Snkholes and collapses, UNAM Ongwediva - 03.12.2025 – www.aberle.biz

And suddenly the earth is gone - geological harzards caused by sinkholes

04.12.2025, Ongwediva
a lecture for the UNAM-JEDS



1 Introduction
2 Geo risks and their impact on the earth's surface
3 Sinkhole or collapse?
4 Collapses caused by human activities
5 Sinkholes caused by nature
5a Karst with salt
5b Karst with sulphate
5c Karst with limestone
6 The search for reasons
7a From real life, an example wiht sulphate
7b From real life, an example with limestone
8 What UNAM-Jeds can do for you
9 The end

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Bernd Aberle

RWTH Aachen, Dipl.-Ing., Civil Engineering
1988 Ingenieurbüro Prof. Wittke WBI Aachen; DMT Essen
2001 Abteilungsleiter STRABAG Köln + Wien; Stump Chemnitz
2005 Managing Direktor BST Mansfeld, Allstedt
2021 Geotechnik Aberle, Kelbra

Lecturer rock mechanics and Special foundation engineering, THGA Bochum
Lecturer mining consequences and construction management, HS Nordhausen







Some projects



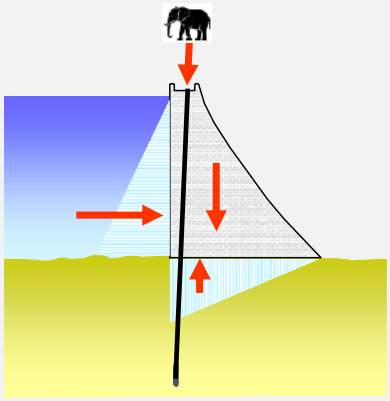
Enhancement of the structural stability of a gravity dam through prestressed rock anchors. Testload 8,000 kN = 133 elephants

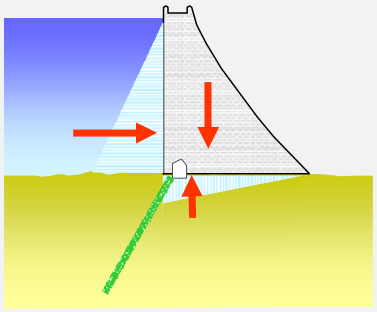


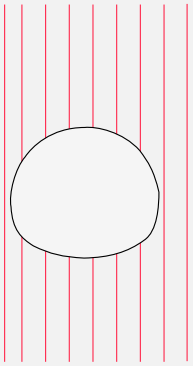
Controlled rock blasting for the construction of an inspection gallery, positioned only 1 m from the upstream face under full reservoir conditions, ensuring minimal impact on dam stability and surrounding structures.

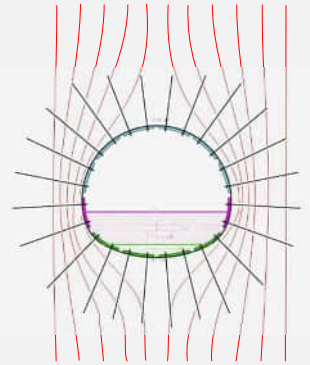












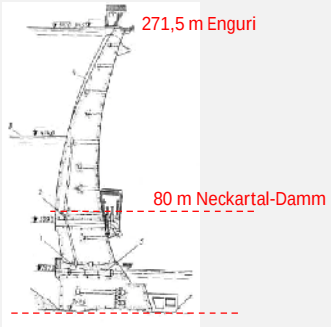
Dams in Turkey, Germany and Georgia





Accountable for the waterproofing of two major dams in eastern Turkey and for the complete instrumentation and measurement systems during the construction of the most recent dam in Germany.





Geological hazard and risks

A geotechnical hazard is a ground-related risk, such as landslides, rockfalls, subsidence, or soil liquefaction, that can threaten structures, infrastructure, and human safety. These hazards arise from the failure of soil or rock due to natural processes like earthquakes, heavy rainfall, or human activities, and they can cause significant damage and economic disruption.

- Settlement
- Subsidence - elevation
- Earthquake - rock burst
- Volcanic eruptions
- Landslide - rock fall
- Sinkhole - collapses
- …



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Perception of risks

risk	=	probability of occurrence	x	severity of damage
		unlikely *possible* *very likely*		*major Injury* *minor Injury* *trivial*
<u>example of low risks:</u>				
getting wet when it rains	=	nearly everybody / often	x	mostly unpleasant
be killed by a shark attack	=	less than 10 person / a	x	loses one‘s life
<u>Example of increased risks:</u>				
?	=	smoking / regulary	x	cancer
?	=	use of a seat belt / never	x	serious injuries



2 Geo risks and their impact on the earth's surface

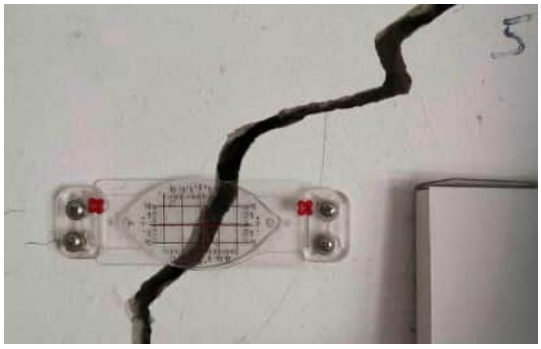
Settlement is the slow subsidence of a structure.
This results in a gradual compaction of the subsoil.

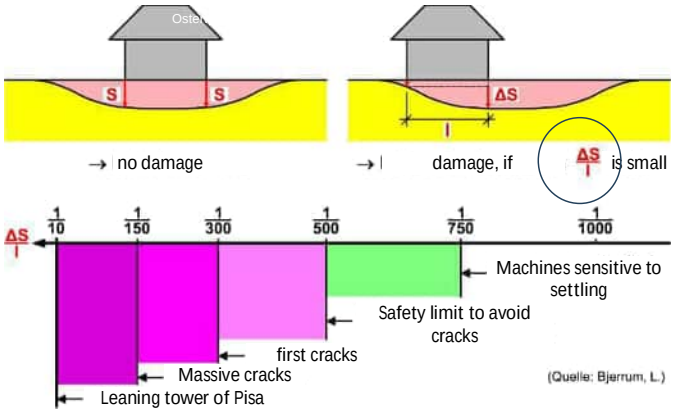
- **Settlement**
- Subsidence - elevation
- Earthquake - rock burst
- Volcanic eruptions
- Landslide - rock fall
- Sinkhole - collapses
- …

Exercise: A building is 16 m wide. At what settlement at the edge can the first cracks be expected to appear?



