FACULTY OF ENGINEERING AND BUILT ENVIRONMENT

DEPARTMENT OF CIVIL ENGINEERING

EDINBURGH NAPIER UNIVERSITY

LUCERNE UNIVERSITY OF

APPLIED SCIENCES AND ARTS

RETAINING STRUCTURES – INTERNATIONAL DESIGN AND BUILD COMPETITION COURSEWORK

Group Members (Napier University):

Group Members (Lucerne University):

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Title: Design and evaluation of soil-nailed earth retaining wall supporting a sandy backfill.

Objective

The main focus of this project was to design a soil-nailed reinforced earth retaining wall to support a Leighton buzzard sand backfill. The design must include a true estimate in the function of a geotechnical structure including detailed elements of the soil, materials used, primary conditions and the applied loading.

Sample Description

Soil sample S1- Leighton buzzard silica clean dry sand, grade 10/18. Particle size distribution illustrated in figure 1.0.

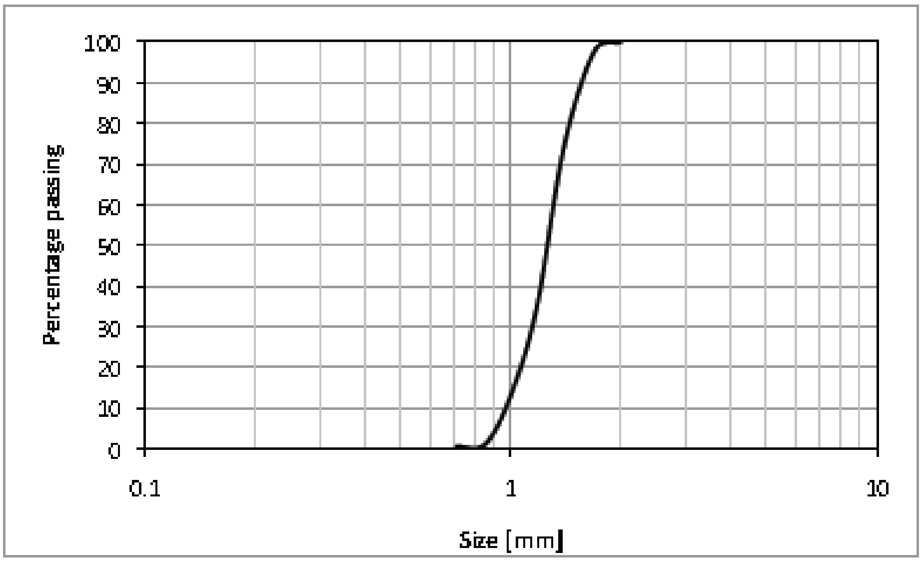


Figure 1.0- Particle size distribution of soil sample S1 *(Leak, 2023)*

Figure 2.0- Leighton Buzzard silica sand

General Introduction

The main objective of this group project was to collaborate with students from Lucerne University of Applied Sciences and Arts, in order to analyse and design a reinforced earth retaining wall utilising the soil nailing method. The goal was to reinforce the soil and create a retaining wall to withstand not only the self-weight of the soil, but also a maximum surcharge loading of 30kg.

The students from Napier and Lucerne got in contact via email, and arranged to have a meeting using Microsoft Teams to discuss various design options and materials that could be used to construct the wall and the soil nails.

Introduction

Soil nailing is an engineering technique that is used to stabilize soil backfill behind a retaining wall or embankment. Slope failure is a failure method that geotechnical engineers must deal with frequently. Slope failure occurs when the shear force exceeds the shear strength of the soil. Methods that activate slope failure include; earthquakes, heavy rainfall, improper slope design, excessive surcharge loading and changes in pore water pressure in the area.

Soil nailing is a method that is adopted by engineers to stabilize the soil and to prevent any movement or landslides. The system involves either natural soil or fill material and is reinforced by inserting tension carrying elements referred to as a soil nail. The nails are grouted bars that are composed of either inox or glass fibre. They can be either placed into a pre-drilled hole and grouted or installed using the displacement approach. A drainage system is also incorporated to direct the water away from the retaining wall. Bearing plates or head plates are then attached to the soil nails.

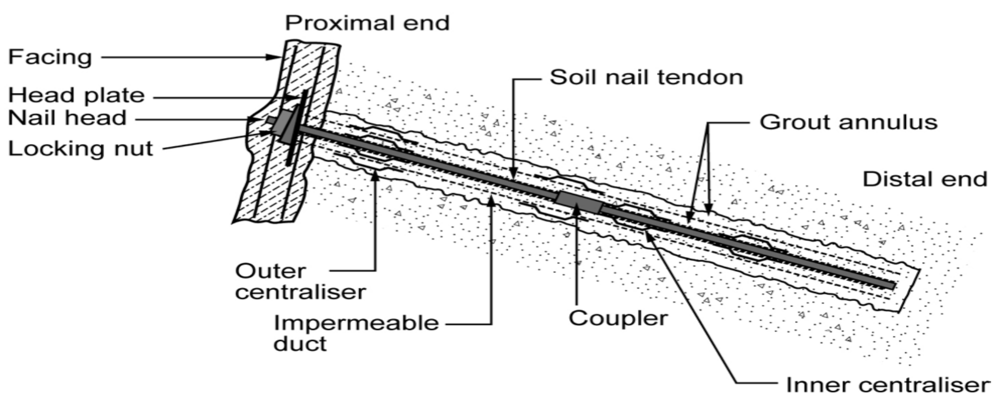


Figure 3.0 Components of a Soil Nail *(CIRIA , 2005)*

The angle of inclination is typically installed at a declining angle to the horizontal plane.

