

Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

TNO report

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**Effects of former coal mining: upward drillings
and sinkhole formation**

Date	21 juni 2021
Author(s)	J. Esteves Martins, E. van Linden, G. de Bruin
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Summary

Decades after the coal exploitation in the Province of Limburg has ceased, the associated after mining effects are still being experienced at the surface in the form of local sink holes. In August 2019, the Ministry of Economic affairs and Climate (MEAC) requested TNO-AGE to study the Upward Drillings (UD's) performed during the coal mining period. The goal of the requested study was to understand if the UD's could have become a pathway for unconsolidated material to flow, inducing or accelerating the process of sinkhole formation.

The proposed study called **Phase I - general knowledge** – had a two-fold objective:

1. Collecting knowledge on the UD's;
2. Understand if there is any relationship between UD's and sinkhole occurrence.

For this, we first performed a literature review, prepared and homogenized relevant data (e.g. UD's logs, historical (mining) maps, surface deformation, mine-water levels, etc). Then, we developed an approach to extract stratigraphic information of the UD's to understand when/where the UD's were going through unconsolidated material. We found no direct relationship between the UD's and sinkhole occurrence. The UD's were not in the origin of the two studied sinkholes.

With the knowledge acquired during the **Phase I - general knowledge** – study we observed several other subsurface mining configurations which were very similar to those under the sinkholes of 't Loon and DSM. Our research shifted to study these areas, which did not have records of sinkhole occurrence. This follow-up study was performed as a next phase of the project.

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1 Introduction

Following the closure of the coal mines, the South Limburg region has been experiencing uplift and moreover several sinkholes formed in recent times (Figure 1):

- In 2008 a sinkhole formed in the parking lot of the DSM building in Heerlen.
- In 2011 a sinkhole formed under the shopping center 't Loon in Heerlen leading to a partial demolition of the building.
- In 2019 a sinkhole occurred near the fountain of castle Erenstein in Kerkrade.

Striking is that the upward drillings (UD's) are present either directly under these sinkholes or within several meters away. This observation has led to the hypothesis that the UD's enable the sinkhole formation. More specifically, if the UD's were/are migration paths for unconsolidated material transported by groundwater flows - eventually inducing the sinkholes at these three locations.

In 2016, the project group GS-ZL finalized a large-scale investigation into the lingering effects of the coal mining in South Limburg, "Na-ijlende gevolgen steenkolenwinning Zuid-Limburg" (GS-ZL, 2016). Whilst an enormous amount of data was collected and made available, the mechanisms inducing recent sinkholes in the South Limburg mining area are still poorly understood, thus preventing reliable sinkhole predictions.

On the request of MEAC made in 2019, TNO conducted a study "Upward Drillings (UD's) and sinkhole formation" described in this current report. This study has the aim to understand if the UD's could induce or accelerate the process of sinkhole formation.

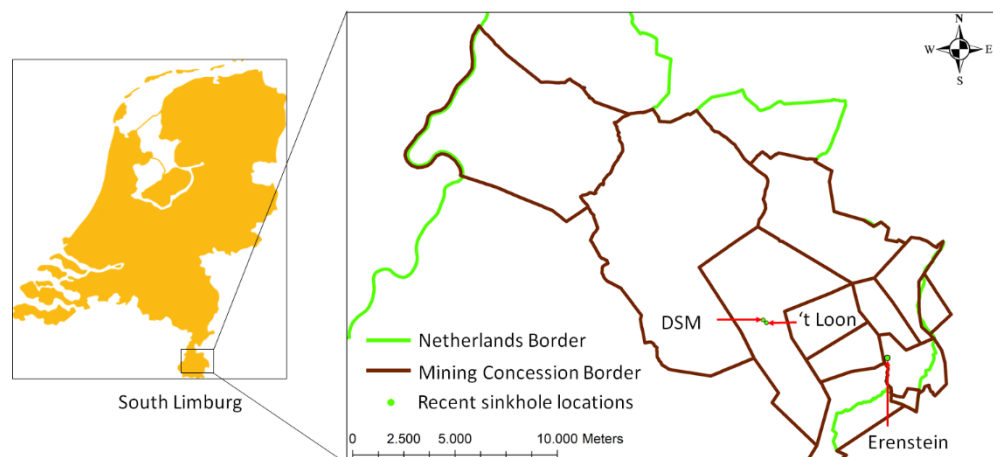


Figure 1: Project area location and the location of the 3 recently formed sinkholes.

1.1 Research questions

Phase 1 of the TNO study (2020) focuses on general knowledge questions regarding the UD's and is described in this report. For supporting information on UD's see the Appendix.

The general knowledge questions of the Phase 1 are:

- What is the reason for the upward drillings? Was there a procedure in place?
- Did the upward drillings always stop in the unconsolidated overburden?
Which upward drillings are actually penetrating these sands?
- What kind of plugs were used to prevent water and other material (sand) to flow through the drill hole into the mine?
- What role plays the Carboniferous overburden in the formation of sinkholes?
- Which subsurface characteristics could play a role in sinkhole formation induced by upward drilling?

2 Upward Drilling and sinkholes

2.1 Upward drilling as a safety measure

As the name upward drilling (UD) suggests, the drilling was in an upward direction from the mine working location for two safety reasons.