Riethnordhausen, 06 2022





Geo risks and their impact on the earth's surface

Subsidence is the gradual sinking of the Earth's surface, which can affect both land and buildings. This can be localised, such as in the case of mining activities, or it can occur over large areas, covering tens of thousands to several million square kilometres, and over periods of many millions of years.

- Settlement
- **Subsidence - elevation**
- Earthquake - rock burst
- Volcanic eruptions
- Landslide - rock fall
- Sinkhole - collapses



Subsidence caused by coal mining has meant that the Emscher river near Herne-Dannekamp has to be carried over the rest of the terrain on a dam.



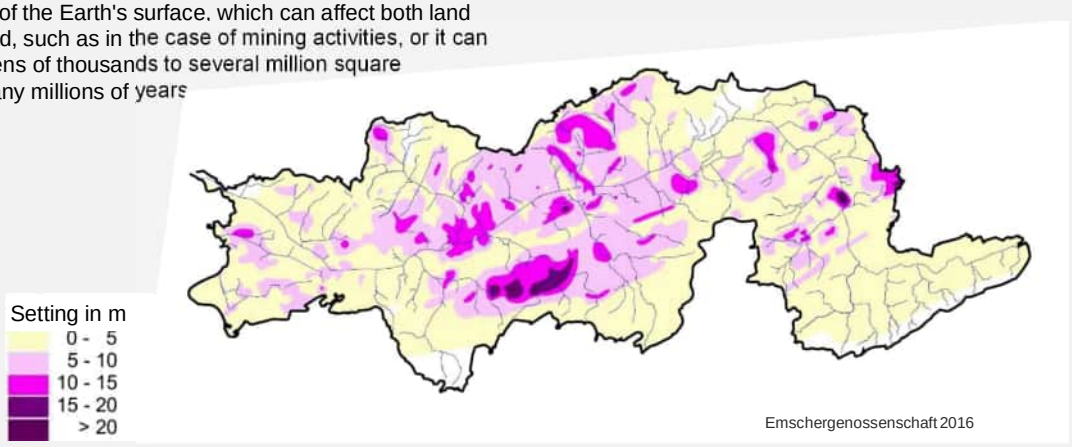
Emschergenossenschaft 2016

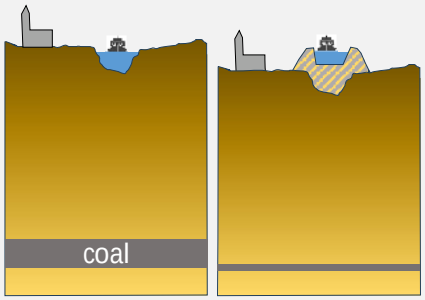
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Geo risks and their impact on the earth's surface

A rock burst is the sudden and violent failure of rock, often occurring in underground mines, due to the abrupt release of accumulated energy under high stress. This catastrophic event can cause significant damage to mine workings and equipment.

- Settlement
- Subsidence - elevation
- **Earthquake - rock burst**
- Volcanic eruptions
- Landslide - rock fall
- Sinkhole - collapses
- …



In 1953, the northern section of the Wintershall mine (Germany) collapsed. The overburden above mining field no. 38 suddenly subsided.

This rock burst was caused by the undersizing of the support pillars between the mining chambers.

The total damage amounted to approximately three million marks.





Alle Bilder: https://www.widdershausen.de/erdbeben-1953.html

Geo risks and their impact on the earth's surface

Landslides are several forms of mass wasting that may include a wide range of ground movements, such as rockfalls, mudflows, shallow or deep-seated slope failures and debris flows.

- Settlement
- Subsidence - elevation
- Earthquake - rock burst
- Volcanic eruptions
- **Landslide - rock fall**
- Sinkhole - collapses
- …





Road to Hopa, Turkey, 2001

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Geo risks and their impact on the earth's surface

A sinkhole is a depression or hole in the ground caused by some form of collapse of the surface layer.

- Settlement
- Subsidence - elevation
- Earthquake - rock burst
- Volcanic eruptions
- Landslide - rock fall
- **Sinkhole - collapses**
- …

Nordhausen, 2022



Hettstedt, 2016



3 caused by nature or human activities?



Benndorf, 2015



Riethnordhausen, 2022

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For clarification: two technical terms

Collapse – (german: Tagesbruch)

Caused by human activities
Settlement or subsidence
due to human activities leaking pipelines, mining, ...



Morungen bei Sangerhausen

Sinkhole – (german: Erdfall)

Caused by nature
Settlement or subsidence
due to geological causes karst, leaching, suffosion



Bad Frankenhausen

4 Collapses caused by

- **Water pipes**
- Groundwater level
- Old buildings (e.g. cellars)
- Bunkers
- Tunnel construction
- Mining



Dec. 5, 2016, San Antonio, Texas. A sink hole in killed a Bexar County sheriff's deputy on Sunday. ….
was a broken 54-inch pipe and a pit measuring 10- to 20-feet deep that stretched the entire width of the road.
www.nbcnews.com/news/us-news/massive-texas-sink-hole-swallows-two-cars-killing-sheriff-s-n692231



Hettstedt, Gartenstraße 2011

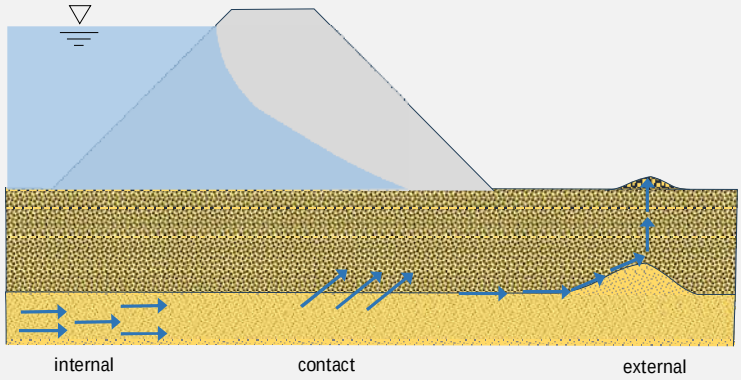
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Suffosion