(CIRIA , 2005) displayed that Johnson et all (2002) explained that for a soil nail inclined at 60° to the horizontal intersecting a failure plane had 100% effectiveness, however the nail effectiveness reduced by 82%.

A soil nail installed at an angle of 15° from the horizontal had a 64% effectiveness with a nail effectiveness of 42%. Consequently a soil nail inclined at angle of 10 to 15° is more effective because there is no increase in pull-out length or rise in strain.

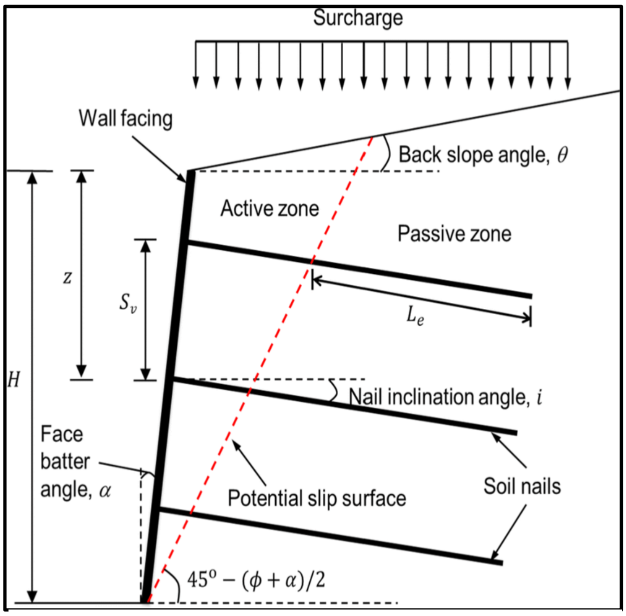


Figure 4.0 Rankine's Failure Plane (Leak, R.E 2023)

Apparatus

Clamps

Two Timber Blocks

Selected wall materials

Retaining Wall- Plywood

Nails- rope/cord/string

Anchor- cotton wool balls

Figure 5.0 Soil Nailed Retaining Wall Napier's Design

[redacted]

Theory

Soil is strong in compression and weak in tension, this is why methods of soil stabilization are adopted to prevent slope stability failure. The method adopted for this coursework employs soil nailing using the displacement approach. The displacement approach is an efficient and effective construction method for the insertion of soil nails, providing the soil type is suitable for this construction method. It involves drilling holes into the soil at the specified declination angle. The depth of the holes are declared by the design and stability requirements of the structure. The soil nails are then inserted into the drilled holes, the nails are typically ribbed or threaded to enhance their bond with the soil. The voids surrounding the soil nails are then filled with a cement grout material and this concludes the displacement approach. The objective of soil nailing is to increase stability within the Leighton Buzzard silica clean dry sand therefore the retaining wall can withstand both, the self-weight of the soil and the applied loadings.

In the active condition of earth pressures, soil wants to fall towards the retaining wall [as outlined in Figure 6.0 below] and this exerts a lateral pressure on the wall, therefore subjecting the wall to failure. In response to this, the passive force needs to be increased for stability of the wall and this is achieved with the installation of soil nails. The shearing resistance of the soil is then increased due to the increase in passive force from the reinforcement, thus providing better stability to the structure. Figure 7.0 below presents the effects the installation of soil nails has on the soil mass.