- First safety reason was to assess the roof thickness above a mine gallery or panel. The mine workers drilled a hole in the roof of a mine gallery or mine panel to ensure that the remaining Carboniferous roof above the mine had the required minimum thickness. This was to prevent collapse of the roof. As a consequence, UD's are mostly found where the mines are close to the top of the Carboniferous. It should be noted, that the required minimum thickness was gradually decreased over the years.
- The second safety reason was to mitigate the uncontrolled influx of a mixture of water and sand into the mine, referred to as "quicksand" by the mine workers, from intervals above the consolidated Carboniferous and Chalk formations. . The UD's allowed to have a relatively controlled influx of quicksand, by relieving the pressure and preventing a catastrophic influx of quicksand as shown in Figure 2.



Figure 2: Two mineworkers inspect a mining gallery that was filled by an uncontrolled influx of quicksand and water. UD's were used to prevent this by allowing a manageable influx of quicksand. Mining gallery heights are in the order of >2 m, through which the 2 mineworkers are only able to crawl now.

2.2 Upward drillings procedure

There was very limited documented information about the procedure. Therefore, we interviewed a mineworker that placed upward drillings. A full description of the UD's practices can be found in Appendix A.

The main steps of the upward drilling procedure are listed below and shown in Figure 3 :

- 1) Install standpipe of 1,5 m with a diameter of 65 mm.
- 2) Install shutoff valve. This allowed the mine workers to close-off the UD, stopping the possible influx of quicksand.
- 3) Drill upward with a diameter of 42 mm until the minimum roof thickness has been reached or till the top of the Carboniferous.
- 4) Plug upward borehole with wooden plug. Wood with a large expansion factor, when in contact with water, was used.

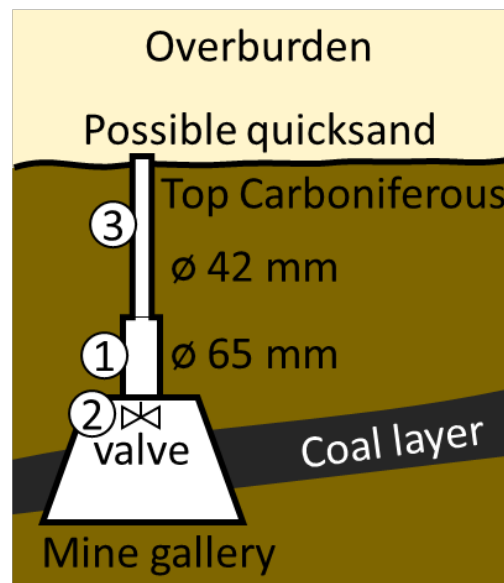


Figure 3: Upward drilling procedure. 1) Install standpipe of 1,5 m. 2) Install valve. This enables the stop of possible influx of quicksand 3) Drill upward until minimum roof thickness has been reached or to the top of the carboniferous 4) Plug upward drilling with wooden plug.

Unfortunately, no research or indication was given by the former mine worker that shows that the wooden plugs would have an effective lifetime of 30 to 50 years, as suggested by SodM (personal communication SodM, 2020). The last Dutch coal mine was closed in 1974, with most UD's being made in the decades before. This suggests that even if these UD plugs had a life expectancy of 50 years, they are by now all long past their suggested lifetime.

From the experience of the former mine worker it became clear that the described procedure was not always followed in reality. A valve was not installed, as this was a 1 hour process, or a wooden plug was not used because the UD section was already clogged with sand. These shortcuts to save time were not uncommon.

2.3 Upward drilling and the role of the overburden

The Carboniferous overburden normally consists of 1) Chalk and Cenozoic or 2) only Cenozoic sediments. When the UD ends in the unconsolidated Cenozoic sediments, it might be a pathway for sediment transport and as such could play a role in sinkhole formation. The situations 3 and 4 (Figure 4) are most common in the

eastern areas of the former mining concessions, where the Carboniferous is closest to the surface and the Chalk is often thin or entirely absent.

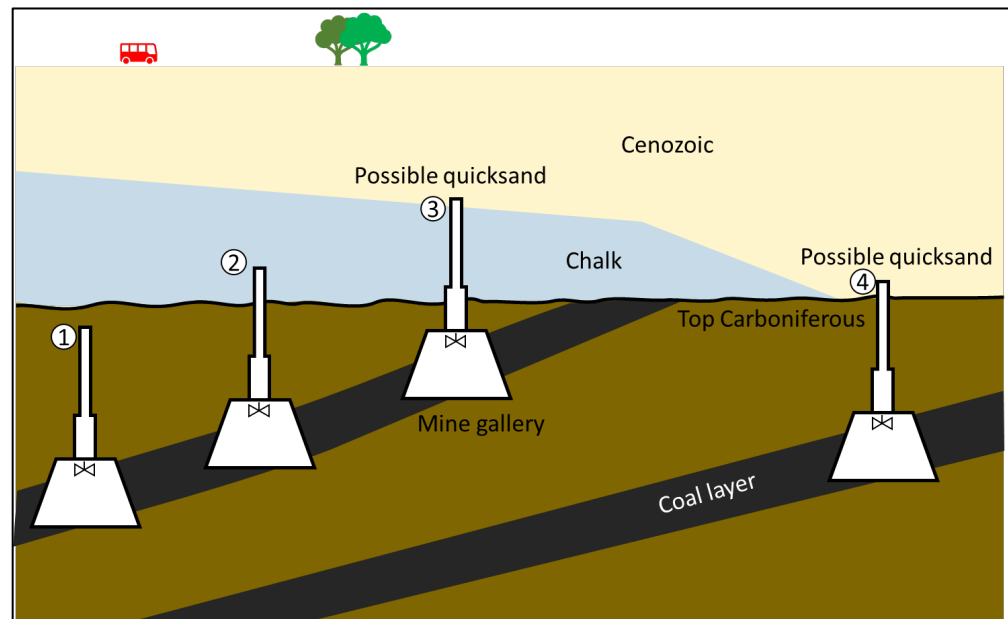


Figure 4: Upward drillings can end in the Carboniferous (1), Chalk (2) or Cenozoic (3 and 4). When upward drillings end in the Cenozoic, they might be a pathway for sediment transport. The upward drilling reaching the Cenozoic is most likely when the Chalk is absent and/or the Carboniferous roof is thin.

