A GEOTECHNICAL WORKING PLAN FOR A THOROUGH BUT QUICK ASSESSMENT OF EXISTING SLOPES IN CLAY MINES

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Report for Bachelor’s end work

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1 Abstract

In the Westerwald area clay quarries are in production. In order to assess the stability of the slopes the geotechnical characterisation of these quarries needs to be improved. This report provides the justification for a working plan for a thorough but quick assessment of existing slopes in clay mines. Literature is consulted for the information for the types of measuring and monitoring equipment for slopes, what instabilities look like in the field, how the safety factor are calculated, what information can be gathered outside the mine and what a field investigation should concern. To come to a working plan a field investigation was conducted to try out the different measurement equipment. For field testing, the needle penetrometer and hand vane shear came out as useful tools for correlating undrained shear strengths parameters of different layers. For thorough correlations, between layers and a dataset of geotechnical parameters, Atterberg limits are used to minimise the number of geotechnical parameters that have to be tested. The parameters are tested with different machines based on the timespan over which the slope has to be stable. Short-term slopes with in-situ conditions are best tested with triaxial tests, but UCS and a theoretical strong shear box can provide useful data as well. Long-term slopes are better tested with either a shear box or ring shear because remoulded or weathered properties are needed. Monitoring is found to be done best by using InSAR monitoring provided a suggestion is added to increase the number of data points inside the mine. The working plan is presented as a flowchart for a good overview.
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3 Introduction

Sibelco NV is a Belgium mining company with more than two hundred quarries worldwide. The German branch (Sibelco Deutschland GmbH) is operating in the production of clays, the raw material for ceramics. Sibelco is operating from more than 20 deposits in the Westerwald, Eifel, Palatinate and Saxonia areas, and from an additional kaolin deposit in the Czech Republic (SCR-Sibelco NV, n.d.). This report’s findings are based on data from the Westerwald area, but can be applied to other clay mining activities. The aim of this report is to find a geotechnical working plan for a thorough but quick assessment of existing slopes in clay mines. The problem with the mines is that, to date, little is known about the slope stability. Previously, the slopes were built upon knowledge obtained in the field, no geotechnical parameters were considered. Several slopes near external infrastructure are only monitored, but this may not be enough as damage may already be done when movements are monitored.

For the assessment whether a slope is stable or not different kinds of geotechnical testing methods can be used. Which to choose, where to test and how many tests have to be done is all in the scope of this research. To test the feasibility of the proposed plan, a test run will be done in one Sibelco’s quarries. This will be done in the Pfeul quarry since a related research will be carried out there as well. The combined forces mean more data can be gathered. The results of this field test will help to confirm or adjust the assessment plan. If the plan proves to be sufficient it can be incorporated in the assessment of the mine stability at Sibelco.

At the start of the research period background knowledge will be acquired. First, the geology of the area will be discussed. This helps to understand the underlying problem and to see whether specific problems may be expected somewhere else due to continuing layers. After that the types of tests available will be discussed. This part will be split up in measuring and monitoring equipment, because of their ability to be used before or after the assessment has been done. Together with operations geologist Dr. Andreas Hoffmann Sibelco’s quarries were surveyed to see the problems and to assess the different kinds of problems that arise in the slopes. The results of these surveys are discussed in Failure recognition in the field. Furthermore in Background knowledge, the different failure mechanisms will be discussed to know how instabilities arise and how to calculate safety factors for different scenarios. After that desk study and field investigation theories will be discussed. In the next chapter, Methodology, the testing done is explained. Chronologically, in Results and Discussion the results of the tests will be presented and explained. A conclusion will be given at the end of the report in the form of a flowchart with explanation, this conclusion justifies or rejects the tests done during the field investigation and presents in what order tests should be done. Lastly appendices are presented with background information and test results.
4 Background knowledge

4.1 Geology

During the Mesozoic period, the Variscan orogeny took place in the Westerwald area. The structure and geological development is closely related to the development of the Harz Mountains in eastern Germany. During the orogeny, the rocks from the Devonian to Carboniferous strata were folded and uplifted in some places basins were formed. Those basins are important for the deposits found today. Because, during the tertiary period those basins act as sedimentary traps for the material that has eroded from the mountains. Afterwards, in Tertiary times volcanic activity began. These volcanoes pierced through the clay layers and covered the top of the clays. The volcanic tuff and basalt formed a protective layer over the clay so it did not wash away by rivers or other erosional processes (Sibelco Deutschland GmbH, 2013). In Figure 1 a schematic overview of the geological development in the Westerwald area is shown.

The clay layers are composed of multiple different kinds of clays. The clays differ on appearance in terms of colour and in terms of chemical properties. This mainly depends on the chemical elements that have been present during the settlement of the resource. The valuable clays can roughly be classified as red firing, coloured and light firing clays. Above those clays lays the overburden consisting of volcanic matter and underneath are basal siliceous clays which have no value today. The basalt layer and especially the tuff layer weathered to smaller particle sizes. Sometimes they weather to such an extent that an extra clay layer is found mostly consisting of Montmorillonites and appear green in colour.

Due to the pressure of the overburden and the removal of the overburden afterwards the clay became over-consolidated. This means that the clay is much harder than expected for the amount of overburden. Over-consolidated clays are much harder than normally consolidated clays, which has implications on the geotechnical engineering with the material.