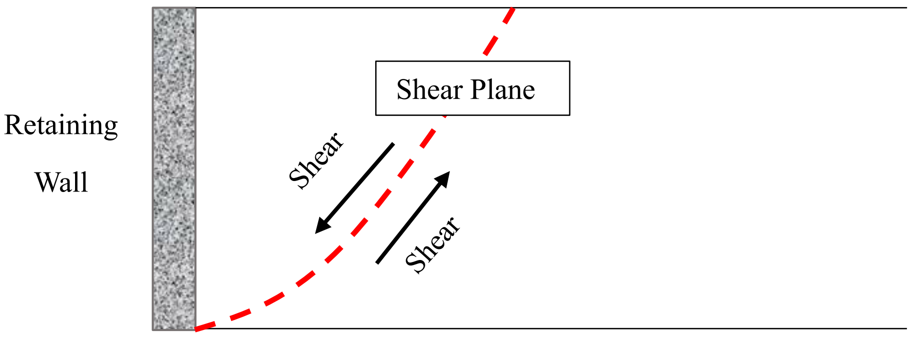


Figure 6.0 Active Pressure Plane

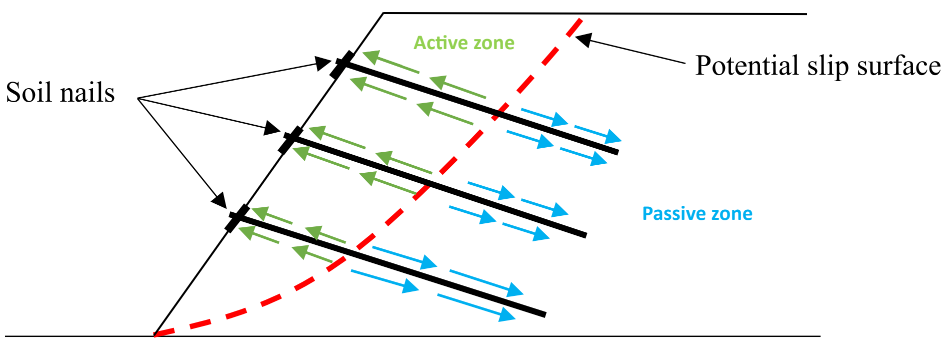


Figure 7.0 Tensile Forces in Soil Nails

Soil Nail Wall design

Methods

The method adopted for this collaborative groupwork was the soil nailing method as outlined per the brief description.

Conceptual design

After discussions and brainstorming layouts and construction designs with the Lucerne students, the system that the team decided on was the 'soldier pile wall'.

The reasons for the selected approach was based on the design layout of the three vertical piles at the front elevation. The piles provide stability and strength to retain the soil backfill. The addition of the soil nails combined with the anchors provides stability and lateral support, to counteract the lateral forces pushing on the retaining wall and to help withstand surcharge loadings.

Material selection

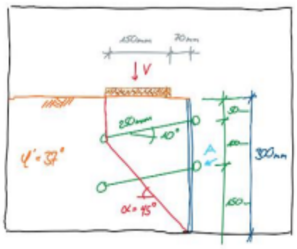
A variety of possible materials was discussed for the retaining wall, soil nails and anchors depending on available materials to both Lucerne and Napier students. Wood was selected for the piles, a PVC plate for the retaining wall, the soil nails were represented by either rope, cord or string and the wool balls to symbolize the anchors.

The students in Lucerne had testing in the laboratory that evening following the teams meeting, where they performed various tests including the pull-out test to analyse the pull-out force of the anchor.

Assumptions

The Lucerne students performed a pull-out test using an anchor pulling attempt, it was determined that the anchor will be pulled out of the ground with a pull of 4kg which corresponds to a force of 0.04kN. Based on this test, the Lucerne students performed a reverse calculation which predicted the load capacity of the retaining wall. Figure 7.0 below, shows how this calculation was completed.

The calculation according to Janbu is described below to make a first estimate of the load-bearing capacity. Our load capacity is calculated to be V = 54 kg.



$$G = \left(0.22m \cdot 0.3m - 0.22m \cdot 0.22m \cdot \tfrac{1}{2}\right) \cdot 15\,kN/m^3 \cdot 0.5m = 0.31kN$$

Ausziehversuch Anker: 4 kg => 0.04 kN

3 Anker: 0.04kN + 0.03kN + 0.03kN (nicht alle gleich gut, da aussen)

$$F = \frac{\left[(G+V) \cdot \tan(\varphi')\right] \cdot \frac{1}{n_\alpha}}{\left[(G+V) \cdot \tan(\alpha)\right] + H} \quad , \varphi' = 37°, \alpha = 45°, n_\alpha = 0.85$$

$$1.0 = \frac{\left[(0.31kN + V + 0.1kN \cdot \sin(10°)) \cdot \tan(37°)\right] \cdot \frac{1}{0.85}}{\left[(0.31kN + V + 0.1kN \cdot \sin(10°)) \tan(45°)\right] - 0.1kN \cdot \cos(10°)}$$

solve V: 0.54 kN => 54 kg

Figure 8.0 Load Prediction Calculation by Lucerne

Differences between building & testing of both Lucerne and Napier retaining walls

There was some variation between the Lucerne and Napier students materials for the construction and testing process of the design. The difference in materials relate to both Lucerne and Napier designs not conforming as per brief specification.

- ***Lucerne University of Applied Sciences and Arts***

Lucerne students acquired polystyrene balls as opposed to wool balls as outlined in the design specification. During the build process Lucerne also wrapped the cord/string around the wooden columns of the retaining wall. Again this design specification was not per brief guidelines. In which it can be assumed that this will increase the stiffness and strength of the retaining wall against failure.

- ***Edinburgh Napier University***

Napier students had diversity for the retaining wall in which the material they possessed included plywood around 5-8mm thick, opposed to the PVC plate outlined in the design brief. During the testing process there was also discrepancy in relation to the location of the reinforcement, which resulted in the reinforcement being placed in the incorrect layout.

