RETAINING STRUCTURES
INTERNATIONAL DESIGN AND BUILD COMPETITION

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December 2023

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Aim and Background

The aim of the design challenge was to produce a retaining wall that would hold a backfill of sand and surcharge load between 10-30kg. This paper will discuss the method used to construct the retaining wall, soil nailing, and the factors that led to the results observed during the tests.

Soil nailing is a method of construction that is typically used on embankments and levees to supply an additional level of stabilisation to counter any forces being applied to the soil. This method can be used on either natural or artificial slopes and involves steel bars being driven into the face of the slope at precise angles and depths. The steel is then fixed in place through a combination of grout and mesh. Soil nailing can also be used on tunnel portals and roadway cuts to provide a further level of reinforcement.

There are a variety of advantages to using soil nailing over more standard methods. The primary advantage is the cost-effective element of soil nailing, which makes the technique applicable to a wide range of projects. Soil nailing is also more flexible in its installation which again allows it to be used on a wide variety of projects.

Design

Initial Design

The test involved a soil nailing reinforcement (Figure 1). The soil nails were timber skewers, 230mm in length and 3mm in diameter, of unknown species and origin (See Appendix 1). Additionally, the Napier soil nails were originally intended to be sanded with coarse grit sandpaper to increase the angle of friction between the reinforcement elements and surrounding fill(δ) (this was not carried out during the test). The test used a 3mm card as the wall material and was inclined at 5.71 degrees from vertical. The backfill had a height of 300mm. Skewers were fixed to 30mm square bearing plates of 3mm plywood. The bearing plates had been drilled with 3mm pilot holes and fixed to the skewer ends with hot glue. The sandbox dimensions were as follows (length, width, height): 660x457x457mm.

Detailed Design

The Napier retaining wall was 300x455mm, comprising 2 rows of 4 soil nails made from timber (Figure 1). The vertical spacing of the nail was 200mm, with the highest and lowest inclusions at 50mm and 250mm depth respectively. The horizontal spacing between the nails was 130mm with a 33mm gap between the nails and the edge of the sandbox. (Figure 2). The wall had an inclination of 5.71 degrees (10:1 ratio). (The skewers were fixed to 30mm square bearing plates of 3mm plywood. The bearing plates were drilled with 3mm pilot holes and fixed to the skewer ends with hot glue.) The pilot holes were drilled at 90 degrees, resulting in a corresponding angle of 5.71 degrees with respect to the horizontal plane (perpendicular to the wall). See Figure 3 for the experiment setup.

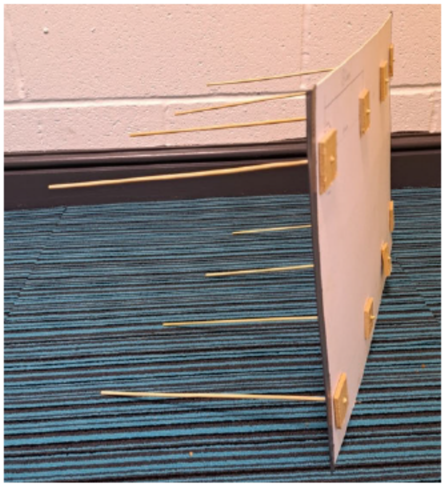

Figure 1 - Nail Arrangement, Side View

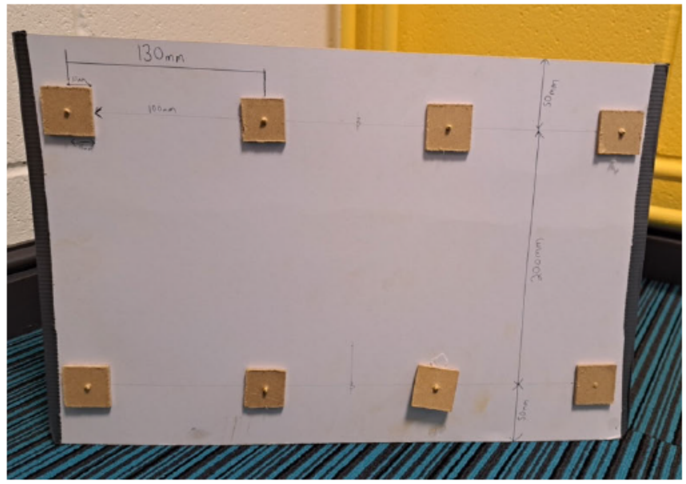

Figure 2 - Nail Arrangement, Front View

Figure 3 - ENU Experiment Setup

Differences in Design – HSLU vs. ENU

Soil nails – Lucerne used 18 nails in a 3-row by 6-column arrangement (See Appendix 2 and Appendix 3), with a horizontal spacing of 80mm and a 50mm gap between the nails and the edge of the sandbox, and the vertical spacing of the nails was 50mm, 200mm and 250mm from the top of the wall. In contrast, the Napier design used 8 nails altogether with larger spacings both horizontally and vertically, as previously described (page 3). The reason for the change was that the Napier experiment had the benefit of hindsight; it was already apparent that the Lucerne experiment had far exceeded the required loading of 10-30kg, although basic hand calculations, following Rankine's method, suggested the wall would fail.