4.2 Measuring and monitoring equipment

To assess the stability in the mine different parameters can be measured. Below the equipment to do this is explained. A distinction is made between devices that can measure parameters needed to predict stabilities and devices that monitor instabilities. As of today, Sibelco Deutschland only uses the latter.
4.2.1 Monitoring

4.2.1.1 Inclinometer

For measuring slope movement an inclinometer can be used. The inclinometer consists of a borehole and a measuring tool. The borehole is situated in the slope to be measured, it must be installed to such a depth where the ground is not prone to movement. When the ground moves the borehole moves with it causing the borehole to deflect. This deflection can be measured by a measuring tool or probe that is lowered into the casing every once in a while. From this the movement of the slope can be calculated (Stark & Choi, 2007).

The tool can be uni- or biaxial and refers to the number of sensors installed. A uniaxial probe has one direction of measuring and should therefore be inserted four times into the hole to measure each direction. The biaxial probe has two sensors that are placed in a ninety-degree angle and has to be inserted only twice to measure all directions. A schematic overview of the probe and deflection is shown in Figure 2.

Advantages of this measurement are that a depth profile of movements is generated and the movements through time can be derived. The difficult thing about using the inclinometer are the difficult instructions that have to be used. For example, the borehole needs to go down to a stable layer, when this layer is reached is difficult to estimate. While measuring it is also recommended to always use the same equipment and operator (Stark & Choi, 2007), this can be difficult to accomplish due to personnel availability. Another challenge with using the inclinometer is that first a baseline measurement has to be established. Therefore, a measurement in an already moving slope is less accurate, and the measurement locations should be planned beforehand.

The system used by Sibelco is a Sisgeo Digital MEMS Inclinometer System. This set includes a datalogger (Archimede) and a 1000 mm long biaxial measuring probe. The accuracy of this system is ± 2.00 mm / 25 m (Sisgeo S.r.l., 2016). However, if multiple baseline measurements are taken a more accurate picture of the system accuracy is known since the operator accuracy is then taken into account as well.
4.2.1.2 Laser

Using laser some or multiple points can be measured to monitor their movement over time. Generally, there is a device from which a laser is sent out and the distance to the device is measured. The scanner is situated at a known and fixed point. The distance to the point being measured can be calculated in two different ways (Vosselman & Maas, 2010). First by using time-of-flight (TOF) measurements. With TOF the time is measured when the light pulse is sent out and when it is received again. Since the lightspeed in air is roughly constant and known the distance can be calculated. Another method is by using triangulation. With this method, the sourced and received angle is known and measured respectively. By using the cosine law, the distance to the point can now be calculated. The two methods are illustrated in Figure 3.

![Figure 3: Active methods for optically measuring a 3D surface: (left) light transit time and (right) triangulation. (Vosselman & Maas, 2010).](image)

Tachymeter

The first device where optical distance measuring is used is the tachymeter (aka tacheometer or total station). The tachymeter is pointed by the operator at specially designed reflectors to measure the distance to that specific reflector. The reflectors are placed beforehand on strategic points that are prone to movement and some at points that should not be moving to check the accuracy. The device owned by Sibelco (Topcon ES-105) has a reported accuracy of ±3 mm (Topcon Europe Positioning B.V., 2012). Advantages of this system is that a large area can be evaluated quickly and the same points can be measured every time. Also, the high precision of the measurements is a benefit. Disadvantages are that the measurements have to be taken from a stable point and all the reflectors should be in line of sight. The usage of reflectors also limits the amount of points that can be taken.

3D laser scanner

The second device where laser distance measuring is used is the 3D laser scanner. In principle, this is the same device as the tachymeter but the laser scanner does not use reflectors instead it uses the ground surface as a reflector. When the 3D laser scanner is scanner it makes a point cloud of the area of interest. This cloud represents the surface and can be compared to previous measurements to know the movement in the area. Since the systems are comparable the accuracy of the 3D laser scanner is the same as the one from the tachymeter. The advantage of the 3D laser scanner over the tachymeter is the higher amount of points, but the laser scanner is more difficult to use on a producing slope since the points aren’t easily comparable to previous measurements. The costs of the 3D scanner are also higher.
4.2.1.3 Aerial

Another non-destructive way of monitoring deformations is by using aerial obtained data with InSAR techniques. InSAR stands for interferometric synthetic aperture radar and is a technique to calculate deformations from two subsequent images. It does this by calculating the interference pattern caused by the difference in phase between the two images (Massonnet & Feigl, 1998). These data can be obtained either by satellite images or by a UAV (unmanned autonomous vehicle, aka drone).

Satellite

Sibelco is already working with a company to get aerial deformation information. The company that provides these data is SkyGeo. SkyGeo promises a semi-daily measurement of the area, this means that almost every day a new measurement is made of the changes in the area. This is done with an accuracy in the order of millimetres (SkyGeo Inc., n.d.). By combining multiple measurements into one the error can be removed from the data even more. Advantage of this system is that it provides a non-destructive measurement that is accurate and with high frequency. However, in an active mine it is difficult to measure the same point again when it has been dug out. Another disadvantage is that there’s no control over what points are going to be measured. The image may miss one point of specific interest, then some inaccurate interpolations have to be made.

UAV

The aerial images could also be acquired by an airborne UAV. The images are then captured from a distance closer to the ground surface. Companies producing these kinds of UAVs are vague about the precise workings of the system, but it should be something that is comparable to InSAR. A company that makes such a device is Trimble Inc. Their UX5 will be taken as an example for the acquiring of data. This device has a resolution of up to 2.0 cm GSD (ground sample distance). The advantage of this type of acquisition is that the company is in charge of when data is produced. Since the system takes RGB photographs, markers can be laid down to evaluate their movement over time, so the same point is measured every time. The downside of using UAVs is that the accuracy is less than the satellite data. Manpower is needed to acquire data which makes it difficult to get the data when needed.