Expected results

- ***Lucerne University of Applied Sciences and Arts***

With the enhancement the Lucerne students made of wrapping the cord/string around the wooden columns, and this improvement not being communicated in the brief or duplicated by the Napier students design. Based on these upgrades it is expected for the Lucerne retaining wall to surpass Napier's wall in regards to stability due to applied loadings.

- ***Edinburgh Napier University***

Consequently one can assume that the design will fail prematurely due to the fluctuation in both materials and measurements. Incorrect location of the reinforcements can be blamed on the miscommunication from the students to the lecturers.

[redacted]

Equations/ Formula's used:

Equation 1: Pull-out resistance

The following equation is used to determine the pull-out resistance 'R' along the effective length of each reinforcing layer.

$$R = 2.b.L_E.\gamma.z.\tan(\delta) \tag{1}$$

Where;

R = Pull-out resistance

2= Reflects the mobilisation of frictional resistance on both sides of the inclusion

b = Width of the reinforcing strip

L_E = Effective Length

γ = Unit weight of soil

z = Height of the retaining structure

$\tan(\delta)$= Soil interface friction angle with the wall {Ø =32°}

Equation 2: Effective length

$$L_E = \frac{F_p\, K_A\, S_H\, S_V}{2btan\delta} \tag{2}$$

Where;

L_E = Effective length

F_p = Pull-out failure

K_A = Active earth pressure

S_H = Horizontal spacing of reinforcement

S_V = Vertical spacing of reinforcement

b = Width of the reinforcing strip

$\tan(\delta)$= Soil interface friction angle with the wall {Ø = 32°}

[redacted]

Calculations

Coursework Calculations:

Equation 2: Effective Length $L_E = \dfrac{F_P K_A S_H S_V}{2 b \tan\delta}$

F_P = Pull-out Failure (Based on Lucerne calculation of 54kg and maximum design of 30kg $F_P = 54/30 = 1.8$)

$\therefore F_P = 1.8.$

$K_A = \dfrac{1-\sin(\delta)}{1+\sin(\delta)} = \dfrac{1-\sin(32)}{1+\sin(32)} \quad \therefore K_A = 0.307.$

$S_H = 0.229m.$

$S_V = 0.150m.$

$b = 0.005m$ (Assumed. 5mm).

$\therefore$ Effective Length L_E:

$$L_E = \frac{F_P K_A S_H S_V}{2 b \tan\delta}.$$

$$L_E = \frac{(1.8)(0.307)(0.229)(0.150)}{2(0.005)\tan(32)}$$

$$L_E = 3.03.$$

[redacted]

Equation 1 : Pull out Resistance R.

$$R = 2 . b . L_f . \gamma . z . \tan(\delta)$$

$b = 0.005m$.
$L_f = 3.03m$ - Based on Previous Calculation.
$\gamma = 20kN$ - Assumed unit weight of L.B Sand.
$Z = 0.3m$.
$\emptyset = 32°$.

$$\therefore R = 2(0.005)(3.03)(20)(0.3)\tan(32)$$
$$R = 0.114.$$

∴ Based on these calculations the wall will fail way before the 30kg limit. This shows that the Napier test result is a more accurate representation of the wall's capacity.

Procedure

Construction procedure:

- ***Lucerne University of Applied Sciences and Arts***
  1. The Lucerne's test apparatus consisted of a wooden box with the mid-section of the walls being cut out and replaced with a Perspex material.
  2. The retaining wall was constructed in layers, with the first layer being constructed 150mm from the bottom of the wall. The soil nailing was angled at a 10° decline and the soil being well compacted upon completion of the first layer.
  3. Another 100mm of soil was laid on top of this layer again with three soil nails being placed at a 10° decline angle. The soil was well compacted once again, with another 50mm of soil being laid on top of the soil nail.
  4. The soil nails were wrapped around and against the retaining wall which may have increased the friction and rigidity of the wall increasing the resistance of the wall.

- ***Edinburgh Napier University***
    1. The test apparatus consisted of a solid smooth concrete box.
    2. Due to miscommunication in the design proposal, the retaining wall was constructed with the first set of soil nails 150mm down from the top of the wall. The nails were angled at the 10° decline angle.
    3. The second set of soil nails was placed 100mm from the top of the wall and also at a 10° negative angle.
    4. The soil nails were drilled straight through the timber columns and piles which would have reduced the friction of the soil mails and may have had an impact on the total resistance of the retaining wall.

<u>Testing procedure</u>

- ***Lucerne University of Applied Sciences and Arts***

1. The wall was set up as explained in the construction procedure. The loading plate was located 70mm behind the retaining wall.
2. A series of weights were applied to the loading plate in increasing increments with no sign of the retaining wall failing.
3. The retaining wall resisted a total applied loading of 139kg still with no sign of failure. The retaining wall eventually failed when a seismic action was performed on the wall causing an overturning failure of the wall.