2.4 Additional question: Did UD's cause sinkholes?

During the project an additional question was raised about the role of the UD's in the formation of the recent three sinkholes. The UD's are also present in the vicinity of these sinkholes. Based on our current study, there are no clear indications of any relationship between the UD's and the sinkholes at 't Loon and DSM locations. However, other research suggests that there is a relationship between the third sinkhole and UD's at Erenstein (IHS, 2019). This particular sinkhole was not studied by TNO.

2.4.1 't Loon & DSM sinkholes are unlikely being caused by upward drillings.

We studied two recent sinkholes at 't Loon and DSM (Figure 5) and found that the UD's ended in solid rock (Chalk) at both sinkhole locations. Therefore, it is unlikely that the UD's at these locations were the pathways for unconsolidated sediment (Cenozoic) transport: i.e. there must be another pathway for sediment transport.

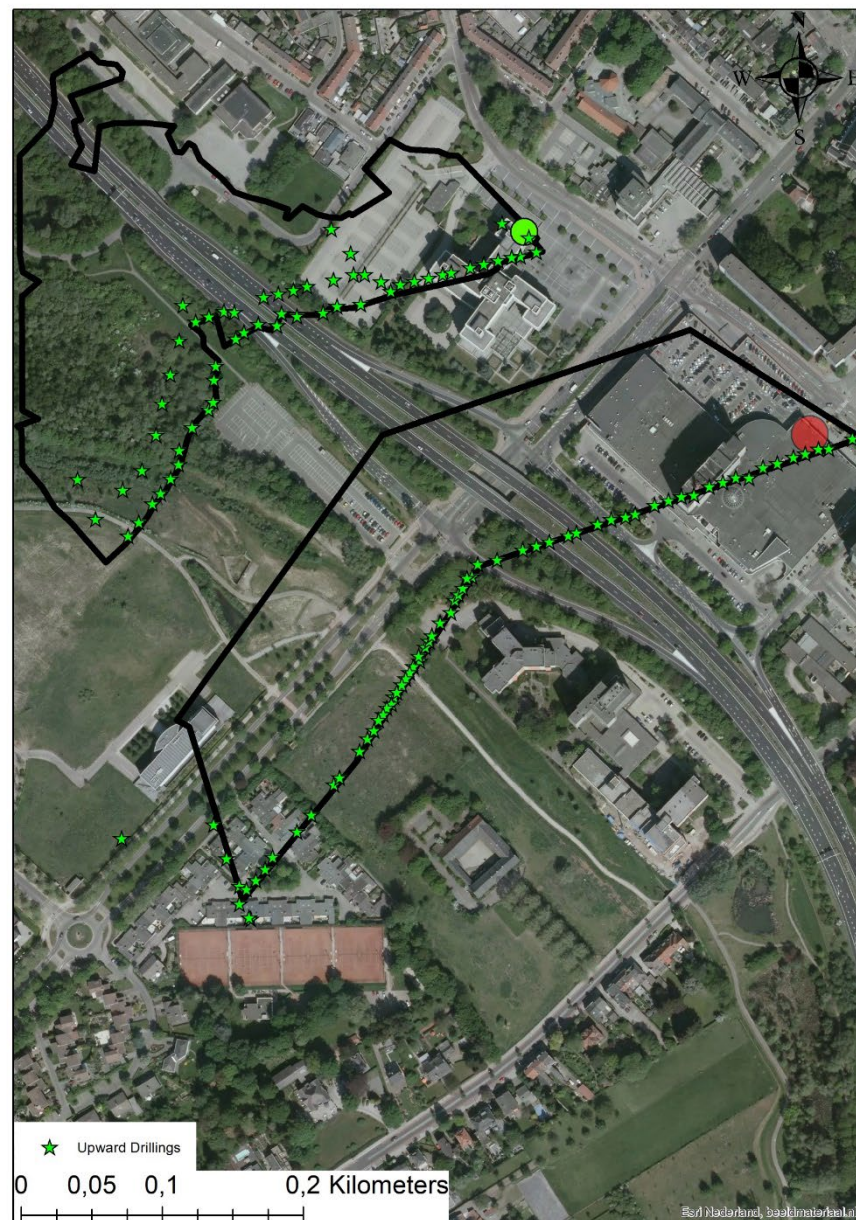


Figure 5: Location of UD's in respect to the recent sinkholes at 't Loon (red circle) and DSM (green circle). Black line is the outline of the mining panel (within which the coal is mined). Green asterisks are upward drillings.

2.4.2 *Did Upward Drillings play a role at the Erenstein sinkhole*

The drilling logs of the UD's in the area of Erenstein were not available at the time of our study began. The complete set of the UD logs has since been digitized, and the quality check on the digitization was still ongoing at the time of writing this report.