Eye observation

A commonly used method of analysing deformations is by looking at the mine. The geologist or geotechnical specialist visits the mine every once in a while, to assess the mine. During this assessment, the observer may notice changes since his last visit. Albeit not being an accurate method it is used a lot in the field. The advantage of observing is that a qualitative description can be made of what kind of deformations are taking place. Quantitative assessments of the deformations are difficult to impossible since the errors produced while measuring are too large.

4.2.2 Measuring

4.2.2.1 Triaxial test

The triaxial test is a test to determine the stress-strain characteristics of a specific soil type. Outcomes of this test provides insight into under what load a soil will start to shear or slide. The test procedure replicates the effectives stresses of the field and then applies additional stresses until the sample loses its strength. A schematic of the triaxial test is shown in Figure 4: Schematic overview of a triaxial test setup.
Figure 4. The test can be executed with different settings. Unconsolidated (U) or consolidated (C) and drained (D) or undrained (U). The different combinations are CD, UU and CU (Bardet, 1997).

4.2.2.2 Atterberg limits

The Atterberg limits are an indication for the behaviour of a soil under different water contents. The three defined limits are; shrinkage limit, plastic limit and liquid limit.

- **Shrinkage limit**: if the water content reduces under the shrinkage limit the soil will not lose any volume by the decrease in water;
- **Plastic limit**: limit where water content drops to a level where the soil is not behaving plastically anymore. Technically this limit is defined as the moisture content where a thread will break apart when rolled out down to 3.2 mm;
- **Liquid limit**: the limit where the behaviour of the soil changes from plastic to solid. Since the transition is gradual a standard is defined just like with the plastic limit. This is defined as follows: the moisture content at which it takes 25 blows with the Casagrande cup to close a groove of 13.5 mm.

If the plastic limit is subtracted from the liquid limit the plasticity index is calculated ($PI = LL - PL$). If this index is then plotted against the liquid limit different soil samples can be correlated. Therefore, in practice only the liquid and plastic limit need to be tested. The Atterberg limits are mostly used for the calculations. For example, when on one side of the mine a triaxial test is done but the stability has to be assessed on the other side a Atterberg limits test can provide insight in whether the triaxial test may be used for the strength on the other side of the mine. To know how the soil behaves in the field the water content should also be noted and compared to the test results.

Results of different soil samples can be plotted in a PI-LL graph (plasticity index vs liquid limits). When a new soil sample is found then the its PI can be plotted in the graph to see if the different samples with already tested geotechnical properties are known. This can cut down in the economics as less tests have to be carried out.

4.2.2.3 Direct shear test

With the shear test the friction angle, cohesion and undrained shear strength are determined. For this the shear box is used. The shear box is a box where an undisturbed sample is placed as can be seen in Figure 5. The shear box consists of two halves that are able to slide over each other. The soil is placed in-between and is then subjected to shear. During the test the lateral force ($T$), normal force ($N$) and corrected area ($A_c$) are observed. Then the parameters can be calculated with the following formulas:

- **Normal stress**: $\sigma = \frac{N}{A_c}$
- **Shear stress**: $\tau = \frac{T}{A_c}$
- **Peak friction angle**: $\phi_p = \arctan\left(\frac{T_{\text{maximum}}}{N}\right)$
- **Residual friction angle**: $\phi_r = \arctan\left(\frac{T_{\text{residual}}}{N}\right)$

![Figure 5: Direct shear box (From eo-miners.eu)](image-url)
4.2.2.4 **Hand vane shear**

When a quick estimation of the shear strength is needed in the field a hand vane shear test can be executed. For this the hand vane shear is used. This is a device with on one end four planes, the vane, that is pushed into the soil, on the other end is a torque gauge. When the gauge end is turned a spring is loaded that increases the torque on the vane and thus on the soil. In this way, the maximum shear stress can be measured. The measuring range of the hand vane can be adjusted to the specific soil with different vanes that can be mounted onto the device. The hand vane in use has a measuring range of 0-250 kPa and has a reported reading accuracy of 0.01 kg m⁻² (Eijkelkamp, 2012). According to Zimbone et al. the hand vane shear test gives an average result for the tested soil in comparison with the torvane and the pocket penetrometer (Zimbone, Vickers, Morgan, & Vella, 1996).

4.2.2.5 **Pocket penetrometer**

Just like the hand vane the pocket penetrometer is also a quick field test, but the penetrometer provides insight in the UCS (unconfined compressive strength) of a soil. Using tables or graphs delivered by the manufacturer UCS readings can be converted to shear strength readings. The pocket penetrometer consists of two telescopic cylinders that are spring loaded. The device is hand pushed into the soil and a reading of the UCS can be made. If the strength of the soil is too high the penetrometer may not be able to penetrate into the soil and a reading cannot be made. The accuracy of the device is dependent on the operator that reads the scale, but half the reading scale is a good approximation (Humboldt Mfg. Co., 2014). This reading scale must be multiplied by a specific factor for the adapter foot used. A typical range for the accuracy is 0.7-3.4 kPa (Zimbone, Vickers, Morgan, & Vella, 1996). According to Zimbone et al. the pocket penetrometer overestimates the shear strength of a soil because it generates both a compression and shear type failure at the same time (Zimbone, Vickers, Morgan, & Vella, 1996).