- ***Edinburgh Napier University***

1. The clamps on either side of the retaining wall that was attached to two pieces of timber were loosened to allow the retaining wall to withstand the weight of the soil.
2. When the clamps were loosened the retaining wall failed to resist the weight of the soil backfill and failed.
3. Therefore no applied loads were added to the wall as it had already failed to withstand self-weight of the soil.

Results

The key aspect of the coursework involved a collaboration between students from Lucerne University of Applied Sciences and Arts and Edinburgh Napier University. The objective was to analyse and design a reinforced earth retaining wall employing the soil nailing method with the aim of withstanding a maximum surcharge loading of 30kg.

The following results display the outcome of testing from both Lucerne University of Applied Sciences and Arts and Edinburgh Napier University. Both university's used the same design approach and measurements, however there was some variation in materials and construction build parameters that could have led to the discrepancies in the results obtained.

- ***Lucerne University of Applied Sciences and Arts***

The Lucerne students built and tested their retaining wall that achieved a maximum surcharge loading of 139kg. The materials used for the construction of the retaining wall included a PVC plate, the soils nails were constructed with cord and they were wrapped around the wooden columns on the retaining wall. The anchor material was polystyrene balls.

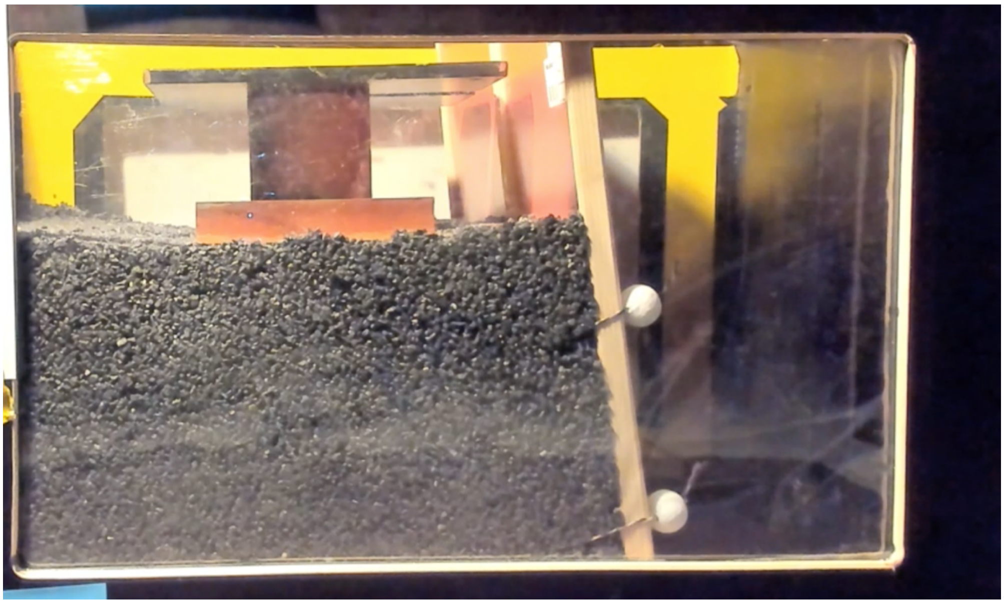


Figure 9.0 Retaining Wall built by Lucerne University

Figure 9.0 above represents the stability effects the addition of soil nailing has on the soil mass. The soil nails increases friction between the soil mass and soil nails thus providing lateral resistance. Lateral resistance reduces the effects of horizontal force exerted by the retained soil on the retaining wall, which overall reduces the possibility of the wall overturning. Bearing capacity is also improved with the addition of friction which we can see is evident from the pictures of the soil particles interlocked tightly, and the load the retaining wall surpassed.

The design displayed ultimate strength in both the active and passive state. Each loading that was applied to the soil backfill inducing the active zone exerting pressure on the retaining wall was resisted in the passive zone due to the reinforcements, hence as to why the soil mass remained very stable. Failure of the structure occurred at 139kg only because failure was intentionally implemented by the students. The students induced various movement in both the lateral and longitudinal plane to force failure of the structure. Figure 10.0 below displays the start of the failure slip surface occurring on the retaining wall orientated from the red dashed line as shown sloped downwards.

Figure's 10.0 and 11.0 below show the start of the slip surface occurring below the wooden plate carrying the applied load.

The applied loading on the soil in the picture's shown was the maximum loading of 139kg.

Forces induced by the students started the slip surface and figure 11.0 displays the failure of the retaining wall caused by the combination of induced forces from the students and the applied load.