Sazlidere Dam, Istanbul, Turkey 1999



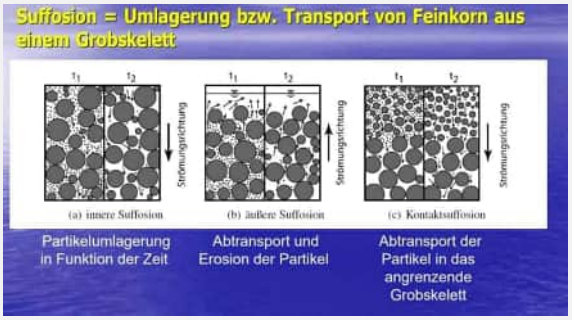
Forms of suffosion
+ internal suffosion (in the soil)
+ external suffosion (on the surface)
+ contact suffusion
(from the finer soil into the pores of a coarser soil)

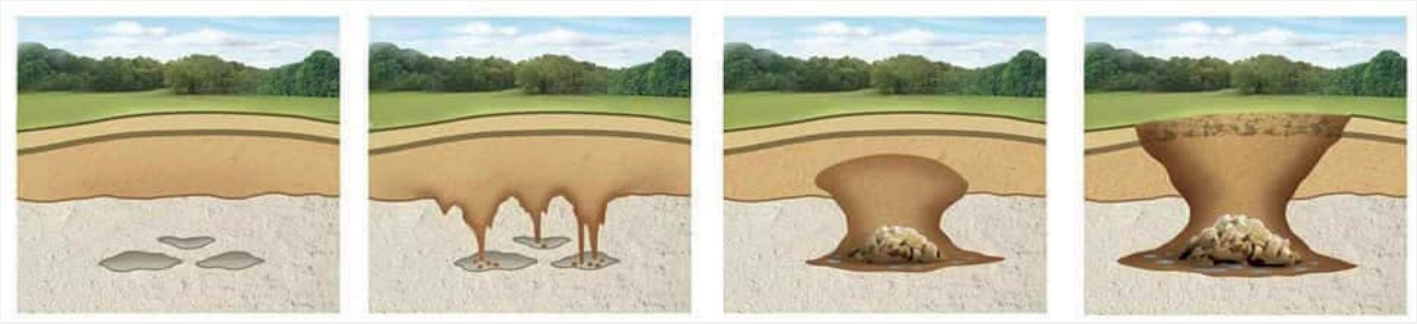
Subrosion and Suffosion

Suffosion (solution erosion, surface solution)
is the rearrangement and removal of fine soil particles in the soil by water. Fine grains of uneven, non-cohesive soil are loosened from the soil by the force of the water flow and transported through the existing pore space.

An example in rock: loess suffusion

Subrosion is often triggered or accelerated by human intervention (leaky pipes, canals, spring catchments, old mining sites, etc.).





Snkholes and collapses, UNAM Ongwediva - 03.12.2025 – www.aberle.biz

4 Collapses caused by

- Water pipes
- **Groundwater level**
- Old buildings (e.g. cellars)
- Bunkers
- Tunnel construction
- Mining


BAZ RATNER/ REUTERS

Israel, Red Canyon 1994



The water level of the Dead Sea drops by more than 1 m every year. This also changes the groundwater level in the surrounding area.
As a result, more than 6,000 sinkholes have formed in recent years.


Foto: picture-alliance/ dpa

Collapses caused by

- Water pipes
- Groundwater level
- **Old buildings (e.g. cellars)**
- Bunkers
- Tunnel construction
- Mining

Keller stürzt unter Wohnhaus ein

In Magdeburg ist unter einem Wohnhaus ein historischer Keller eingestürzt. Verletzt wurde niemand.
MZ, Von Thomas Schulz 26.07.2020
Am Samstagabend wurde die Magdeburger Feuerwehr zu einem nicht gerade alltäglichen Einsatz in den Stadtteil Ottersleben gerufen. Gegen 18.45 Uhr hatten Anwohner in einer Straße ein starkes rumpeln wahrgenommen. Auslöser dafür war der Einsturz eines rund 100 Jahre alten Gewölbekellers unter einem Wohnhaus. Nach Angaben der Feuerwehr war ein Wohnraum durch den Einsturz leicht abgesackt.



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Collapses caused by

- Water pipes
- Groundwater level
- Old buildings (e.g. cellars)
- **Bunkers**
- Tunnel construction
- Mining

Pionierstollen Aldinger Straße, Stuttgart 2021



Bunker Am Kräher Wald, Stuttgart 2021



Collapses caused by

- Water pipes
- Groundwater level
- Old buildings (e.g. cellars)
- Bunkers
- **Tunnel construction**
- Mining



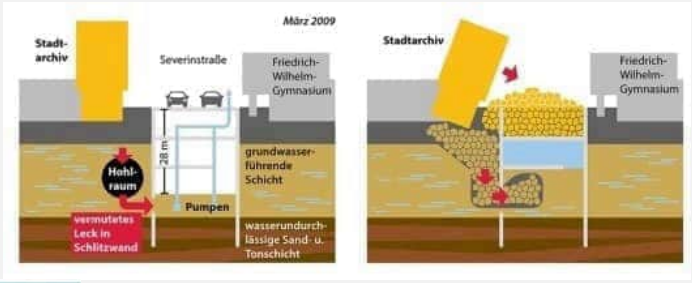


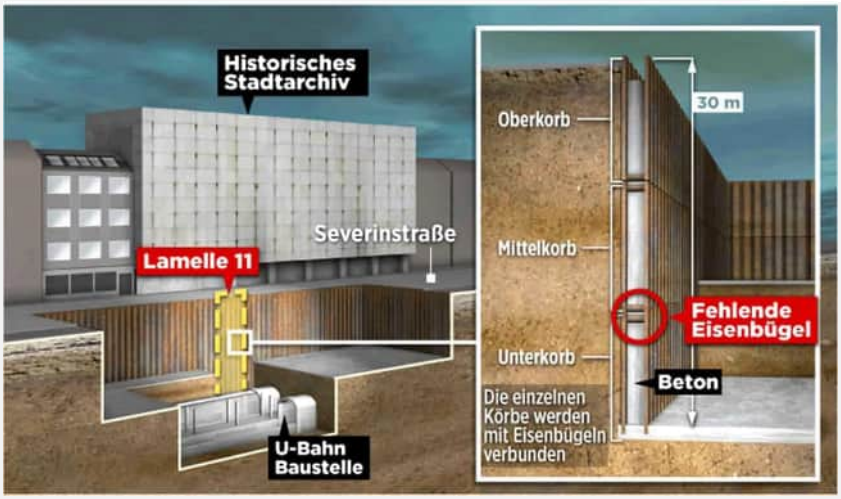
City archives of Cologne 03.03.2009

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Collapse of the Cologne Municipal Archives

Years of research have confirmed that a hole in an underground wall was the decisive factor in the collapse. Two residents were killed in the accident, which caused billions in damage. The treasures of Germany's most important municipal archive were buried.
Three former employees of the company involved in the construction and two engineers from Cologne's public transport company responsible for supervision are facing trial. They are charged with negligent homicide and endangering construction safety.