4.2.2.6 **Cone penetration test (CPT)**

As opposed to hand operation used with the penetrometer a cone can also be penetrated mechanically, this kind of test is called a CPT. A CPT is performed by pushing a cone into the ground at a constant rate. During this test the cone effort \( Q_c \), total insertion effort \( Q_t \) and most of the times the lateral friction \( Q_s \) are measured directly (Monnet, 2015). From these parameters, the strength of the soil can be derived. Other parameters can be measured on the cone as well. For example, the water pressure can be measured, which provides insight in the depth of the water table and whether the soil is subject to undrained shearing. A big advantage of performing a CPT is that a profile of the soil is made. On this profile, different strata can be seen and problematic layers can be identified immediately. To establish a CPT measurement specialized tools and equipment are needed. Therefore, an external contractor has to be hired to perform the test. This makes the CPT more costly than other in-situ tests, but it provides huge insight into different layers and in-situ parameters.
4.3 Failure recognition in the field

4.3.1 Cracks

When a failure is developing it develops along a failure plane. The plane may outcrop at the surface or in the wall as can be seen in Figure 8. The cracks are deep, about half a meter, and follow a common direction that is usually parallel to the face and with a normal directed to the pit. As can be seen multiple cracks develop at the surface. This and the fact that they are deep makes them distinguishable from erosional paths formed by streams.

At the toe of the wall the failure plane outcrops as well. These can be recognized by the material that slipped downwards. When the inside of the failure plan is examined one notices that the plane is smooth. This distinguishes it from a plane where the material topples as those are rough surfaces.

Cracks in clay can also form due to the material drying out. This process is caused by the fact that clay swells when it gets wet and decreases in size when drying out (Krakow, 2010). The cracks formed may propagate and form a continuous crack causing the material to be loose. A part of the wall may then break loose and topple over.

4.3.2 Overhangs

When a stable layer is underlain by a layer that is less stable the bottom layer may erode more easily. The top layer may then be undercut leaving the upper to be hanging freely. This kind of situation is unstable and potentially very risky, since a large rock mass may come down in one time. These kinds of instabilities happen more often when water is at stake. As can be seen in the example of the Pfeul quarry in Figure 10.

Overhangs can also come into existence by drying out of the clay. The cracks that form then may cleave the lower side of the face from the rest of the material. The upper part of the wall is hanging loose and can easily collapse. This process is shown in Figure 11, on the left side the cracks are formed by the drying process. The right most picture shows the lower
part being slipped down, now the upper part of the wall is hanging over.

4.4 Failure mechanics

4.4.1 Vertical slope

For the calculation of the stability of a vertical slope, two different situations can be evaluated, with and without cohesion. Since clay is a highly cohesive material the cohesive situation is explained. The stability of a vertical slope is judged upon the calculation of a maximum and minimum vertical slope height ($h_c$). From literature, a minimum height for the lower slope was found in the following formula (Verruijt, 2001):

**Equation 1:**

$$h_c \geq \frac{3.7752c}{\gamma}$$

This is the maximum value for the lower bound of a vertical slope. The $c$ here represents the cohesion and $\gamma$ the volumetric weight of the soil. An upper bound for the slope height can be calculated in two different ways; with a straight slip plane and with a circular one (Verruijt, 2001). The straight slip plane is shown in Figure 12. The maximum height for this kind of failures is described with the following formula from A. Verruijt:

**Equation 2:**

$$h_c \leq \frac{4c}{\gamma}$$

A circular slip plane can also be considered. This case has been calculated by Fellenius in 1927 and improved by Pastor in 2010 (Verruijt, 2001). He found the following upper bound:

**Equation 3:**

$$h_c \leq \frac{3.776c}{\gamma}$$

This concludes to the following narrow stable wall height:

**Equation 4:**

$$\frac{3.7752c}{\gamma} \leq h_c \leq \frac{3.776c}{\gamma}$$
4.4.2 Dry slopes

For slope stability analysis, generally a circular failure plane is considered for an arbitrary slope. This method is found by Fellenius (Verruijt, 2001). To figure out a factor of safety the ratio of strength and load is determined. For this the following formula is crucial:

Equation 5:

\[ \tau = \frac{1}{F} (c + \sigma'_n \tan \phi) \]

Where; \( \tau \) is the shear stress, \( F \) is the factor of safety, \( c \) the cohesion, \( \sigma'_n \) the effective soil strength and \( \phi \) the friction angle. This formula provides a basic calculation for the stability of the slope, the calculation is proved to be rather basic. Therefore, a factor of safety of 1.05, for instance, does not mean the slope is actually stable in practice. For the calculation, the slope is divided into slices. Then, for every slice the factor of safety is calculated. This system assumes that for all of the slices the Geotechnical properties are the same. The division into different slices is shown in Figure 13, also the circular failure envelope is shown. If the FOS for a whole slope is needed the formulas for the different slices can be added. To simplify it is recommended to give all the slices the same width. Because then the addition reduces to the following formula:

Equation 6:

\[ F = \frac{\sum \left[ \frac{c + \sigma'_n \tan \phi}{\cos \alpha} \right]}{\sum \gamma h \sin \alpha} \]

In this formula \( \alpha \) is the angle of the slope.

4.4.3 Flow parallel to slope

When there is water flowing parallel to the slope the stability is greatly reduced. This situation occurs when water is flowing over the slope, then this water can penetrate into the slope surface and generate ground water flow that is parallel to the slope in the downward direction. In the clay mines this situation might happen during periods of rainfall. Since the clay is impermeable all the water will run off over the slope which can cause the instability. This situation is however more applicable for sandy layers between the clays, those have higher permeabilities and are therefore more susceptible to instabilities. Flow parallel to the slope can also occur when a wall around a water basin is overtopped. Then the water flows over the slope and causes instabilities when it penetrates into the soil (Verruijt, 2001). To assess the stability in such a situation the following formula is used to describe the FOS:

Equation 7:

\[ F = \frac{\gamma - \gamma_w \tan \phi}{\gamma \tan \alpha} \]

Where \( \gamma_w \) describes the volumetric weight of water (1000 Nm\(^{-3}\)).
4.4.4 Horizontal outflow

Groundwater that is present in-situ can flow out when a mine is constructed. Then the flow path of the water is horizontal outflow. As mentioned before clays have a low permeability and are therefore less susceptible to flow problems but the sandy layers are capable of causing instabilities under flow. A. Verruijt again calculated a general formula to calculate the FOS for a horizontal outflow problem:

\[ F = \frac{\gamma - \frac{\gamma_w}{\cos^2 \alpha}}{\tan \phi \tan \alpha} \]

Since the value of \(\cos^2 \alpha\) is always smaller than 1. The FOS for horizontal outflow will be lower than for parallel flow (Verruijt, 2001).