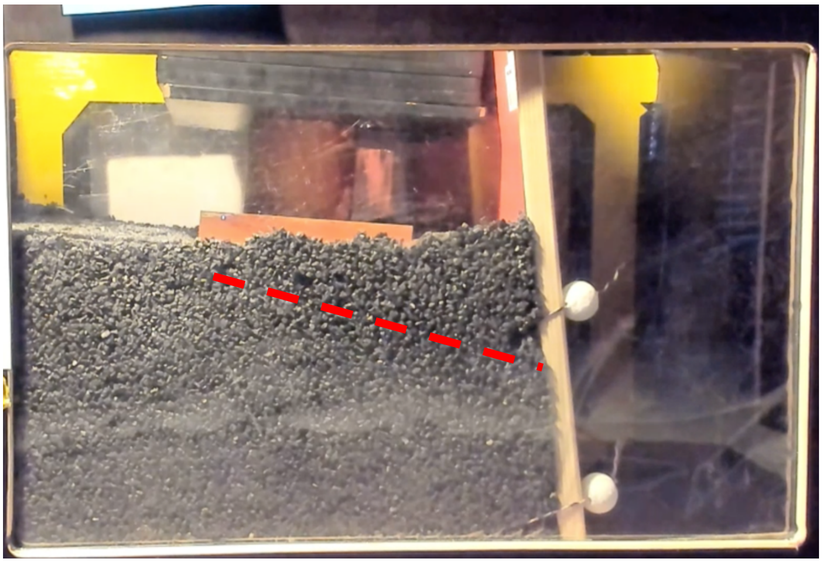


Figure 10.0 Beginning of the soil's failure plane

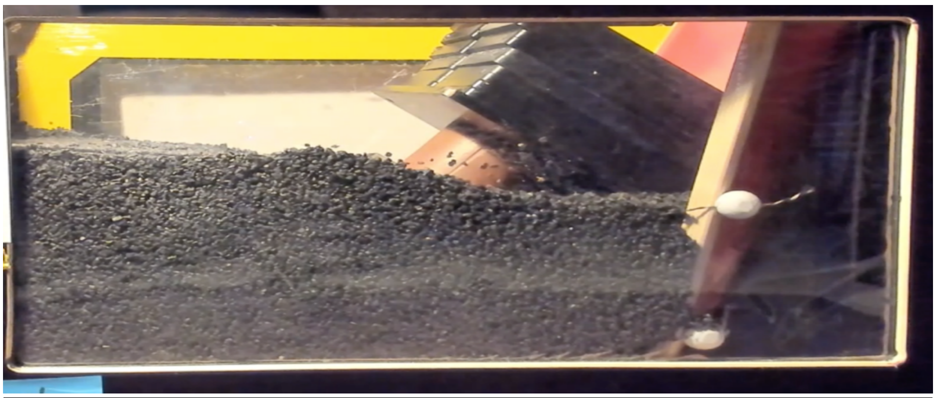


Figure 11.0 Failure point of Lucerne's retaining wall

The calculations represented the prediction of the retaining wall failing at a maximum load of 54kg. Reasons as to why the wall impressively exceeded this figure are further explained in the conclusion section below.

[redacted]

- ***Edinburgh Napier University***

The retaining wall that was built and tested at Edinburgh Napier University failed as outlined by the photos below. The materials used for the construction of the retaining wall included plywood and the soils nails were constructed using string. An aspect of the soil nails compared to the Lucerne students was that the string was not wrapped around the wooden columns but instead holes were drilled in the columns and the string was threaded through. Woollen balls represented the anchors that was attached to the soil nails.

The retaining wall failed to withstand the self-weight of the soil backfill as soon as the clamps were loosened from either side of the wall thus resulted in slope failure. A source of error that could have potentially led to failure of the wall, was the orientation of the reinforcement.

Failure of the retaining wall when both clamps were loosened

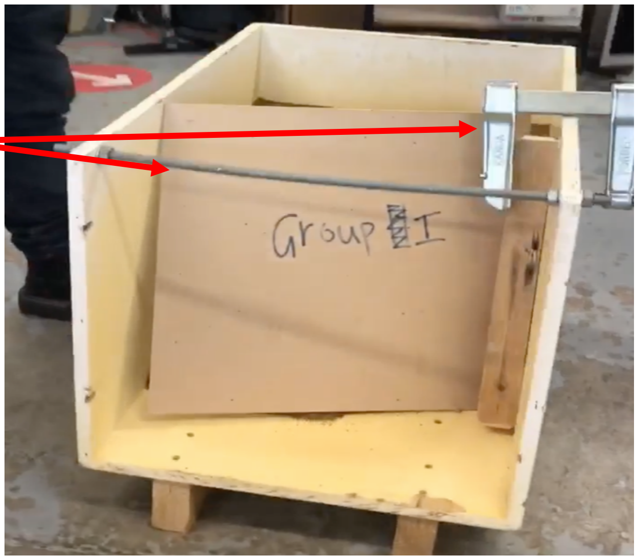


Figure 32.0 Retaining wall built by Edinburgh Napier University

Figure 13.0 Failure of the retaining wall built

The reinforcement was supposed to be at the bottom of the wall as opposed to the top, as seen in the photos below. This error could have occurred due to misinterpretation of the conceptual design layout and the miscommunication from the students to the lecturers clarifying the design measurements.

The failure plane of the retaining wall represented a rotational slip surface where the reinforced earth used the reinforcement as a pivot angle to overturn the retaining wall from the bottom. The active pressure exerted by the retained soil overpowered the lack of passive pressure from the reinforcement, failing to counteract the overturning of the retaining wall resulting in failure.