Collapses caused by

- Water pipes
- Groundwater level
- Old buildings (e.g. cellars)
- Bunkers
- Tunnel construction
- **Mining**

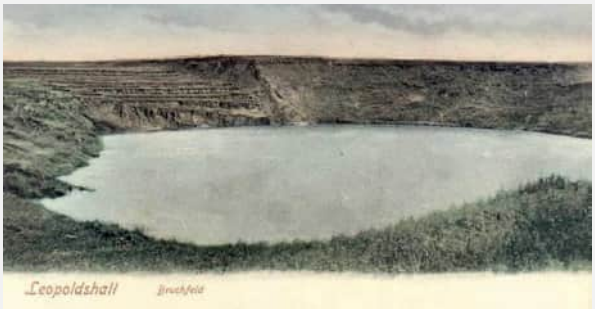
Potash mining in Staßfurt (Germany)
Flat to semi-steeply dipping potash seam World's first underground potash mining since 1861

Since 1878, signs of breakage in the mine workings with sinkholes and rock bursts, subsidence up to max. 0.5 m/a, continuing to this day (max. approx. 15 mm/a)
Mining damage area of approx. 100 ha (= 1 km²)

Caused by risky mining practices and inappropriate mining methods:
- Superimposed initially unstaggered mining chambers
- insufficiently dimensioned supports and pillars

In 1929, a sinkhole was converted into a saltwater spa, 240 – 260 m from the uppermost mining area







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Underground mining



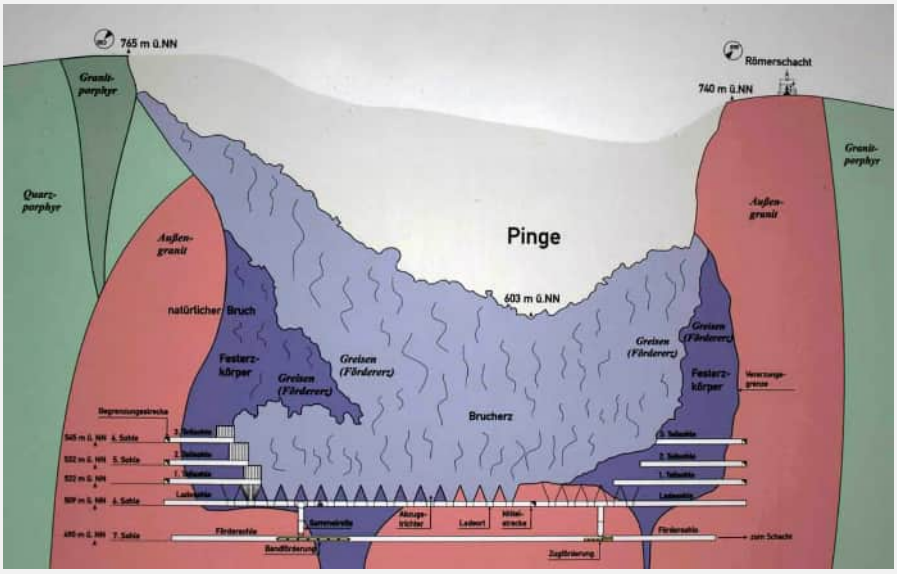
Workshop nuclear waste repository, Asse



Foto: K + S

Abandoned mining

The Zwitterstock deposit was opened up from 1436 onward. Tin ore with a relatively low metal content (about 0.35 %), but finely distributed throughout the entire rock volume, was once again mined here in blocks using fire setting from 1545. The gradual collapse of the stopes, adits, and shafts eventually led to the catastrophic cave-in of the mine workings in 1620. This created a collapse crater of two hectares at the surface. Afterwards, the broken ore continued to be extracted through underground mining, and from 1976 the remaining solid ore body was mined.
As a result, the sinkhole was significantly enlarged. Today it has an average diameter of 400 meters, a depth of up to 160 meters, and an area of about 12 hectares.



http://www.montanregion.cz/de/saechsische-bestandteile/bergbaulandschaft-altenberg-zinnwald/altenberger-pinge.html

Pinge Altenberg



http://www.montanregion.cz/de/saechsische-bestandteile/bergbaulandschaft-altenberg-zinnwald/altenberger-pinge.html

Karst phenomena are found in

- **salt rock**
- **sulfate rock**
- **carbonate rock**
- silicate karst (only under tropical-humid climate)

Karstification always begins at rock surfaces, especially along water-conducting discontinuities or primary large capillaries, but particularly in fault and fracture zones.

Karstification initially leads to joint enlargements and karst conduits, shafts, and small or large cavities that penetrate the rock irregularly, but mostly in accordance with the system of discontinuities. The depth to which karstification develops depends on the thickness of the karst rock, the various (including former) karst water levels and their position relative to the base level of erosion, as well as the flow conditions. It should be noted that the karst water level may show short-term fluctuations of well over 10 m.

The principle of self-reinforcement is also of crucial importance for the formation of karst features.



named by the karst area in Slovenia

Existing initial water pathways in the rock attract water, causing the cavities to continuously enlarge.

Especially in the transition zone of the groundwater table, this results in extensive cave systems in both limestone and gypsum or anhydrite.