Connection between nails and wall – Lucerne used only hot glue to keep the wall and the nails together while Napier used pieces of timber acting as bearing plates between the nails and the wall, as well as hot glue.

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Differences in soil type - Lucerne used soil that is classed as a sandy gravel, with a particle size distribution of 2.0-4.0mm, an angle of friction of 39º, and a unit weight of 16kN/m^3 (SIA 261, 2003). Napier used Leighton Buzzard sand, with a particle size distribution of 0.7- 2.0mm, an angle of friction of 32º (Cheuk, White and Bolton, 2008), and a unit weight of 16.5kN/m^3 (Cavallaro, Maugeri and Mazzarella, 2001; Al-Aghbari and Mohamedzein, 2004). Both soils are coarse-grained, and thus an apparent cohesion of 0 kN/m^2 was assumed.

Water content – Lucerne added an unspecified volume of water into their soil, while Napier's soil had a water content of 3%.

Thickness of wall – Lucerne used 3mm card while Napier used 1.5mm card for the retaining wall.

Analysis of Design Changes

Soil water content plays a critical role in the shear strength of a soil. When the water content is too high the soil loses strength while if it is too low the soil may lose 'apparent cohesion'. "The decrease in shearing strength with an increase in water content seems to be caused by a decrease in the portion of strength contributed by interlocking of particles" (Haruyama, 1969). Testing of how the moisture content of Leighton buzzard sand and Lucerne's unspecified soil type impacts cohesion and shearing resistance would have had to be carried out using a triaxial or oedometer test to discover whether this may have affected the experiments.

Napier used Leighton Buzzard sand with a particle size distribution between 0.7-2.0mm while Lucerne used a soil classed as a sandy gravel with a particle size distribution between 2.0-4.0mm. Both absolute particle size and particle size distribution have a significant impact on how the soil reacts in certain situations. For example, soils with small particles such as clays are cohesive with a large number of particles of the same volume and a greater surface area, resulting in more cohesive bonding and low permeability. However, due to the limited void space water struggles to drain through (HMTRI, 2000). Larger particles, such as the soils used at ENU and HSLU, have more voids which allow water to drain through them more readily, and have higher interparticle friction: "With an increase of particle size, the maximum shear strength as well as angle of internal friction increases and the normal load also plays important role" (Islam *et al.*, 2011).

Predictions

Calculations for the experiment are based on achieving a target surcharge of 20kg. All calculations in this report were carried out using Rankine's method, based upon a vertical wall (the marginal inclination of the wall was considered to not have a signification effect on the outcome). With the alterations made based on the high loading at failure of the experiment that HSLU had completed a week prior to Napier's, calculations using Rankine's method, predicted that the wall would fail using the two rows of four nails arrangement. The wall would fail by pull-out, with a factor of safety (FS) of 0.062. On the other hand, the wall would not fail by rupture, as the FS is 6.00. Detailed calculations can be found in Appendix 4. HSLU had predicted a surcharge of 19kg, based on their 18-skewer design.

Results

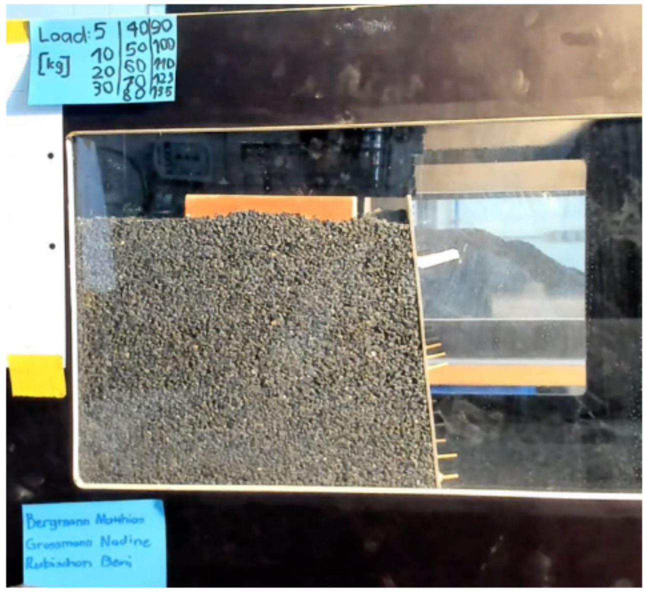

Figure 4 – ENU Experiment – Pull-out Failure   *Figure 5 - HSLU Experiment - Over-engineered*

Observations and Analysis - ENU

It can be seen in Figure 3 that even before the temporary supports were removed, which were used in the experiment setup process, the supporting wall exhibited significant bending and buckling in response to the forces from the backfill. The bending allowed for some sand to escape around the sides of the wall. The wall rapidly failed by pull-out under its own weight and as such no additional weights could be added, and consequently, failed to achieve the goal of 10-30kg (See Figure 4).