IHS has studied the Erenstein sinkhole in detail and several research boreholes were drilled as a part of this study (IHS,2019). They concluded that Tertiary sands entered a mining gallery through an UD and cracks/fractures present in the Carboniferous. The Chalk formation is not present at these locations (IHS,2019).

Upward drillings are not mentioned by IHS in their 2020 (IHS, 2020) report, and after consultation they confirmed that upward drillings do not play a role in the formation of sinkholes. Therefore, upward drillings were not considered (by IHS) for the identification of areas where potentially a sinkhole could form.

3 Conclusions

3.1 Conclusions

Upward drillings were used to verify the remaining thickness of the Carboniferous roof of a mining panel as there was a requirement on the minimum thickness.

According to the former mine worker, the boreholes were supposed to be sealed with a wood plug but in practise this was not always done.

The overburden may play a role in the sinkhole formation. The Cenozoic unconsolidated sand might be washed down into Carboniferous cavities by groundwater flows. Migration paths for the sand/water could be formed by UD's or by fractures in the consolidated Chalk and Carboniferous roof. Absence of the Chalk in some mining areas shortens the distance from the Cenozoic sands to the Carboniferous.

3.2 Additional findings

TNO and IHS (2019) have formulated the hypotheses on the relation of UD's and sinkhole formation. Both hypotheses are based on unconsolidated Cenozoic sediments being washed out from their original location and ending up within the former coal mining workings in the Carboniferous. The space thus created in the shallow Cenozoic sediments eventually (gradually or instantly) collapsed creating the sinkhole. These processes differ in the role contributed to the UD's. TNO study concludes that the UD's do not function as a transport pathway for the sinkholes of 't Loon and DSM. Furthermore, they most likely do not function as transport pathways for formation of the Erenstein sinkhole as concluded by IHS (2020).

Depending on the heterogeneity of the stratigraphic sequence in the former mining concessions, a number of subsurface criteria can be identified indicating surface areas vulnerable to the formation of a sinkhole.

During the research of the 't Loon and DSM sinkholes we found several locations that have comparable subsurface conditions (mining configuration, geology, stratigraphic thicknesses and surface observations) as found at 't Loon and DSM. Some of these locations were in areas not listed by IHS in the Risk Assessment study (2016). The IHS definition of risk areas is based on the dip of the mining panel and documentation of coal mining activity close to the top of the Carboniferous (GS-ZL, 2016).

This observation of potential risk areas outside the currently defined areas by the IHS risk assessment led to the definition of new research questions. These questions should help to better understand the cause of the sinkholes at 't Loon and DSM and to identify buildings located above subsurface configurations comparable to those at 't Loon and at DSM.

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source: PCMW - Personal communication former mine worker

Appendix A – supporting information for Part A

1 Geologic setting & coal mining history

1.1 Faults & coal layers

The Dutch coal mining setting is defined and limited by two components, the fault system and the geological setting of the coal layers.

The former coal mining region is characterized by a southeast-northwest running fault system, part of the Roer Valley Rift System (Figure 6). In South Limburg the Feldbiss is the main fault zone running through the region. This fault zone consists of three major faults; the Feldbiss, Geleen and Heerlerheide/Benzenrade faults (Houtgast et al., 2002). Cross-cutting these major faults are several smaller southwest-northeast fault structures which have not been active since the Variscan phase. The fault system confines the former mining concessions between the Feldbiss fault in the North, which off-set the Carboniferous by several hundred meters, and the Benzenrade fault in the south, the Dutch border is the confining factor in the East and West.

Due to the complex geological setting, the South Limburg coal-bearing Carboniferous can be anisotropic, therefore found at varying depths. These strata outcrop in the east near Kerkrade bordering Germany, while they are at a depth of over 400 m below the surface in the western part of the coal mining area bordering Belgium (Dinoloket DGMdiep v4.0 source). The overburden stratigraphy of the Carboniferous consists of unconsolidated Tertiary and Quaternary sediments – the soil - in the eastern parts of the mining region, Chalk deposits in the middle and western parts of the region, and locally Triassic deposits in the western area (Dinoloket DGMdiep v4.0 source). This means that the rock-soil interface is situated directly on top of the Carboniferous in the East and at the top of the Chalk in the middle and Western parts of the mining concessions (Figure 9).

The Carboniferous at the location of the former coal mining concession outcrops near the German border in the East and is found at several hundreds of meters of depth at the Belgium border in the West. The coal layers within the Carboniferous dip steeply in a Northwestern direction.

1.2 History of coal mining in South Limburg

Coal mining in South Limburg already occurred in the 12th century near the city of Kerkrade where the Carboniferous coalbeds could be found at or near to the surface. Coal mining on an industrial level started in South Limburg towards the end of the 19th century and continued until the closure of the last mine in 1974. A total of twelve mining concessions were granted, four owned by the Dutch State and eight by private companies (Figure 6). A thirteenth, the Beatrix concession, was never granted. Eventually the Neu-Prick mining concession merged into the Dominiale mining concession in 1960.