Lake Otjikoto, and Lake Guinas Namibia 2025



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Migration of a cavity



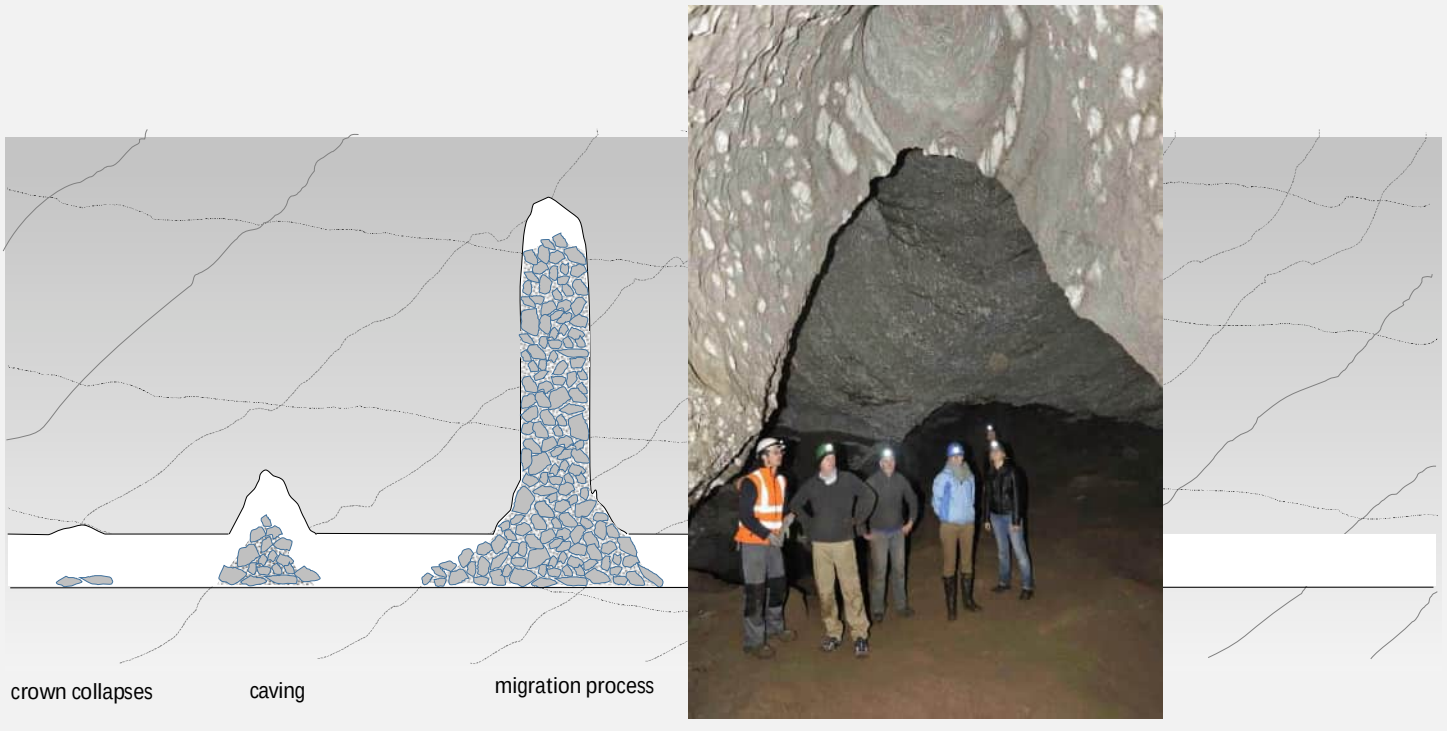
crown collapses

Migration of a cavity



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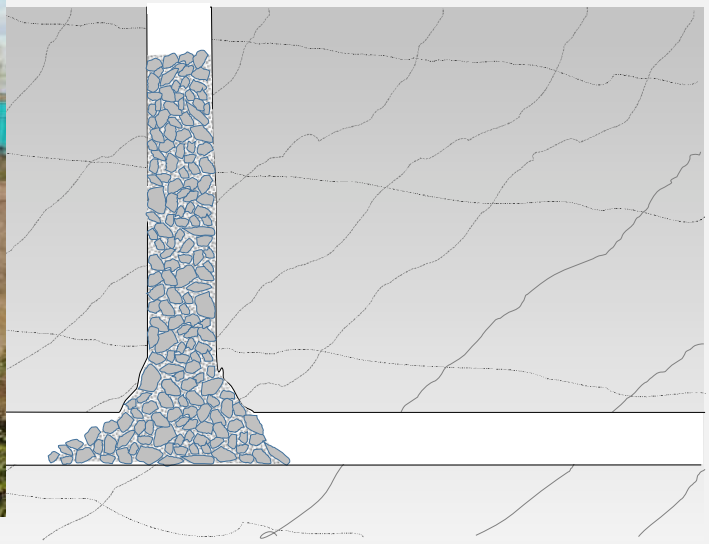
Migration of a cavity



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Migration of a cavity

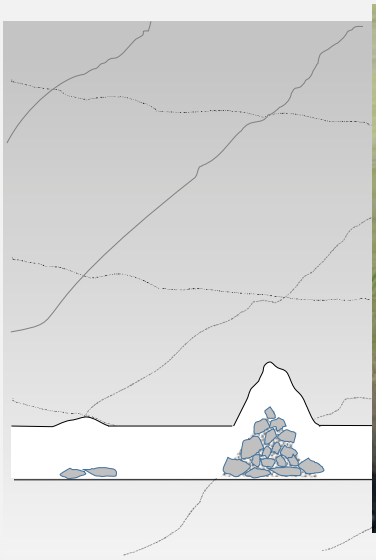




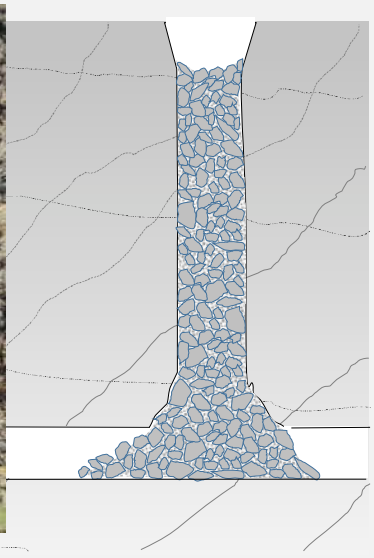
crown collapses caving migration process sink hole