4.5 Desk study

Before a field test is conducted some data can already be gathered in the office. A good way could be by viewing satellite data. SkyGeo can provide deformation data around the mine and sometimes inside as well. The data inside the mine is limited since SkyGeo’s software requires point to be stable over time. In a mine, the constant movements of earth disturb the reflections and causes points inside the mine to be thrown away. The advantage of this package is that for a large area deformations can be observed.

Observing deformations with inclinometer data is also possible. Inclinometers can also provide insight into what layer is causing the sliding. But the tedious measurement process makes that little measurements are made in practice. Sibelco currently strives to do measurements every 4 months, this may be too little for a good insight in the movements.

Overall the usage of satellite data is favourable. Although inclinometers gather exact data about ground kinematics, they are only installed into slopes that are already known for having stability issues. The satellite system is measuring at every location so unidentified instabilities can be detected before large slides occur.

4.6 Field investigation

In a field investigation samples are taken to acquire data about the stability of the slope. During the site investigation, the type of failure that may occur and its reason can also be determined. The reason for failure partly determines what kind of investigation technique must be used (whether or not to measure groundwater pressures).

To plan an investigation a cross section should be drawn over the slope of interest. Because all the failure mechanisms develop perpendicular to the slope the cross section should also be perpendicular to it. The number of cross sections required to map the slope depends on the length of the curvature of the slope. If the slope is long (measured along the strike) then more cross sections are needed to rule out spatial variations. If the geology is known to be irregular more cross sections should also be considered. To rule out anisotropic variations more sections should be taken if the slope is curved for example in a corner of the mine. When field test support that the clays are laterally isotropic, then extra cross sections for the curvature can be neglected.

A good support for planning the field investigation is by using Eurocode. Eurocode is a set of standards that ensure safe building of civil projects. A part of the Eurocode specifies the stability of slopes and the requirements that have to be met in a field investigation, this part is Eurocode 7:
Geotechnical Designs. Albeit Eurocode is aimed at civil engineering some parts can be applied to the mining industry. Requirements for the investigation are based on the longevity of the slope. Since the slopes have to have a decent factor of safety at the end of their lifetime, a longer standing slope requires more investigation to guarantee this requirement. Ground properties obtained during a field investigation can be acquired by directly testing the ground, or by correlating grounds to one another. After a field investigation is performed, Eurocode requires to monitor the slope on different criteria (British Standards, 2004). Those criteria are to monitor:

- Ground deformations affected by the structure;
- Pore-water pressures of the soil;
- Displacements and forces acting inside the soil.

### 4.6.1 Water related problems

A previous site investigation performed in the Hohewiese quarry consisted of multiple CPTs and inclinometer data already acquired in the area. In the slope, an area was observed where water crept out. As explained in Failure mechanics (page 11) water can greatly reduce the stability of a slope. To assess whether the failure will be based on flow parallel to the slope of horizontal outflow the flow of the water must be known. The flow direction can be estimated by measuring the pore water pressure in different locations. Then by using Darcy’s equation the flow direction and magnitude can be calculated (Fitts, 2012). Darcy’s law is displayed below in Equation 9. With the specific discharge vector, the type of groundwater flow problem can be evaluated and consequently the factor of safety can be calculated.

\[
\vec{q} = -K\nabla p
\]

- \(\vec{q}\), flux or discharge per unit area (m/s)
- \(K\), hydraulic conductivity
- \(\nabla h\), groundwater gradient

The groundwater heads can be measured in different manners. But, most easily in the field is either by using already drilled inclinometer boreholes or by using a CPT. Albeit the CPT is more expensive, the critical layers can be identified as well. If a detailed cross section of the slope is already known the borehole water depth is just as reliable.

The minimum amount of water pressure readings that have to be performed is two, only then a direction of the flow can be calculated. This requirement holds per cross section taken over the slope. If multiple cross sections in different directions are considered more pressure heads are needed. However, if two cross sections are parallel, the slope perpendicular to the two cross sections and the geology constant the same groundwater conditions can be assumed for the two sections. This reduces the costs since less measurements have to be made. When the flow situation is known the geotechnical parameters of the soil can be evaluated. This is done as described in Geo-technical parameters of soils (page 14).

### 4.6.2 Geo-technical parameters of soils

To determine the geo-technical parameters of the soil, samples have to be taken and tested. Since the behaviour of clays depends on the water present, the water content is measured in the lab. Then Atterberg limits tests are performed. The plasticity index is used to compare the samples to previously tested ones. When a match is found between the present and past samples the geotechnical parameters from that soil can be used as opposed to testing the new samples. If the
strengths are not known yet they should be tested. This can be done either by using a shear box or by using a triaxial test.

The number of samples depends on the cross section that is evaluated. The samples should at least be taken in every layer or every 1.5 meters (Look, 2007). It is assumed that the geological model is known and is correct. This is done to be able to extend the tested parameters into the slope. If for practical reasons the sample cannot be taken on the cross-section line it can also be taken close to the cross section, as long as the same layer is sampled.
5 Methodology

To know what has to be done to make a quick but thorough assessment of the stability of the slopes first a field test was performed to find what devices are appropriate for testing. The data that is generated also provides a springboard for future assessments of slope stability, since Sibelco then already has some data to correlate tests.

