm} \)

Figure 2.11  Net Lateral Soil Pressure Distribution along the Soil Nail in 100 mm Numerical Zone Shear Box Test Simulation (Sheet 1 of 2)
(c) Boundary Shear Displacement, $\delta = 25$ mm

(d) Boundary Shear Displacement, $\delta = 50$ mm

Figure 2.11  Net Lateral Soil Pressure Distribution along the Soil Nail in 100 mm Numerical Zone Shear Box Test Simulation (Sheet 2 of 2)
(a) Boundary Shear Displacement, $\delta = 5$ mm

(b) Boundary Shear Displacement, $\delta = 10$ mm

Figure 2.12  Net Lateral Soil Pressure Distribution along the Soil Nail in 200 mm Numerical Zone Shear Box Test Simulation (Sheet 1 of 2)
Figure 2.12  Net Lateral Soil Pressure Distribution along the Soil Nail in 200 mm Numerical Zone Shear Box Test Simulation (Sheet 2 of 2)
(a) Shear Force
Maximum Shear Force = 0.704 kN

(b) Bending Moment
Maximum Bending Moment = 0.06 kNm

(c) Axial Force
Maximum Axial Force = 0.28 kN

Figure 2.13  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 5$ mm
Figure 2.14  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 10$ mm
Figure 2.15  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 25$ mm
Figure 2.16  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 100 mm Zone Numerical Shear Box Test Simulation When $\delta = 50$ mm

(a) Shear Force
Maximum Shear Force = 2.15 kN

(b) Bending Moment
Maximum Bending Moment = 0.42 kNm

(c) Axial Force
Maximum Axial Force = 1.70 kN
(a) Shear Force
Maximum Shear Force = 0.59 kN

(b) Bending Moment
Maximum Bending Moment = 0.06 kN m

(c) Axial Force
Maximum Axial Force = 0.26 kN/m

Figure 2.17  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 5$ mm
Figure 2.18  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 10$ mm
(a) Shear Force
Maximum Shear Force = 1.36 kN

(b) Bending Moment
Maximum Bending Moment = 0.24 kNm

(c) Axial Force
Maximum Axial Force = 0.94 kN

Figure 2.19  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When $\delta = 25$ mm
Figure 2.20  Distributions of Shear Force, Bending Moment and Axial Force along the Soil Nail in the 200 mm Zone Numerical Shear Box Test Simulation When \( \delta = 50 \text{ mm} \)
Figure 2.21 Details of Numerical Direct Shear Box Test Simulation with Soils of Contrast in Stiffness

Steel plate size: Equivalent to 40 no. x 25 mm diameter steel bar x 3 m (length)

Steel plate parameters:

\[ \sigma_y = 460 \text{ N/mm}^2 \]
\[ E_{\text{steel}} = 205 \text{ kN/mm}^2 \]

Soil sample size: 6 m (length) x 1 m (width) x 3 m (depth)

Soil parameters:

\[ c' = 0 \text{ kN/m}^2 \]
\[ \phi' = 40^\circ \]
\[ \gamma = 16 \text{ kN/m}^3 \]
\[ E_{\text{soil}} = 60 \text{ MN/m}^2 \]
\[ \nu = 0.4 \]

Prescribed downward boundary shear displacement \( \delta \) along y-axis = 0, 5, 25, 50 mm at the RHS of the shear box
Similar to those results in numerical direct shear box and zone shear box test simulations, the bending failure mechanism is the critical failure mode if a steel soil nail is subjected to shearing between soils of different stiffness.

2.3 Technical Implications

The results of the numerical simulation have the following technical implications:

(a) When a nail reinforcement is subject to direct shearing, e.g. when the reinforcement is more or less normal to the sliding surface, bending failure is the most critical failure mode. This finding is consistent with the observations in the mode of failure of the nail reinforcement in some soil-nailed slope failures where some steel bars were bent and no shear rupture of the bar was seen.

(b) Because of the high shear ductility of steel reinforcement, which renders the failure mode of a soil-nailed system likely to be ductile, it is generally not necessary to check against bending and shear failure of steel reinforcement in the design. However, if materials other than steel are used for nail reinforcement, their capacity under combined actions of tension, shear and bending should be considered in the design.

3 Conclusions

The behaviour of a steel soil-nail reinforcement subject to shearing has been examined by means of numerical shear box test simulation. The results are consistent with those determined theoretically. The following observations are made:

(a) The mobilisation of axial force, shear force and bending moment in soil nails for a given boundary shear displacement depends on the width of a shear zone. The narrower the shear zone, the higher will be the shear force and bending moment.

(b) The degree of mobilisation of bending moment of a soil nail for a given boundary shear displacement is the highest among the three actions (i.e. axial force, shear force and bending moment). Bending failure will occur first if a steel soil nail is subject to shearing across the nail.

(c) The sharper the contrast in soil stiffness between the two shearing zones, the higher will be the mobilisation of axial force, shear force and bending moment in the soil nails for a given boundary shear displacement.
4 References


A selected list of major GEO publications is given in the next page. An up-to-date full list of GEO publications can be found at the CEDD Website http://www.cedd.gov.hk on the Internet under “Publications”. Abstracts for the documents can also be found at the same website. Technical Guidance Notes are published on the CEDD Website from time to time to provide updates to GEO publications prior to their next revision.

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