Snkholes and collapses, UNAM Ongwediva - 03.12.2025 – www.aberle.biz

Migration of a cavity



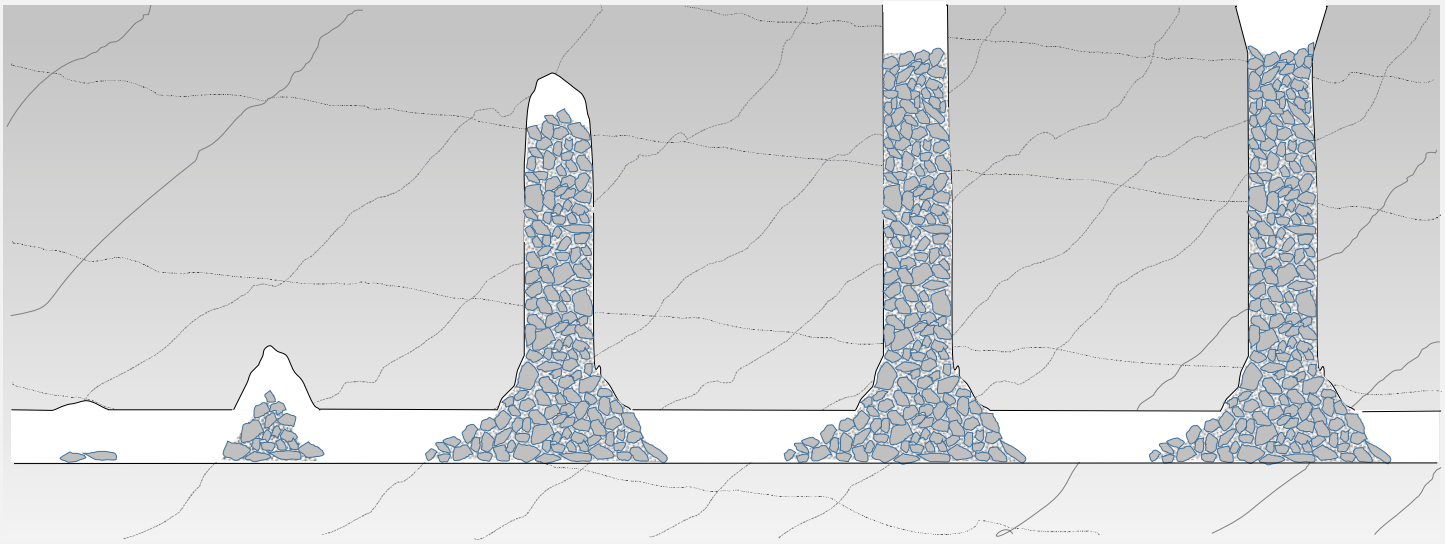




crown collapses caving migration process sink hole Soil erosion

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Life span of a sinkhole

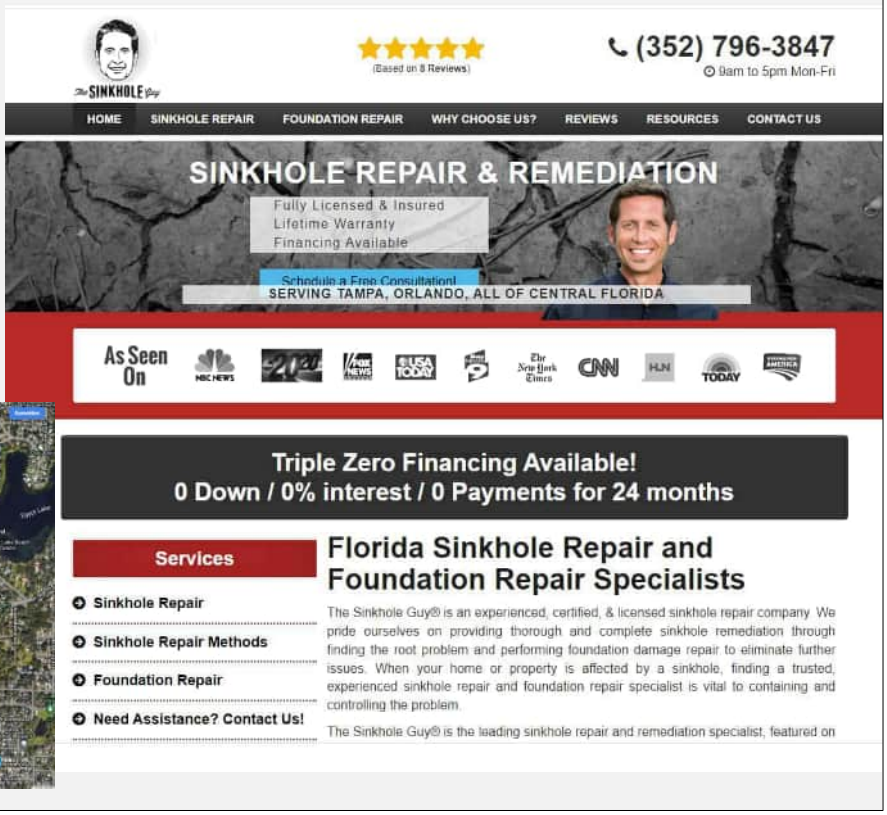


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Another area, some problems!

Mehr zu sinkhole hunter in Florida:
https://orf.at/v2/stories/2326147/2326258/



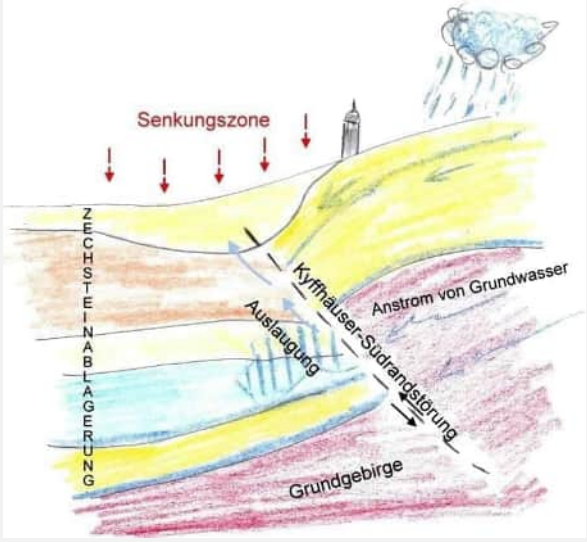


soluble rock - Halides



Typ	Salt rock, potash
mineral	Halit (NaCl), Sylvin (KCl), Carnallit ($KMgCl_3 \cdot 6\ H_2O$) Kainit ($KMg[Cl|SO_4] \cdot 3\ H_2O$) Kieserit ($MgSO_4 \cdot H_2O$)
	$NaCl \xrightarrow{H_2O} Na^+_{(aq)} + Cl^-_{(aq)}$
hardness, bulk density	1.5 – 2.0 Mohs 1.9 – 2.3 g/cm³
solubility in groundwater	NaCl with 10 °C up to 358 g/l moving groundwater 100 g/l Atlantic ocean 35 g/l Dead sea 310 g/l





Halides - sodium chloride (rock salt, halite) and potassium chloride (sylvite)
temperature-dependent
in groundwater (10 °C) with NaCl up to 358 g/l
In moving groundwater only partial saturation 100 g/l
Brine springs are signs of ongoing solution processes at depth

Rock salt erosion is generally restrained, as a zone of largely saturated salt water of higher density is established at the level of the salt deposit. Subrosion is accelerated when the hydraulic situation changes and fresh groundwater flows in, whether through brine operations or mining-related dewatering.
Larger cavities that remain stable over a longer period of time are unlikely in salt, as rock salt reacts with creeping deformations in the long term from an overburden of around 200 metres.
The springs at Bad Frankenhausen produce 250 tonnes of salt - per day!