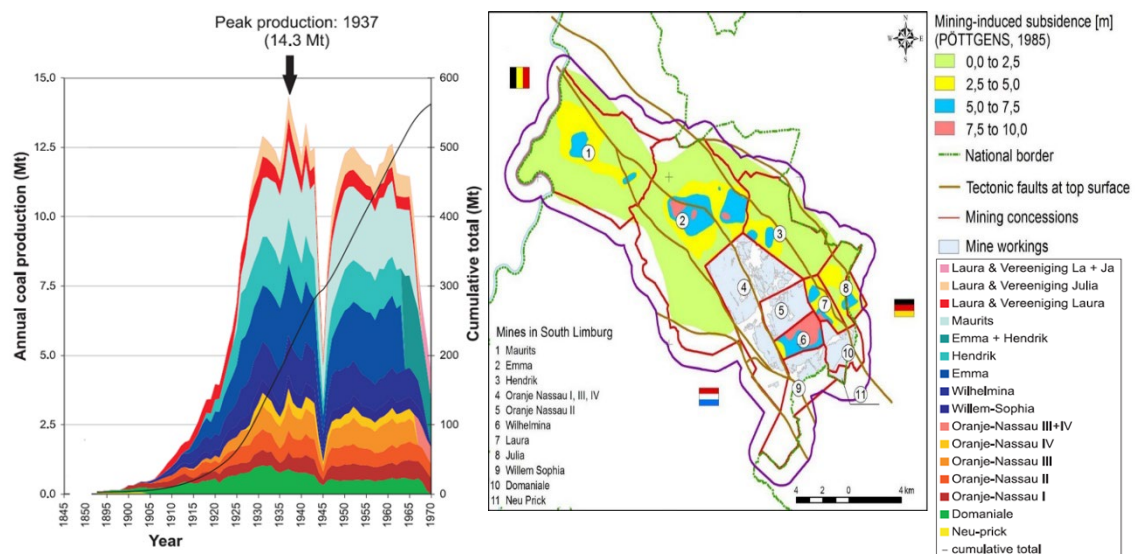


Figure 6. Left image) Coal production in the Limburg mining concessions. modified after van Berendsen, 2008. Right image) Outline of the former mining concessions, the total subsidence that occurred throughout the active mining period and the main tectonic faults at the surface. Data is based on Pöttgens, 1985. Image is modified

During peak mining activities, from 1930 to 1965, twelve to fourteen million ton of coal was produced each year (Berendsen, 2008). A total of 560 million ton of coal was removed from the subsurface of South Limburg over an area 230 km² (Berendsen, 2008).

1.3 Mining method

Coal was produced using the longwall mining technique, which relied on the controlled collapse of the roof in previously mined areas of the panel (Figure 7). As a consequence of the longwall mining technique the consolidated formations above a mining panel (Carboniferous & Chalk) became considerably fractured and weakened (van den Heuvel & Kimpe, 1953; Pöttgens, 1995). Also due to the longwall mining technique subsidence occurred throughout all of the mining concessions in the order of meters, as multiple coal seams were often mined above one another (Figure 9c). This subsidence, however, was considered acceptable as long as safety of the mineworkers was assured.

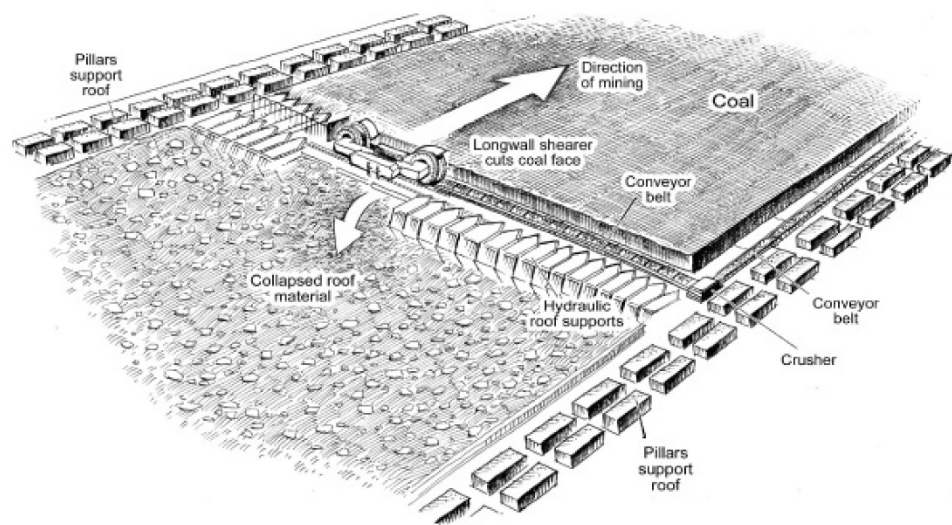


Figure 7. Typical longwall mining configuration. The longwall shearer cuts the coal face, broken off coal is transported to the sides by conveyor belts, both the hydraulic roof supports and the longwall shearer move up in the direction of mining and the process is repeated until the entirety of the mining panel is mined. (Image courtesy of the United States Securities and Exchange Commission)

To ensure the safety of the mineworkers a minimum Carboniferous thickness of fifty meters above the mining panel was required to be left intact. Early in the 20th century this roof thickness requirement was in practice often reduced to twenty meters. This exception could be given to the mining concessions at the authority of the Dutch Ministry of Economic Affairs. Towards the end of the 1930's this minimum roof thickness was further reduced at specific locations in some of the mining concessions for commercial reasons. Locally the roof thickness could even be lowered to 0 m.

A first experiment with a roof thickness of 0 m was performed in the Oranje Nassau concession. Once it was proven that safety of mine workers could be maintained while simultaneously increasing profits these practices were expanded upon to other mining concessions and locations. In order to assess the possibility of roof thickness reductions insight had to be gained into the overburden of the Carboniferous. To this end UD's were carried out in galleries and mining panels. The closer coal extraction took place near the top of the Carboniferous the more closely spaced UD's had to be made. *In coal mining all drillings started below top*

level Carboniferous bedrock and in addition deliver level indications of the top of the bedrock are referred to as 'UD's' (GS-ZL, 2016). For example the moisture content of strata above the Carboniferous was an important measurement as quicksand inflow into the mining panels and galleries was a major concern. Upon finding low moisture content, easily drained layers or strong consolidated material above the Carboniferous, approval was given for numerous location throughout the mining region to reduce the minimum required roof thickness (Dresen, 1941).