It is also important to mention that the skewers used were not sanded down as stated in the initial design, thereby probably reducing the frictional resistance from the reinforcing elements and impacting the predicted failure by pull-out (albeit not significantly enough to affect the outcome of the experiment).

From an observational point of view, the sand used in the ENU experiment seemed dryer than the soil used by HSLU. The side walls for the two experiments were also different: painted wood and plexiglass for ENU and HSLU respectively.

Observations and Analysis - HSLU

For the experiment performed by HSLU students, it is possible that the wetter soil imparted greater strength. The initial number of nails (18), the thicker wall (and the fact that the latter was tightly fitted between the side walls), the moisture content, and the shear strength of the soil, may have all contributed to an additional mass of over 135kg being able to be supported (See Figure 5). The experiment was soon ended after the 135kg mark: the HSLU team needed to shake the box to incite the wall to fail under simulated seismic activity.

Modelling

Based on the data used for the ENU experiment, modelling was undertaken to examine what effect changing the variables would have on the outcome of the experiment. The FS equation for pull-out was amended to account for the circular cross-section of the reinforcement as follows:

$$\text{Equation 1: } Fp = \frac{\pi L_E \tan(\delta) d}{K_A S_V S_H}$$

(d = reinforcement diameter)

Because the original equation uses b, the width of reinforcement, it was considered appropriate to amend the calculation to include the underside of the reinforcement as a semi-circle in the numerator.

Similarly, the equation for FS (rupture) was amended to account for the cross-sectional area of a circle:

$$\text{Equation 2: } F_R = \frac{\sigma_F \pi \left(\frac{1}{2} d\right)^2}{K_A \left(\gamma z_l + q\right) S_V S_H}$$

Where: q = surcharge (kPa) and z_l = lowest reinforcement inclusion. This then accounts for the impact of surcharge as seen in the test.

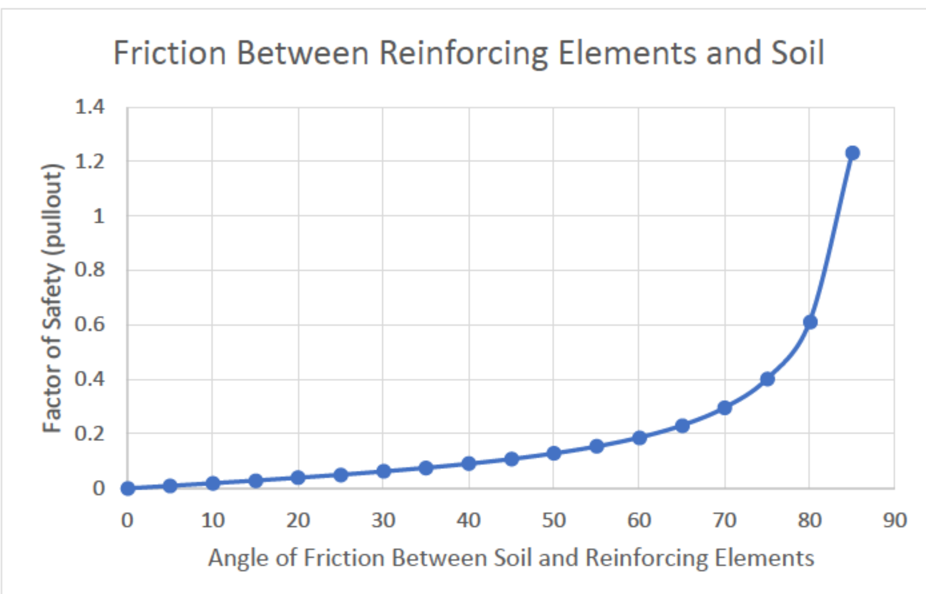

Figure 6 – Friction Between Reinforcing Elements and Soil

As expected, an increased angle of friction between the soil and reinforcing element (δ) increased the pullout resistance of the wall. It is noticeable that improvements are not linear, and angles of friction in excess of 60 degrees show the greatest increase in pull-out resistance (See Figure 6).