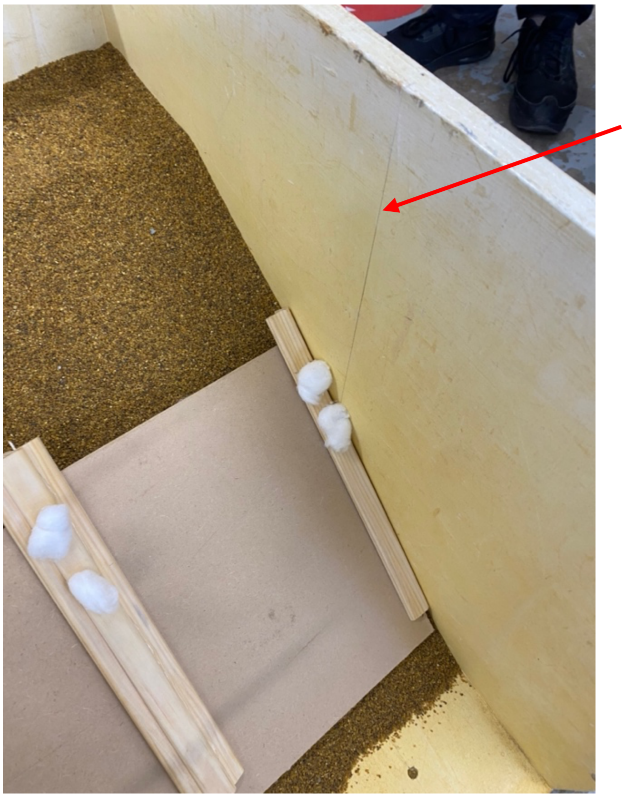


Figure 14.0 Location of the retaining wall before failure

Figure 14.0 displays the slip surface of the reinforced earth. The pencil mark outlined by the red arrow is an indication of the original location of the retaining wall prior to the clamps being loosened.

This shows the distance travelled by the wall and soil due to the exerted forces of the retained soil on the wall.

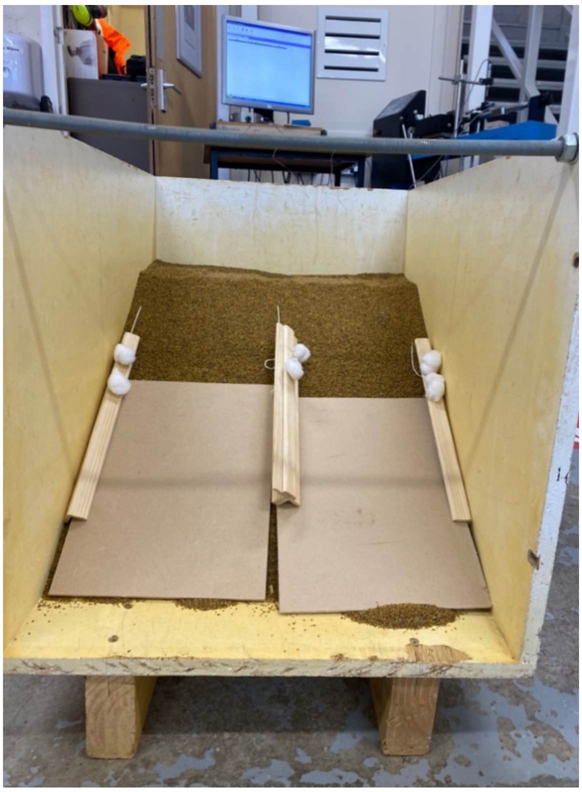


Figure 15.0 Wooden columns split during failure

Figure 15.0 shows failure mechanism of the retaining wall. The results of this design was ineffective and ultimately introduced more movement within the wall which assisted the soil in the momentum to overturn the retaining wall.

The idle middle section of the wall was intended to be used as a method of buckle prevention in the wall. However the input of this middle pile allowed for further movement of the wall, increasing the opportunities for failure rather than solely buckling failure.

Conclusions/ Discussion

The main findings that can be highlighted from the coursework is that one of the soil nailed reinforced earth retaining walls built and tested in Lucerne surpassed a surcharge loading of 139kg, while a soil nailed reinforced earth retaining wall built and tested in Napier failed to sustain the self-weight of the soil backfill.

Both walls were constructed using the same method and measurements however as highlighted in the results section, there was variation between both the materials and the construction process of the soil nailed reinforced earth retaining walls. Variation in relation to materials was solely down to quality control of each group. However notable differences include the following;

1. The Lucerne students used a wooden plate with a thickness around 10mm for the retaining wall. Cord was used to represent the soil nails and they were also wrapped around the wooden columns on the retaining wall. They adopted polystyrene balls for their anchor heads.
2. The Napier students used plywood with a thickness of about 3-5mm for the retaining wall, string modelled soil nails and woollen balls were used as the anchors.