1.4 Coal layer overburden

Approximately 7.250 UD's have been executed in the South Limburg coal mining area over the course of the active mining period (Figure 8). These UD's are considered to be potential connection between the unconsolidated overburden and the underground mine voids (GS-ZL, 2016). UD's could be migration paths for groundwater which may lead to sub-surficial erosion and subsequent collapse of the overburden – forming a sinkhole.

Experience from Hollmann, F. & Niirenberg, R. (1972) in the Westphalian coal fields showed that sinkholes could form when excavation took place within 20 m of the top of the rock-soil interface. Excavation of coal in South Limburg often occurred within this 20 m section, especially in the easter coal mining concessions.

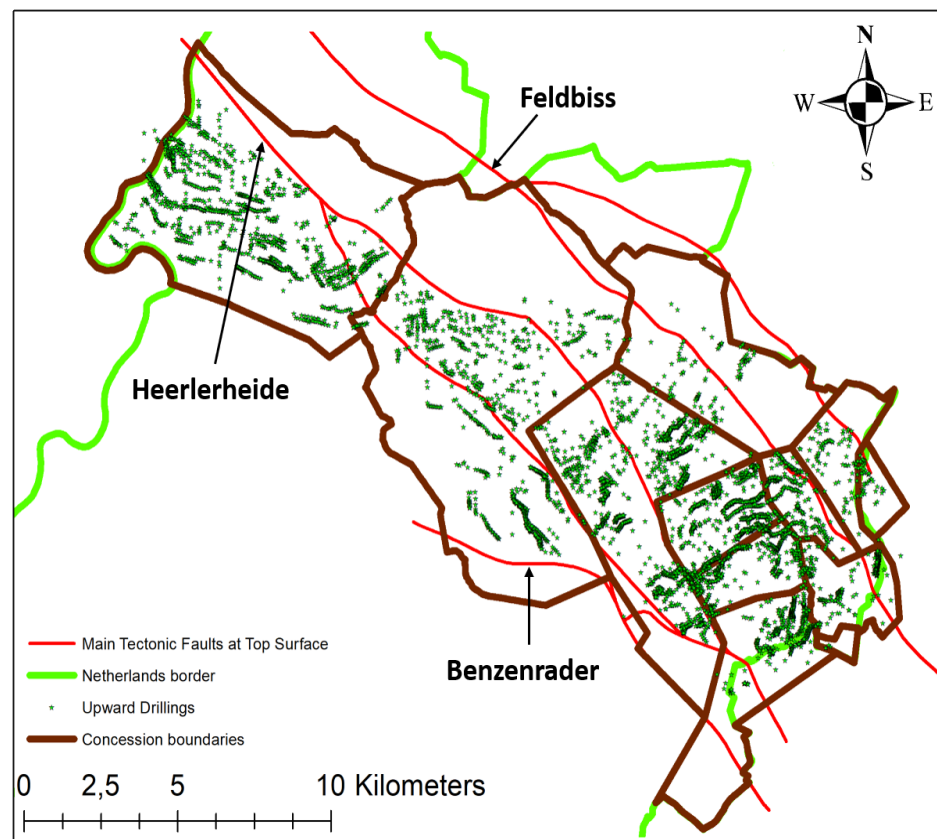


Figure 8. Overview of all (~7250) upward drilling locations, locations are based on scanned and georeferenced mining maps. The 3 main tectonic faults; Feldbiss, Heerlerheide and Benzenrader are also indicated.

The unconsolidated overburden in former coal mining concessions are the North Sea Group sediments. These sediments overlay the Carboniferous directly in the east and overlay the Chalk and Triassic deposits in the middle and western former mining concessions (Figure 9).