To know exactly with what kind of soil is dealt, a field test was executed. The main questions of this field test were:

- What is the geotechnical variation between different layers?
- Can hand tests like the hand vane shear and the pocket penetrometer be used on these clays?
- What are the geotechnical parameters of the clay?

To answer these questions the field test was performed in conjunction with the geologist. The geologist is able to identify different geological layers in the field. From every layer then samples were collected and the hand tests were performed. These samples are used in Atterberg limits tests, to assess the geotechnical variation. From two selected layers, larger samples were taken. These larger samples form a basis for geotechnical tests performed in the laboratory (triaxial and/or shear box tests). As opposed to the criterium set out by Look (2007) to sample every layer or every 1.5 meters, the layers were only sampled once independent of their height. The reason behind this is that every layer has its own bench and thus the layer is only accessible at the toe of the bench. Such considerations are normal when doing field tests. The risk of leaving out data is mitigated by doing a visual inspection to ensure the layer has a homogenous appearance.

In the field both the pocket penetrometer and the hand vane shear were used. The pocket penetrometer provides data that can be correlated to an UCS test. The vane shear provides insight into the shear strength of the soil. The problem with these devices in the field is their low upper limit for testing. Most of the times the tests were not performed because the clays are too hard.

As mentioned before, the samples taken in the field were used to perform some tests in the laboratory. The Atterberg limits are performed on every sample to be able to correlate all the different layers. Atterberg limits are also relatively quick and cheap to perform, which makes it feasible as well to conduct these tests. One of the larger samples was taken from a layer which looked like the other layers in the mine, so this could be correlated to the other layers. One particular layer was found to be wet while no rain had been falling lately, also this layer felt much more sandier than other layers in the quarry. Therefore, this layer was chosen to take out a large sample as well.

The shear box used was a device constructed by ELE Intertest BV and has a maximum shearing load of 4.5 kN. The shear box test was performed unsuccessfully, since the clay is too hard for the testing device. Therefore, it was opted to first cut the sample and then do the shear test. During this test, an estimate for the residual shear strength is obtained. Another downside of the clay being hard is that the preparation of samples for the device is hard. To make a sample of the correct size the clay was cut wet. This consequently changed the moisture content of the sample. The shear box sample was therefore returned to its original moisture content before executing the test. To model the behaviour of the clay the outcome of the test is modelled in a Mohr Coulomb failure envelope. Cam clay which is usually better at modelling clays does not provide a benefit since the clays are so hard they behave more like rock.
To get the in-situ strength conditions as well an UCS test was performed as well. The samples for this test were prepared by core boring cylinders from the sample taken in the field. This is again done wet because of the specifications of the machine. After boring was done one core was pulled apart to see how deep the water percolated into the sample. The water got into the core by an amount of 4 mm. To compensate for this the sample was again left to rest so the water spread evenly throughout the core or was able to evaporate. The sample was weighed and its dimensions were taken before and after the test to calculate wet and dry densities and the moisture content.

In the laboratory, a needle penetrometer test was conducted on the samples brought in for the shear box and UCS tests. This was done to see whether this test does provide a quick readout that can be used in the field. As opposed to the pocket penetrometer the needle penetrometer has a sharp pointy probe that is pushed into the soil. The Maruto SH-70 needle penetrometer came with a formula to convert the measurements to the standardized UCS measurements. The formula for converting to UCS is presented in Equation 10.

\[ UCS = 0.4 \cdot NP1^{0.929} = 0.4 \cdot \frac{F}{D} \]

Where:
- \( UCS \), UCS equivalent strength (MPa);
- \( NP1 \), needle penetration index (N/mm);
- \( F \), force required to penetrate the sample (N);
- \( D \), penetration depth into the sample (mm).

Satellite data acquisition by SkyGeo is limitedly useful for the Sibelco case. The data points inside the quarries are very limited due to the frequent excavations. At the borders of the quarry more data is available if the vegetation is limited. It would be nice if the reflectors inside the quarry can be used despite the frequent excavations. Therefore, a meeting was set up with the team behind SkyGeo to ask whether they can improve the number of data points. During this meeting, the technology behind the data and the accuracy will be discussed as well.

To know whether the stabilities can be calculated analytically, the program Slide by RocScience was evaluated. In this program, the slope is modelled with for every layer its corresponding strength parameters. Then the slope stability is calculated using different methods. The methods also take the water pressures into account to get a realistic estimation of the stability factor. Before the calculation is executed the user has to specify whether a block slide or circular slip surface is expected. Block slides are assumed to be expected on fresh slopes, so the soil has its in-situ parameters, circular slides are expected when the material has weathered and became softer.

6 Results and Discussion

6.1 Atterberg limits

The different layers can be geotechnically correlated using the Atterberg limits. The classification shown in Figure 14 is based on the plasticity index distilled from the Atterberg limits. As can be seen in the graph there is a flock of layers in the middle of the graph, the properties of these layers are ought to be correlated. On the lower right side of the flock samples 20, 9, 4 and 17 are on the edge of sharing the same properties as the rest of the cloud. If instabilities are found to be around these layers it is advisable to conduct extra tests to assess the geotechnical properties. Other samples (7,
21 and 23) are not close to other samples and their properties are therefore not extractable from previously tested samples. Samples 10, 13 and 14 were tested, but the groove made in the sample already closed after one blow no matter the water content. Albeit those layers are all in the same spot, they should not be correlated. These results also show that the usage of different laboratories does not make a difference for the correlation. The inhouse test results lay in the same point cloud as the samples tested by Fugro. It is important to always test corresponding to the same standard (here ASTM), as this makes it possible to correlate the outcomes. An overview of the tests done per sample and their locations is in the appendix.