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Dead Sea in Namibia



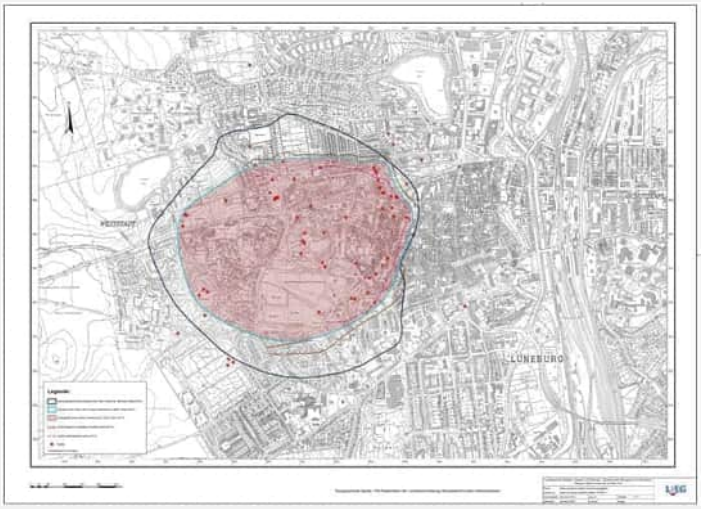






Subcidies by salt mining

Mining of a salt dome beneath Lüneburg in the 15th and 16th centuries.
The Lüneburg saltworks has been closed since 1980. For much longer, however—since the end of the Second World War—the Hanseatic City of Lüneburg has been continuously monitoring the subsidence area. The subsidence zone under geodetic observation covers 1.8 km². At around 300 measurement points, ground movements are recorded and evaluated in order to be able to react to changes in time. The natural processes in the subsurface are difficult to predict. In the 1970s it was mainly the western part of the old town where the ground subsided significantly and many buildings could not be saved. Today, in many places the ground there is only moving by a few millimetres per year.






1931 und 2003

https://www.hansestadtlueneburg.de/Home-Hansestadt-Lueneburg/Stadt-und-Politik/Geschichte/Senkung.aspx

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Collapses caused by

- Water pipes
- Groundwater level
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soluble rock - sulfate





Typ	Salt rock, potash	Sulfate rock	
mineral	Halit ($NaCl$), Sylvin (KCl), Carnallit ($KMgCl_3 \cdot 6\,H_2O$) Kainit ($KMg[Cl|SO_4] \cdot 3\,H_2O$) Kieserit ($MgSO_4 \cdot H_2O$)	Anhydrit ($CaSO_4$)	Gypsum ($CaSO_4 \times 2H_2O$)
	$NaCl \xrightarrow{H_2O} Na^+_{(aq)} + Cl^-_{(aq)}$	Water free Anhydrit + H_2O => Gips	hydrated
Hardness bulk density	1,5 – 2,0 Mohs 1,9 – 2,3 g/cm³	3.0 – 3.6 Mohs > 2,9 g/cm³	1.5 – 2.0 Mohs Up to 2.3 g/cm³
solubility in groundwater	NaCl with 10 °C up to 358 g/l moving groundwater 100 g/l Atlantic ocean 35 g/l Dead sea 300 g/l	volume increase to 61 % swelling pressure: 1.3 – 4.5 MPa	Poorly soluble*) until 2.1 g/l *) In Bad Sachsa leaching of 10- 30 cm/a in the last 100 years