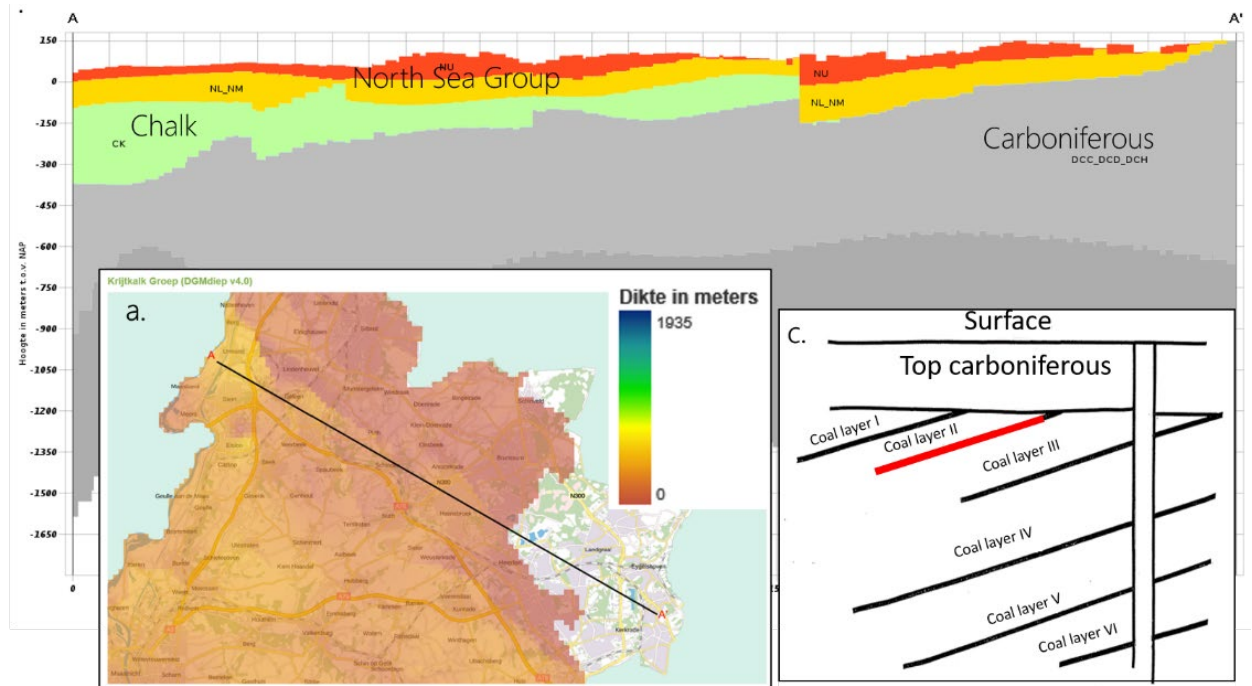


Figure 9. a. Thickness map of the Chalk Group in South Limburg. Chalk is absent around the municipalities of Landgraaf, Kerkrade and Eysgelshoven. Inset location the overburden stratigraphy profile AA'. b. Cross-section AA' showing the overburden stratigraphy of the Carboniferous consisting of: unconsolidated Tertiary and Quaternary sediments in the eastern parts of the mining region, Chalk deposits in the middle and western parts of the concession, and intermittently Triassic deposits in the western area (Dinoloket DGMdiep v4.0 source). c. Simplified cross-section of the Carboniferous rock with coal layers in the region dipping towards the northwest. The main vertical shaft is the starting point from which horizontal hallways and panels are build. The red line in coal layer II indicates how much coal was removed in the subsurface, a small sliver of coal usually remains towards the top of the Carboniferous.

1.5 Inventory of available information on UD's

1.5.1 Background on recent studies

No literature has been found on sinkholes formed in a similar geological setting as the South Limburg former coal mining concessions have.

Sinkholes as a result of mining are more widely known as crown holes. Drop-out sinkhole is also known to occur over former mine workings. A suffusion sinkhole seems more appropriate to describe for instance 't Loon sinkhole (based on sinkhole classification and nomenclature 2005).

1.5.2 Procedure for UD's and plugs in South Limburg

It is very difficult to assess what the exact procedures were during the mining times, since this was over 50 years ago. There is very little documentation and also very scattered (source: PCMW).

Most of the drillings were executed at a regular interval following a fixed procedure (source: PCMW). The UD's were done in a sequence of steps (Figure 7);

1. Drill a 1.5m long 65 mm wide core.
2. Insert a 1.5m "standpijp" into the open hole.
3. Install an "afsluiter" onto the bottom of the "standpijp", this "afsluiter" has the function to close of the hole in case quicksand starts to flow through the upward drilling core path at a later point in the procedure.
 - a. Installing this "afsluiter" takes a lot of time (~1 hour) and was therefore often not installed by the mine workers as a means to save time (source: PCMW).
4. Continue drilling upwards through the "standpijp" with a 42 mm wide drill until the determined desired length of the upward drilling was reached, usually this was when the top of the Carboniferous was found.
5. Close off the upward drilling hole with a wooden plug (~1-1.5 m long), this was done with a type of wood that expands a lot when it comes into contact with water.
 - a. These plugs were not specifically made for this purpose, but were rather pieces of wood that fit the above mentioned criteria and were at hand. (source: PCMW)
 - b. Sometimes these holes were left unplugged since during the drilling procedure quicksand was encountered, eventually clogging up the hole on its own with sand. (source: PCMW)

UD's are made at set intervals from each other, this interval became smaller the closer mine workings were near the top of the Carboniferous. The distance between 2 UD's indicated on mining maps appears to be separated by the thickness length of the overlaying Carboniferous, however this information could not be confirmed. In reality, this resulted in a relatively high number of UD's in areas where the roof was nearing the minimal required thickness. A roof thickness of more than 50 m was considered to be safe during the early years of industrial coal mining. This 50 m thickness was lowered to 20 m several years after the coal production started by decree of the Minister of Economic Affairs, there is no clear indication when exactly this became the new norm. However, shortly after World War II during the reconstruction period, a redefinition of these safety distances lead, in several occasions, to a decision that allowed a reduced roof thickness. Carboniferous roof thickness reduction down to 3 m was permitted if the Carboniferous strata was sufficiently sampled by means of UD's. These UD's were used to identify not only

the thickness of the Carboniferous above mining activities, but also to detect water-bearing layers or quicksand. When strong water-bearing layers or quicksand were found the UD's could function as a means of dewatering the mining practices (De Man, 1988). Locally coal extraction could take place up to the Carboniferous overburden, leaving a 0 m crown pillar (De Man, 1988). This reduction of roof thickness may have resulted in a fractured top Carboniferous which may lead to suffusion with possible damages at the surface.