6.2 Shear box
As said before, the shear box used had too little force to make the sample shear. Therefore, the sample was first cut and then sheared. This test represents the residual shear strength of the sample. The different confining pressures used enables to make a Mohr Coulomb failure envelope. The points in Figure 15 represent the different failure points from the tests. A line is fitted through the points to estimate the failure envelope. As can be seen the failure envelope has a negative cohesion, something which is physically not possible. Therefore, the orange trendline is fitted while forcing it to go through the origin. An explanation for this behaviour is that the shear test might be executed too quickly, resulting in an overestimation of the shear stress at higher confining pressures. Still, this test has some significance to it. It shows that the cohesion is greatly reduced when the soil is in a residual state.
With the UCS test the failure stress can be determined. Two different samples have been tested, one in a layer resembling the others in the mine, the other in a different looking layer. The corresponding sample numbers are 23 and 22 respectively. Unfortunately, it turned out that the sample, which resembled the other layers in the mine, sample 23, is geotechnically not correlatable to the other layers. This can also be seen in the Atterberg classification in Figure 14. In Figure 16 the different
failure pressures for the samples are shown. The tests are conducted twice on different cores from the same sample, hence the A and B suffix. Sample 23 provided good results and gives an average failure point of 2.21 MPa. This is a reasonable number; a quick calculation gives that this sample can hold 129 meters of clay with a common specific weight of 1700 $kg/m^3$. The calculation is shown in Equation 11.

\[
\begin{align*}
\text{theoretical maximum overburden} &= \frac{\sigma}{\gamma} = \frac{2.21 \, MPa}{1700 \, kg/m^3 \cdot \frac{10 \, N}{kg \cdot m^2}} = 129 \, m
\end{align*}
\]

Sample 22 provided an interesting measurement. During the testing of sample 22A a failure surface developed. The residual strength in this failure surface was higher than the load applied when the surface developed therefore the test was continued. However, the machine came to maximum amount of travel hence the test had to be stopped prematurely. The failure surface of the sample preserved even after the sample dried out completely. Sample 22B was measured normally but the strength turned out to be very low, as can be seen in Equation 12. The theoretical maximum overburden of 44 meters is a debatable number since the original overburden was much thicker, up to 60 meters. Changes in water content due to the wet drilling and wet cutting might explain this.

\[
\begin{align*}
\text{theoretical maximum overburden} &= \frac{\sigma}{\gamma} = \frac{0.75 \, MPa}{1700 \, kg/m^3 \cdot \frac{10 \, N}{kg \cdot m^2}} = 44.1 \, m
\end{align*}
\]

These tests show that the UCS test is applicable to most of the clays in the Westerwald area. Softer clays which may be present in other quarries might not be testable with the UCS test. The UCS can provide a quick estimate of the strength of the sample. If a more advanced failure profile is needed the triaxial test can be used. The confining pressure enables the creation of a Mohr Coulomb failure envelope.

6.4 Field tests

In the field two different tests are used; the pocket penetrometer and the hand vane shear. However, the two apparatuses did not provide enough measurements in the field. The pocket penetrometer was not able to penetrate into the soil because the soil is too hard. On one layer in the quarry the penetrometer did get into the clay but the reading was very unreliable. As can be seen in Table 1 the standard deviation was, at 44%, too high to call the result reliable. Three measurements were taken on the same sample. If the pocket penetrometer works, it gives a quick and cheap indication of the strength of the soil.

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<td><strong>Average</strong></td>
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<tr>
<td><strong>Standard deviation</strong></td>
<td>0.98 (44%)</td>
</tr>
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</table>

The other device that was tested in the field was the hand vane shear. This device provided more measurements, 9 out of the 25 layers tested. The quality of the measurements was also higher, an average standard deviation of 10%. This is a reasonable number for a field test. Still this test should
be used only to correlate different layers, as the results are too unstable for major design decisions. Just as the pocket penetrometer, the vane shear gives a quick and cheap estimation of the undrained shear strength of the soil.

After the measurements of the pocket penetrometer, the needle penetrometer was tested in the lab. Due to its sharper probe, it penetrates easily into the clay. The decision to use the needle penetrometer was made at a later point therefore only three samples could be tested. When the tests are compared to the outcome of the UCS test, the needle penetrometer can provide reliable results. With sample 22 the needle penetrometer has a deviation of only -5%. Sample 23 was less accurate. The needle penetrometer got an overestimation of 103% relative to UCS. This difference between the deviations could be explained by the properties of the soil. Sample 23 was finer grained than 22 this could have an effect on the measurement taken by the needle penetrometer, but this is no clear relation. Another possibility is that the formula to convert from NPI (needle penetration index) to UCS is not correct. Still, the needle penetrometer does provide an estimation of the strength of the soil, which in turn can be used to correlate different layers.

6.5 Test applicability

The different soil tests that can be performed are able to test different parameters. When clays erode their properties change from a hard rock like substance to a blubber. This distinction should also be made in the types of tests. The hard clays are referred to as the in-situ conditions and the blubbery substance as remoulded conditions. In Table 2 the different types and applicability are outlined. The X means the test is suitable for the mentioned parameter. The ± means that the test is suitable under specific conditions only. The shear box can only test in-situ parameters when the shear box is strong enough to make the sample shear. The pocket penetrometer cannot be used on any parameter since the clays in the field are too hard and the standard deviation is too big. The hand vane shear can be used to correlate layers, but the number of layers the hand vane can test is limited to whether the vanes can penetrate the soil.