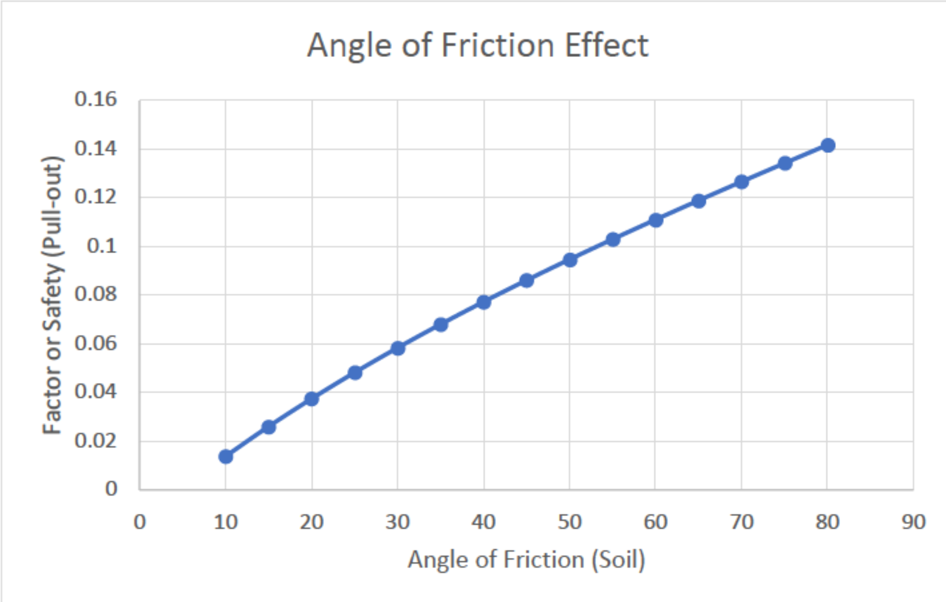

Figure 7 - Angle of Friction Effect

The angle of friction of the soil (ϕ') also increased pull-out resistance. However, in this situation we have the opposite case, whereby by the magnitude of FS improvement declines with increasing angles of fiction (See Figure 7).

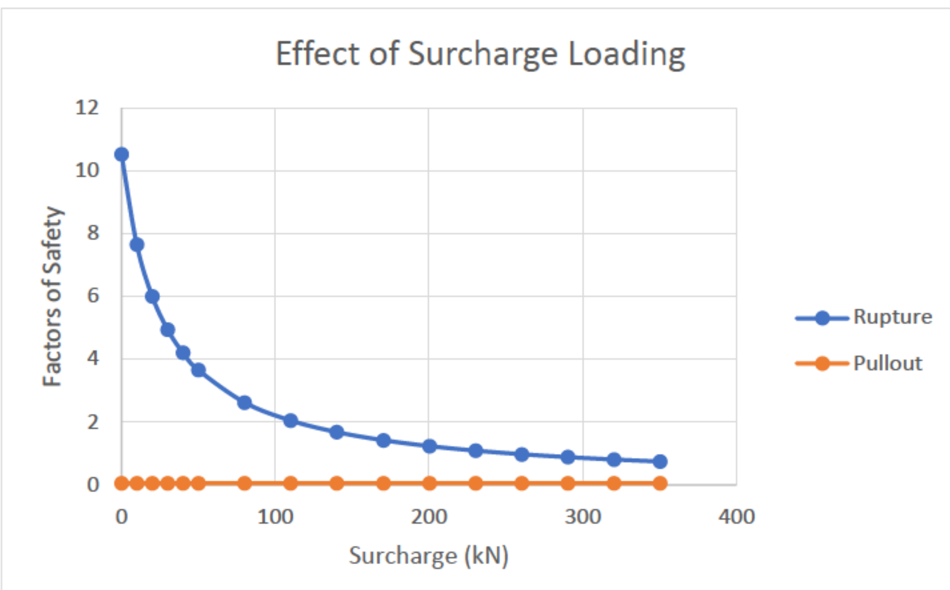

Figure 8 – Effect of Surcharge Loading

[redacted] Equation 1 it is evident that FS against pull-out is a function of effective length, reinforcement width and spacings, angle of friction between soil and reinforcement, and the active earth pressure coefficient (which is itself a function of the soil's angle of shearing resistance). It can therefore be concluded that the self-weight of the soil and the surcharge loading have no effect upon the FS against pull-out (See Figure 8). Therefore, providing the wall appears initially stable upon construction, increasing the surcharge loading will not initiate pullout failure.