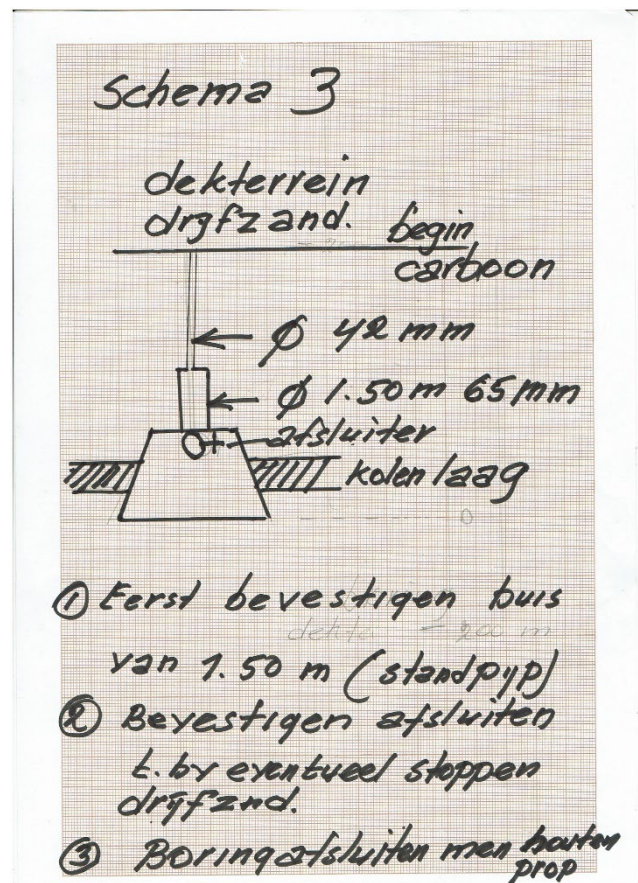


Figure 10. Upward drilling procedure (in Dutch). (source: PCMW)

1.5.3 Upward drilling logs

Each drilling was logged in a standard core format form (Figure 11). This standard format (in Dutch) details the following information;

- Indication whether it is an upward or a downward drilling. (respectively “Opw”. Or “Neerw”)
- Indication with which tool the drilling was made, chisel or core. (respectively “beitel” or “kern”)
- In which mining concession the core was made.
- The number of the core.
- The place within the mining concession where the core was made, this could be indicated by mining level, hallway number etc.
- Coordinates of where the core was made, the coordinate system used is specific to each mining concession as the center of the coordinate grid is the main shaft of the mining concession. This was indicated by an Abscissa and Ordinate based coordinate system. (Respectively “ord” and “absc”)
- The inclination at which the core was made. During the active mining period 2 different degrees indicators were used; a 360 degrees circle and a 400 degrees circle, also known as a Gradian. (Respectively indicated with a “°” symbol or a “g” symbol)
- A coring direction, this was relevant when the core was not drilled perfectly straight upwards or downwards. During the active mining period 2 different degrees indicators were used; a 360 degrees circle and a 400 degrees circle, also known as a Gradian. (Respectively indicated with a “°” symbol or a “g” symbol)
- The NAP based level at which the core was initiated, for an upward drilling this was the height of the roof, of a gallery or mining panel.
- Starting- and end-date of the coring process.
- A detailed stratigraphic log of the core. Additional notes of the core were detailed here; whether quicksand was encountered, which lithostratigraphy was encountered and other potentially relevant information.

The goal of an upward drilling log was to investigate the thickness of the remaining overlaying Carboniferous rock and what the conditions were of the strata directly above this lithostratigraphic layer. As such almost all upward drilling logs investigated in this project were cored through the entirety of the Carboniferous. The coring was not in UD's that encountered problems during the procedure and had to be ceased prematurely. Depending on the locations in the mining concessions the UD's ended mostly either in unconsolidated material (when the unconsolidated material lay directly on top of the Carboniferous) or in the Chalk which is a consolidated rock (Figure 11). With the Chalk overlaying middle and western concession areas, most of the UD's that reach unconsolidated material are situated in the eastern concessions.

Opw. *beitel* Ondergrondse boring. Mijn O.N. I nr 1983
Meer *Meer*

Plaats: uit lg V oostelijk van opbr. 21

Doel: verkenning dekterrein

Coördinaten: Ord. + 89 Blad A 3
 Abse. - 672

Helling: + 90° Richting: Mondgat: + 17,67 m.A.P.

Begindatum: 29.10.1955 Einddatum: 31.10.1955

Van m	Tot m	Dikte m	AARD DER GRONDLAGEN
0,00	1,80	1,80	zachte en harde leisteen
1,80	3,60	1,80	harde zandsteen + leiriffels. vanaf 1,80 tot 5,00
3,60	5,00	1,40	harde zandsteen
5,00	6,50	1,50	zachte en harde leisteen afw. zachte en harde kalksteen
6,50	10,00	3,50	afw. zachte en harde kalksteen
			dekterrein + 24,17 m A.P.

47,67
 6,50
 34,17

613-2-6

Carboniferous

Chalk

Figure 11. Standard format for reporting the drilling details. In this example a 10 m long 90° upward drilling core was taken in the Oranje Nassau I mining concession just below shopping center 't Loon. The core consists of 6.5 m of Carboniferous material followed by 3.5 m of Chalk material.

2 Signature

Utrecht, 24 August 2023

TNO

A handwritten signature in blue ink, appearing to be 'R. van Steveninck', with a long horizontal stroke extending to the right.

R. van Steveninck
Head Advisory Group
for Economic Affairs