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<td>Triaxial</td>
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<tr>
<td>Pocket penetrometer</td>
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<td>±</td>
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<tr>
<td>Hand vane shear</td>
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6.6 SkyGeo

The results of the meeting with SkyGeo were positive. SkyGeo first explained what criteria are set to determine whether a reflector is shown or thrown away. At the moment, SkyGeo collects data in a specific geographic location. If through the entire time domain, the signal is not distorted the data point is kept. However, if the signal is distorted (in the quarry usually due to excavations made), the data for that location is entirely thrown away. The suggestion was to not discard all the data but save it until the signal is distorted. A more elaborate explanation with example is included in the appendix. SkyGeo responded positively to the proposed change and said they will look into the integration of this suggestion. If this is implemented and more data is available in the quarry InSAR is a useful tool.
for monitoring the deformations in and around multiple quarries. Downside of the data is the high price it is sold for.
7 Conclusion and recommendations

Based on the results a flowchart is made that represents the geotechnical working plan for a thorough but quick assessment of existing slopes in clay mines. The flowchart is presented in Figure 17. Starting with the quarry on the left side of the flowchart, this is where the plan is made for. The mine planning then determines whether the investigation should focus on the long-term or short-term stability this has implications for the site investigation as some tests should or should not be used. If the plan considers long-term stability the red paths are followed, for short-term stability the blue paths are followed. Whether long or short-term stability is chosen was not covered in this research and should be part of future research. With the help of satellite data historic deformations are localised. These deformations provide insight into the stability of the mine in previous times. The other monitoring techniques, inclinometer and laser data do not provide enough historic data unless by coincidence this is already available. The satellite data is however known to have historic data. The benefit of SkyGeo data is even stronger if the proposed additions are made. Next, a field investigation is conducted. During this field investigation, the geotechnical parameters are collected. Along a cross section that is perpendicular to the failure surface samples are collected of every layer. The field test made clear that taking samples every 1.5 meters as proposed by literature is not feasible in the clay quarries, but every layer is doable. During the field investigation, it also becomes clear whether water is an issue in the slope by looking whether layers leak water or they have a much higher sand content. If water is a problem then water pressures should be measured to find the profile of the water table. How these water pressures should be measured was due to limited time not in this report. The samples should be tested with a needle penetrometer and a hand vane shear. The needle penetrometer is able to make measurements while the pocket penetrometer was not able to obtain measurements. Albeit the hand vane shear generates a limited amount of data, the test is quick and can therefore be easily incorporated in the field investigation. These two field tests provide the first insight in the parameters of the different layers, but due to their unreliable measurements the tests should only be used for correlations and to select whether a new layer is tested or the layer is still the same. Samples from unique layers are taken and tested with Atterberg limits. Atterberg limits are used to correlate layers to each other and to previously tested layers. The tests are relatively cheap, but with the help of the field test correlations the number of samples should be limited because the price increases quickly with many samples. With the correlations and water content in hand, previously tested soils can be coupled to the layers newly correlated. If no correlation can be made geotechnical parameters should be tested. The advantage of first making correlations versus directly testing the layers is that the geotechnical parameters are more expensive than Atterberg limits and therefore costs can be reduced. The type of test depends on the stability term, short-term stability should be based on in-situ parameters while long-term should be based on remoulded properties because of the weathering. For remoulded clays shear box or ring shear tests should be used. These tests are better fit for softer materials because they cannot exert high pressures. Which of the two should be used should be part of another research, but until the outcomes of that are clear shear box is recommended because of its one third lower pricing. For in-situ tests a strong shear box (theoretical), UCS or triaxial test can be used. The triaxial test is favourable since then the complete failure envelope can be constructed. The strong shear box is theoretical and should be built and tested for another research. If all the layers have geotechnical parameters the model can be computed. In software, the block or circular surface has to be chosen, it is assumed that a block model is more representative for the hard clays (i.e. short-term stability) and the circular slip surface more representative for the remoulded soft clays (i.e. long-term stability). Whether this assumption is correct should be tested further. After the stability factors are known monitoring is required as specified in Eurocode. This monitoring can be done with the SkyGeo
suite, as the data is already available since it is already being used at the start of the investigation. SkyGeo should roll out the suggested update to ensure short-term instabilities can be measured as well. This multifunctional usage of the InSAR data helps justify the high price tag that comes with it. For short-term stability issues a tachymeter should be used. The tachymeter can provide data where it is needed and when it is needed. This flexibility is useful for short-term slopes since they only need monitoring for a short period of time.
Figure 17: Flowchart for a geotechnical working plan for a thorough but quick assessment of existing slopes in clay mines
8 References


9 Appendix

9.1 Sample locations and tests performed

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9.2 Suggestion to SkyGeo explanation

In Figure 18 a signal of the heights through time in one location is shown. This particular sample is taken at the location ID L120420P244340. It is clear that the signal has a reflection over the entire span of the data set. The particular data set ranges from fall 2014 to summer 2017 and the particular location has an undisturbed reflection over this entire period. If an excavation was made in say end 2015, all the data would have been thrown away. Since starting end 2015, the reflection changed and did not correlate to the previous reflections. The suggestion now is to not throw away the data but display the data until the end of 2015 and after that do not show any new data.

9.3 UCS test results

![Figure 19: stress strain relation sample 23A](image)
Figure 20: stress strain relation sample 23B

Figure 21: stress strain relation sample 23A

Figure 22: stress strain relation sample 23B
Figure 23: stress strain relation sample 24

9.4 Failure plane sample 22A

Figure 24: failure plane after UCS test of sample 22A