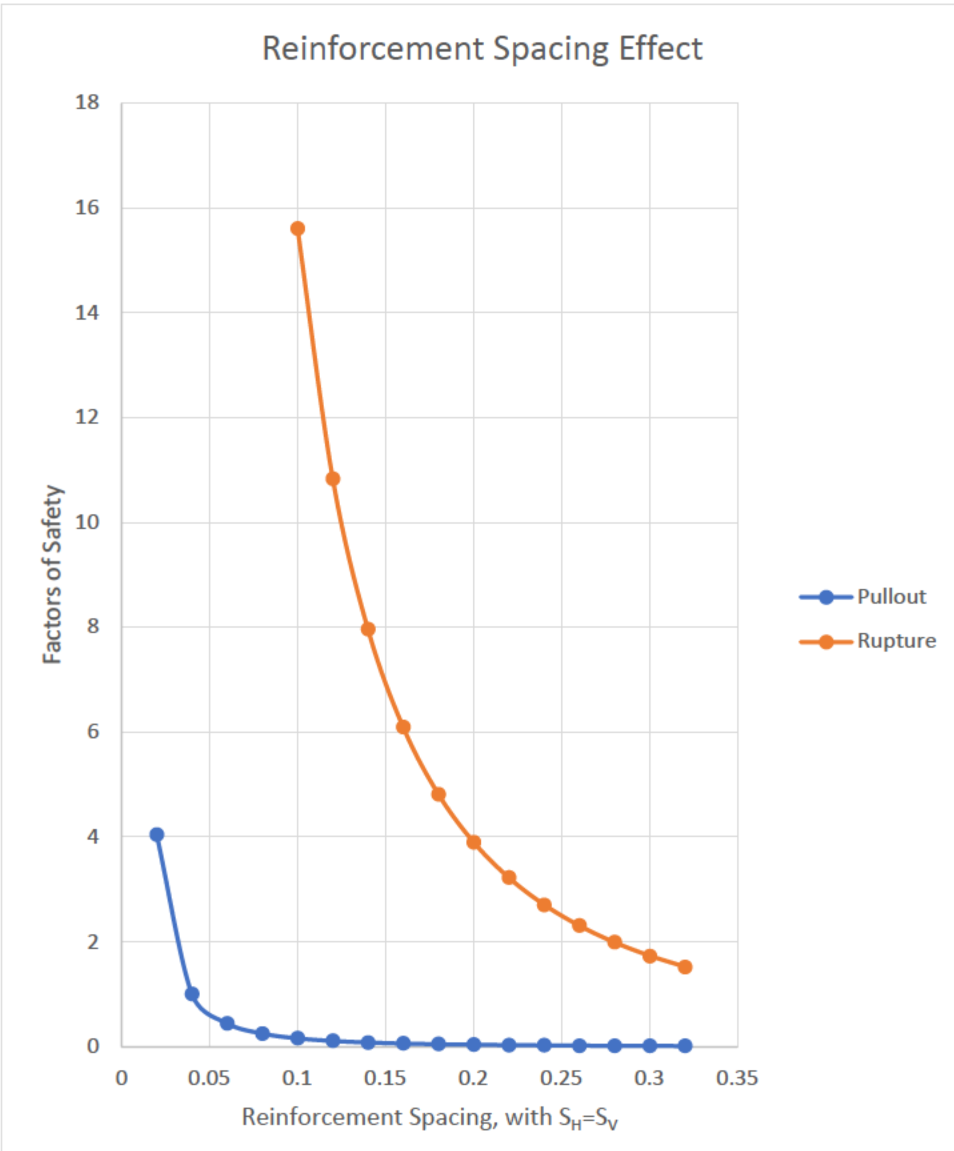

Figure 9 - Reinforcement Spacing Effect

It is apparent from examining Equation 1 and Equation 2, and particularly from Figure 9, that the most substantial declines in factors of safety for both pullout and rupture failure are at the smaller spacings. This is intuitive, because if S_H=S_V, a doubling of the spacing distance results in a squaring effect, and a corresponding fourfold reduction in reinforcement provision.

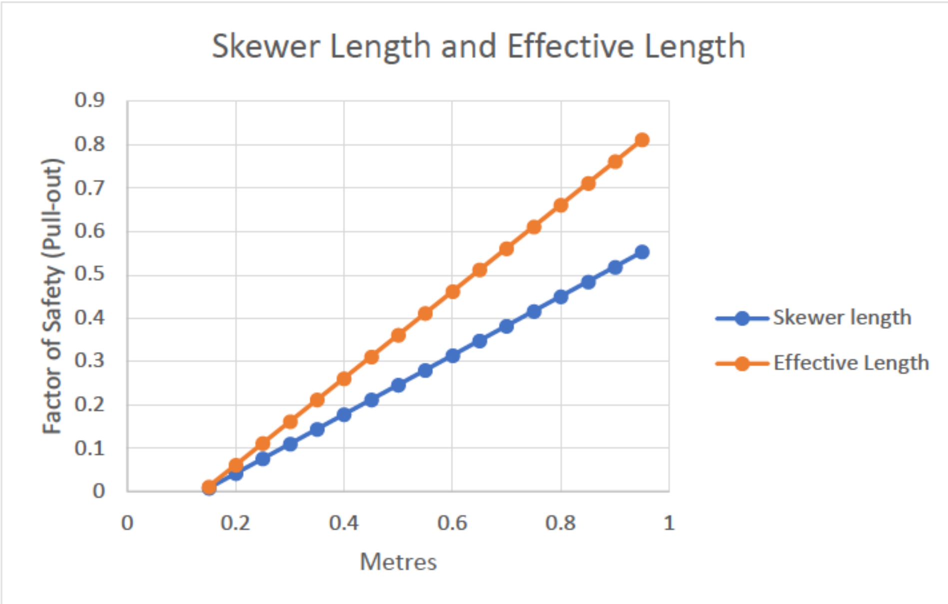

Figure 10 - Skewer Length and Effective Length Vs. Factor of Safety (Pull-out)

As the Rankine failure line is a constant, and thus the active length (L_A) is also a constant, it makes sense that the increases in skewer length (and therefore L_E) result in linear improvements in pullout resistance, corresponding to the surface they are providing by the reinforcement in the effective length region (See Figure 10).