The orientation of the cord being wrapped around the wooden columns on the retaining wall evidently could have increased the friction and stiffness of the Lucerne students wall and soil, making it stronger to hold back the retained soil mass and withstand the surcharge loadings.

Another factor that could have contributed to the failure of the Napier retaining wall was the misinterpretation of the conceptual design and the reinforcement of the soil nails installed in the wrong location. The soil nails were situated 150mm from the top of the retaining wall opposed to as design specification of 150mm from the bottom of the wall. Consequently there was no reinforcement at the bottom of the retaining wall and when the clamps were loosened the reinforcement located at the top of the retaining wall acted as a pivot point for the soil to exert active pressure on the retaining wall. This resulted in the wall being overturned as the force exerted by the retained soil exceeded the passive resistance of the soil nails.

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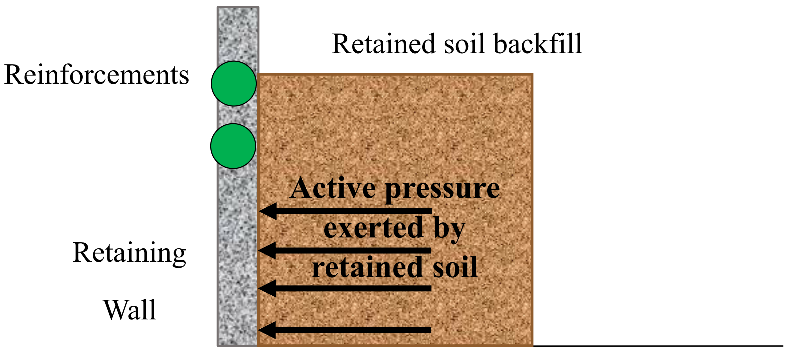


Figure 16.0 Retaining wall before failure

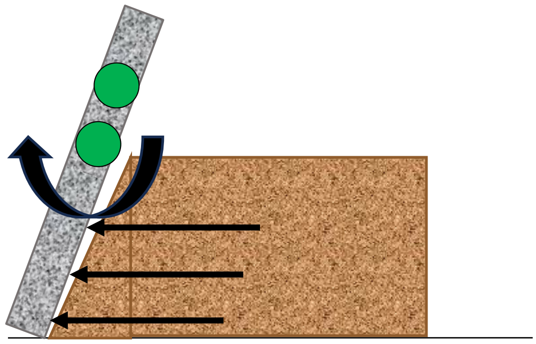


Figure 16.1 Resulting retaining wall failure

Construction of the retaining wall, emphasizing on the middle column, the result of this gap could have also contributed to the tilt angle of the retaining wall. Introducing elements within the wall that allow movement participated and contributed in the action of overturning the wall. The failure plane/ slope surface can be considered as rotational due to the manner in which it failed.

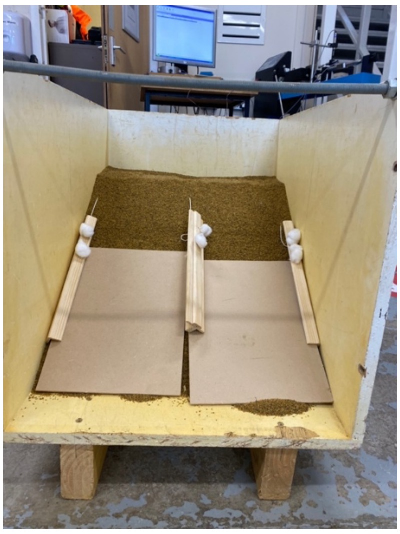
In conclusion, identifying the differences between the Lucerne students wall and Napier students wall, ideally the failure of Napier's wall is what we would expect based on theory knowledge. Active condition is when the self-weight of the retained soil backfill wants to fall and this exerts lateral pressure on the wall creating the opportunity for the wall to rotate and overturn. Passive condition is where the soil wants to push itself back into the soil i.e., creating a stabilising force providing resistance to movement of the wall. The addition of the soil nails helps contribute to the stabilizing of the soil mass due to their interaction with the soil helping distribute the forces more uniformly. Although as we can see from the results, location and layout of the reinforcing elements is fundamental to evenly distribute and stabilize the forces.

If too much emphasis is placed on resisting surcharge loading, placing reinforcement at the top of the retaining wall and disregarding active earth pressure on the bottom, then the wall will fail trying to withstand self-weight of the soil from the bottom.

This is an important factor which is a key learning curve for geotechnical engineering graduates. Understanding failure modes of retaining walls is crucial to mitigate these events occurring in real-life scenarios. Analysing failure helps engineers learn by comprehending why certain methodologies failed. It contributes to better and safer design strategies that mitigates these risks and enhances future designs and overall stability.

Revaluating the design of the wall and considering the mistakes made that resulted in failure, an idea that could have increased the strength of the retained soil would be the addition of piles in the centre of the soil. Adding piles into the centre of the soil backfill would enhance stability by distributing the load to provide more support and hence destabilizing sliding forces that caused the wall to overturn and slide.

Appendix A



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