Conclusions and Improvements

If the test were to be repeated based on the calculations within this report, several factors would be considered in more detail, and changes made as follows:

- Soil nail spacing of S_V=S_H=40mm to achieve an Fp of 1 (Figure 9), with 66 nails arranged in an 11-column by 6-row matrix (according to revised calculations in Appendix 5)
- Increase the wall card thickness from 1.5mm (or use a stiffer material). This is because buckling of the wall was evident in the recorded video of the test.
- Reconsider the surcharge distribution. In this report, it was assumed that the surcharge was distributed as a UDL over the active wedge and converted from a force into a pressure (kPa). More research would be required to consider how the loading could be distributed, and its effect upon the reinforcing elements.
- Based on our calculations where Fp=1, and S_V=S_H=40mm, a reinforcement material with a breaking strength around 500kN/m^2 would be required to achieve an FS (rupture) of 1, based on the 10-30kg surcharge loading requirement (See revised calculations in Appendix 5) this would give a Fr value close to 1. This would require a substantially weaker material than the timber (49000kN/m^2) (Mou, 2023), such as paper (Goyal, 2023).

[redacted]

There are many variables that come into play when designing a retaining wall and this test and report represents a gross simplification of real-world scenarios and the complexities involved in designing a retaining wall. In addition, it should be remembered that this test greatly reduced the scale when compared to an industry scenario, with far smaller values for reinforcement spacing, length and maximum embedment depth.

The interesting question from these two experiments is: why did the Napier test fail from its own self weight, and the Lucerne test fail at such a high surcharge loading? Rankine's method and the equations for rupture and pullout imply that surcharge loading can only affect rupture, yet it is apparent that rupture did not occur in the Lucerne test (it may be that the Lucerne experiment could have gone up to much higher surcharge loads before failure – failure was artificially initiated).

A significant flaw in the project was the use of different soils, moisture contents and sandbox materials at ENU and HSLU, as well as the different soil nailing arrangements, which may have had an effect on the outcomes. It would have been interesting to change one variable at a time and evaluate the outcome. Overall, the project was a thoroughly interesting experiment which, although many questions are left unanswered, gives valuable insight into the construction of retaining walls with soil nails, and the factors which may affect their outcome.

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Appendices

Appendix 1 – Skewers

Figure 11 - COOP Skewers (Lucerne)

Figure 12 - B&Q Skewers (Napier)

Appendix 2 – HSLU Design

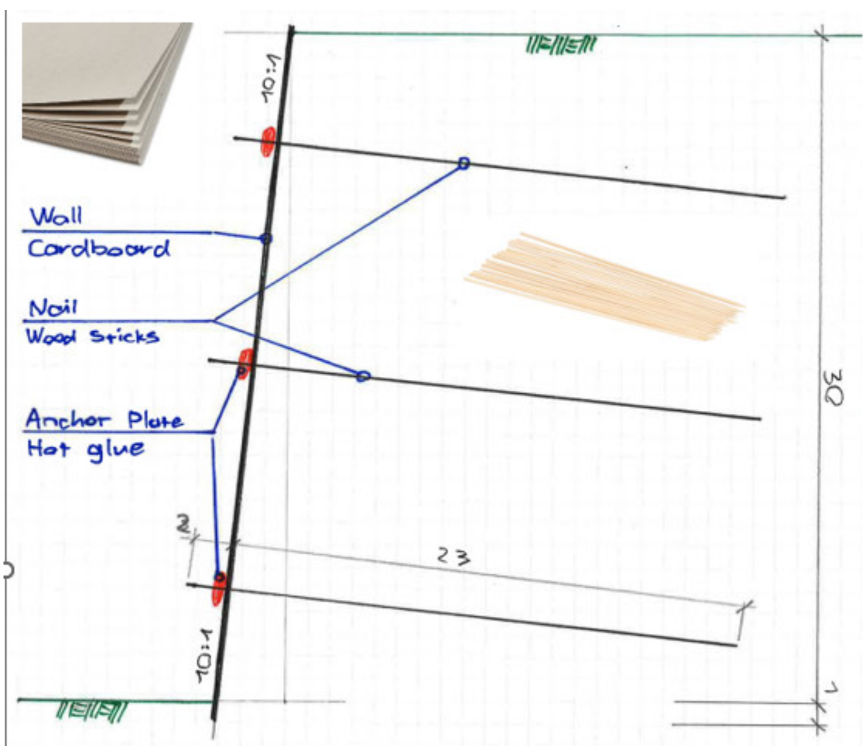

Figure 13 - Soil nailing method. Napier technique will use 3mm plywood bearing plates fixed with polyurethane glue. Number, angle and spacing of soil nails, as well as card thickness, will be confirmed in the final report.

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Appendix 3 – HSLU Experiment Setup

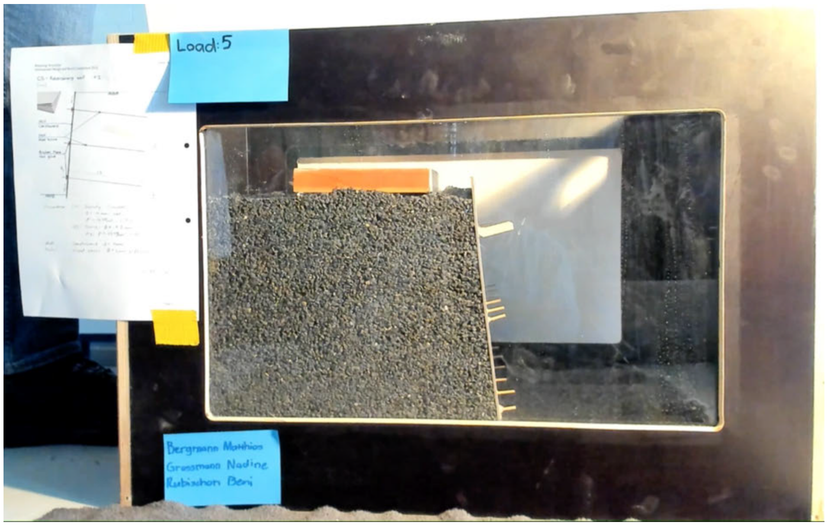

Figure 14 - HSLU Experiment Setup

Appendix 4 – Initial Calculations

Table 1: Values and Variables

Wall area (m^2)	0.1371
H (m)	0.3
S_H (m)	0.13
S_V (m)	0.2
Z_l (m)	0.25
Z_H (m)	0.05
b (m)	0.003
t (m)	0.003
Half circumference (m)	0.0047
Area of cross section (m^2)	7.06858E-06
Angle of friction WOOD/SOIL	30˚
Angle of friction	32˚
K_A	0.307
Breaking strength timber kN/m^2	49000
Unit weight sand kN/m^3	16.5
Target weight kg	20
Target weight Kn	0.1962
Width (m)	0.457
Length (m)	0.139
Pressure area	0.0633
As pressure kPa	3.098

[redacted]

$$K_A = \frac{1 - \sin\phi'}{1 + \sin\phi'}$$

$$K_A = \frac{1 - \sin 32°}{1 + \sin 32°}$$

$$\boldsymbol{K_A = 0.307}$$

$$L_A = \frac{H - z}{\tan(45° + {}^{\phi'}/_{2})}$$

$$L_A = \frac{0.3 - 0.05}{\tan\left(45° + {}^{32°}/_{2}\right)}$$

$$\boldsymbol{L_A = 0.139m}$$

$$L_E = L - L_A$$

$$L_E = 0.23 - 0.139$$

$$\boldsymbol{L_E = 0.091m}$$

$$Fp = \frac{2 \times L_E \tan(\delta)\, \pi d \times 0.5}{K_A S_H S_V}$$

$$Fp = \frac{2 \times 0.091 \times \tan(30) \times 0.047}{0.307 \times 0.13 \times 0.2}$$

$$\boxed{\boldsymbol{Fp = 0.062}}$$

$$F_R = \frac{\sigma_F A}{K_A \times (\gamma Z_l + P_A) \times S_H S_V}$$

$$F_R = \frac{49000 \times 7.069 \times 10^{-6}}{0.307 \times (16.5 \times 0.25 + 3.098) \times 0.13 \times 0.2}$$

$$\boxed{\boldsymbol{F_R = 6.00}}$$

[redacted]

Appendix 5 – Revised Calculations

Table 2: Revised Values and Variables

Wall area (m^2)	0.1371
H (m)	0.3
S_H (m)	0.04
S_V (m)	0.04
Z_l (m)	0.25
Z_H (m)	0.05
b (m)	0.003
t (m)	0.003
Half circumference (m)	0.0047
Area of cross section (m^2)	7.06858E-06
Angle of friction WOOD/SOIL	30˚
Angle of friction	32˚
K_A	0.307
Breaking strength timber kN/m^2	49000
Unit weight sand kN/m^3	16.5
Target weight kg	20
Target weight Kn	0.1962
Width (m)	0.457
Length (m)	0.139
Pressure area	0.0633
As pressure kPa	3.098

$$Fp = \frac{2 \times L_E \tan(\delta)\, \pi d \times 0.5}{K_A S_H S_V}$$

$$Fp = \frac{2 \times 0.091 \times \tan(30) \times 0.047}{0.307 \times 0.04 \times 0.04}$$

$$\boxed{\boldsymbol{Fp = 1.01}}$$

$$F_R = \frac{\sigma_F A}{K_A \times (\gamma Z_l + P_A) \times S_H S_V}$$

$$F_R = \frac{49000 \times 7.069 \times 10^{-6}}{0.307 \times (16.5 \times 0.25 + 3.098) \times 0.04 \times 0.04}$$

$$\boxed{\boldsymbol{F_R = 97.54}}$$

[redacted]

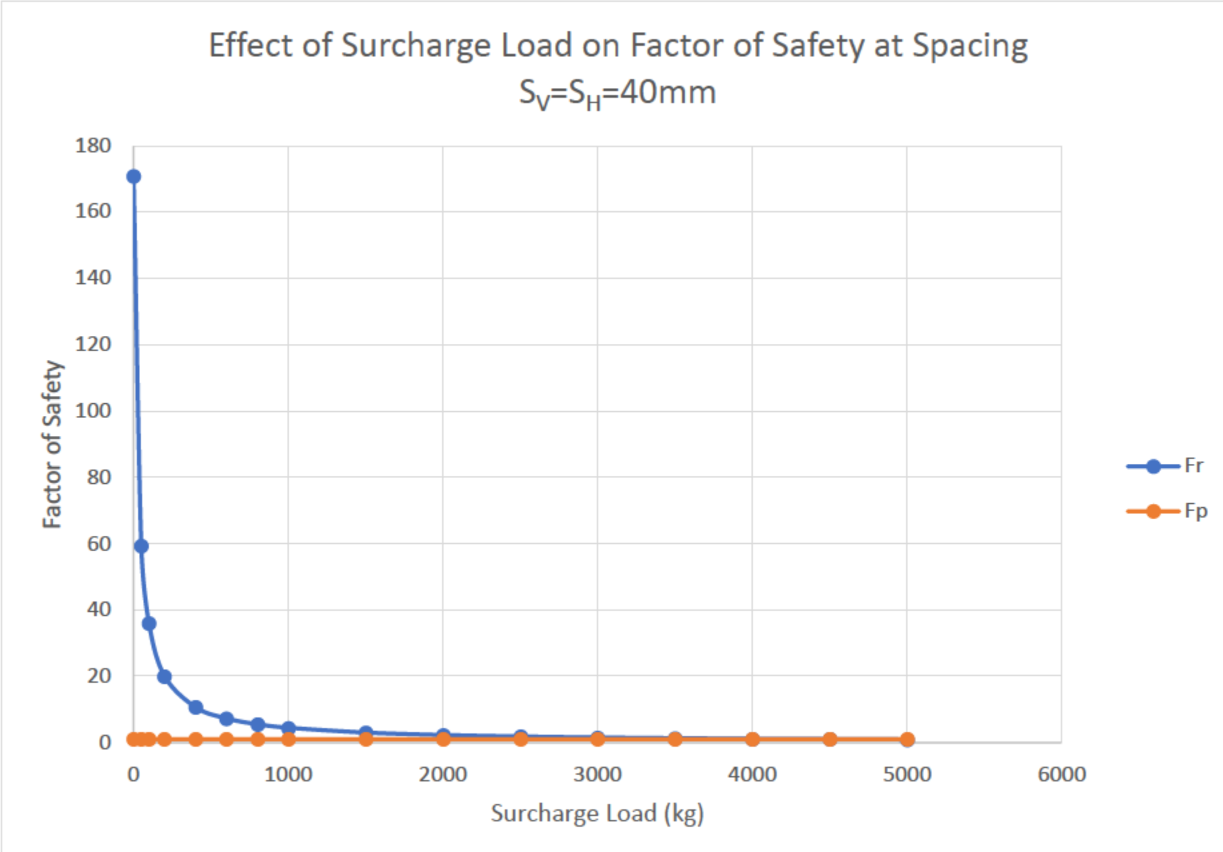

Figure 15 - Effect of Surcharge Load on Factor of Safety at Spacing S_V=S_H=40mm

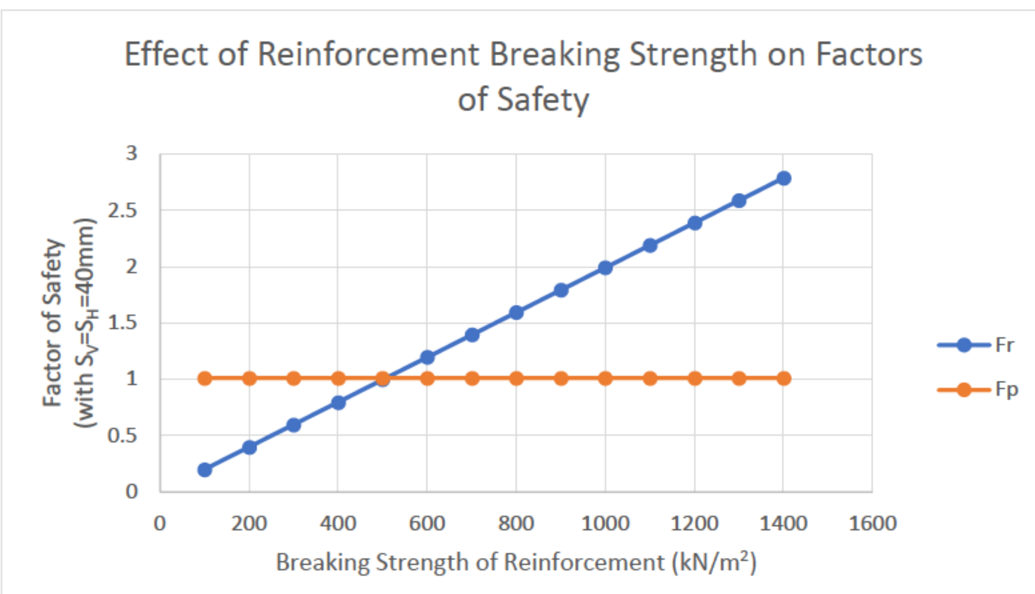

Figure 16 - Effect of Reinforcement Breaking Strength of Factors of Safety

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