Kelle bei Appenrode 2022



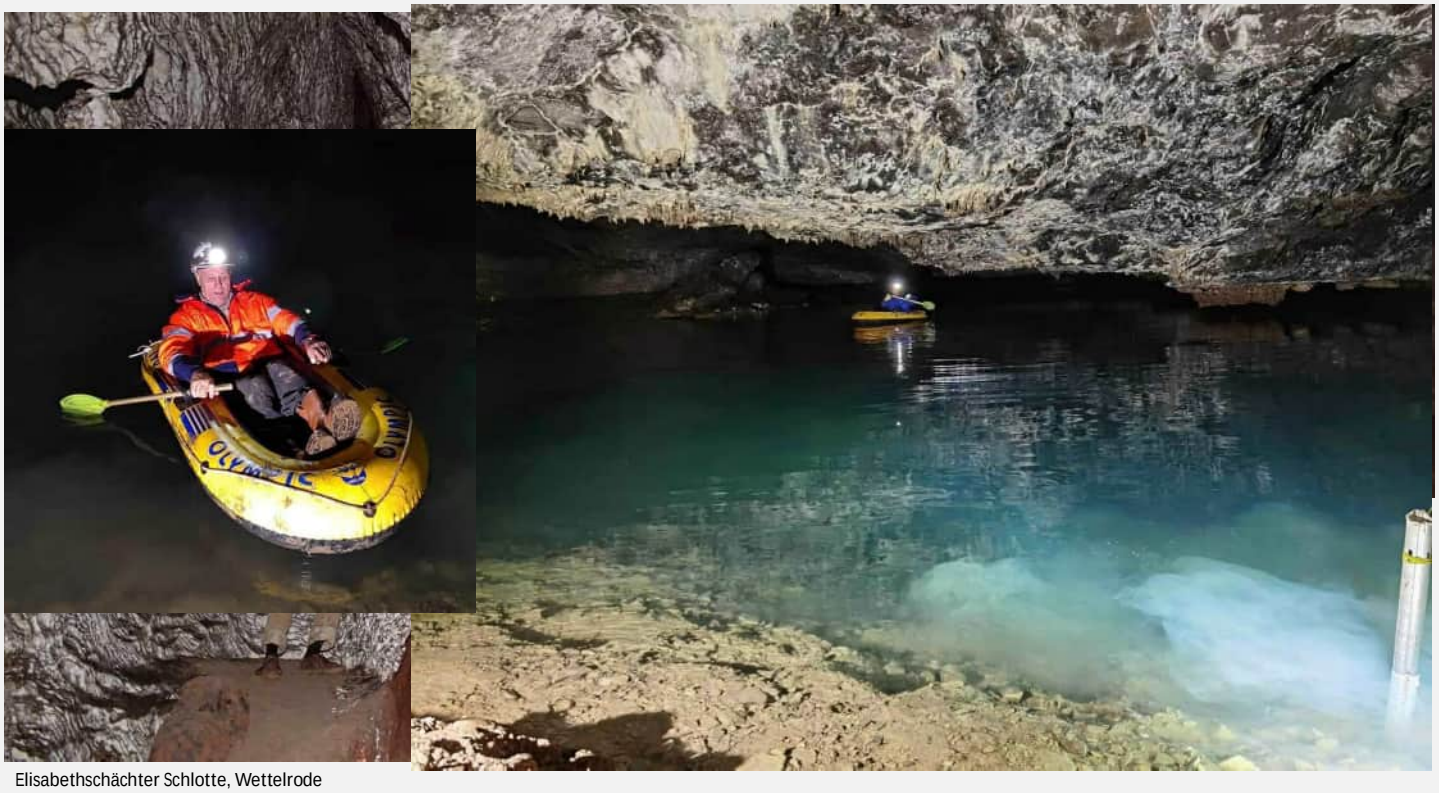
Questenhöhle unter Questenberg 2022



Heimkehle, Südharz 2008

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Sulfate Caves



Elisabethschächter Schlotte, Wettelrode

soluble rock - carbonate





Typ	Salt rock, potash	Sulfate rock		carbonate rock
mineral	Halit ($NaCl$), Sylvin (KCl), Carnallit ($KMgCl_3 \cdot 6\,H_2O$) Kainit ($KMg[Cl|SO_4] \cdot 3\,H_2O$) Kieserit ($MgSO_4 \cdot H_2O$)	Anhydrit ($CaSO_4$)	Gypsum ($CaSO_4 \times 2H_2O$)	Kalkmergel, Muschelkalk Dolomite ($MgCa(CO_3)_2$) Kalziumkarbonat ($CaCO_3$)
	$NaCl \xrightarrow{H_2O} Na^+_{(aq)} + Cl^-_{(aq)}$	Water free Anhydrit + H_2O => Gypsum	hydrated	$H_2O + CO_2 \rightarrow H_2CO_3$ (Kohlensäure) $H_2CO_3 + CaCO_3 \leftrightharpoons Ca^{2+} + 2HCO_3^-$ Kalziumhydrogenkarbonat
Hardness bulk density	1,5 – 2,0 Mohs / 1,9 – 2,3 g/cm³	3,0 – 3,6 Mohs >2,9 g/cm³	1,5 – 2,0 Mohs bis 2,3 g/cm³	3 – 4 Mohs 2.3 – 2.9 g/cm³
solubility in groundwater	NaCl with 10 °C up to 358 g/l moving groundwater 100 g/l Atlantic 35 g/l Death sea 300 g/l	volume increase to 61 % swelling pressure: 1.3 – 4.5 MPa	Poorly soluble*) until 2.1 g/l *) In Bad Sachsa leaching of 10 - 30 cm/a in the last 100 years	CO_2-free with 10°C: 0,014 g/l rainwater: bis 0,050 g/l Seapage water*) bis 0,200 g/l *) high CO_2-level from ground air

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Carbonate Karst (limestone, marlstone, dolostone)

Carbon dioxide is partly absorbed and dissolved by rainwater from the atmosphere, and partly originates from the vegetation zone—specifically biogenic CO_2 in the soil air or from the decomposition of organic matter. A frequently underestimated role appears to be played by carbon dioxide rising from deeper layers and of post-volcanic origin. Agents that accelerate the dissolution process include sulfate ions and humic acids.

$$H_2O + CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \Leftrightarrow CaCO_3 + H^+ + HCO_3^- \Leftrightarrow Ca(HCO_3)_2 \Leftrightarrow Ca^{2+} + 2HCO_3^-$$



Li Fluss bei Yanshuo, China, 2003



CO_2 content:

14 mg/l	CO_2-free groundwater at 10 °C
up to 50 mg/l	Rainwater
up to 200 mg/l	Percolating water with a high CO_2 content from soil air
about 2.5 mg/l	The solubility of dolomite ($MgCa(CO_3)_2$) in CO_2-free groundwater under the same conditions

soluble rocks



Typ	Salt rock, potash	Sulfate rock		carbonate rock
mineral	Halit (NaCl), Sylvin (KCl), Carnallit ($KMgCl_3 \cdot 6\ H_2O$) Kainit ($KMg[Cl|SO_4] \cdot 3\ H_2O$) Kieserit ($MgSO_4 \cdot H_2O$)	Anhydrit ($CaSO_4$)	Gypsum ($CaSO_4 \times 2H_2O$)	Kalkmergel, Muschelkalk Dolomite ($MgCa(CO_3)_2$) Kalziumkarbonat ($CaCO_3$)
	$NaCl \xrightarrow{H_2O} Na^+_{(aq)} + Cl^-_{(aq)}$	Water free Anhydrit + H_2O => Gypsum	hydrated	$H_2O + CO_2 \rightarrow H_2CO_3$ (Kohlensäure) $H_2CO_3 + CaCO_3 \leftrightharpoons Ca^{2+} + 2HCO_3^-$ Kalziumhydrogenkarbonat
Hardness bulk density	1,5 – 2,0 Mohs / 1,9 – 2,3 g/cm³	3,0 – 3,6 Mohs >2,9 g/cm³	1,5 – 2,0 Mohs bis 2,3 g/cm³	3 – 4 Mohs 2.3 – 2.9 g/cm³
solubility in groundwater	NaCl with 10 °C up to 358 g/l moving groundwater 100 g/l Atlantic ocean 35 g/l Dead sea 300 g/l	volume increase to 61 % swelling pressure: 1.3 – 4.5 MPa	Poorly soluble*) until 2.1 g/l *) In Bad Sachsa leaching of 10- 30 cm/a in the last 100 years	CO_2-free with 10°C: 0,014 g/l rainwater: bis 0,050 g/l Seapage water*) bis 0,200 g/l *) high CO_2-level from ground air

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Karst causes sinkholes and caves

Factors determining the karstification process:
+ the karst favourability of the rock
+ the interface structure
+ the quality of precipitation
+ the quantity of precipitation
+ the hydrogeological conditions
+ the relief
+ time period
+ changes due to human intervention

In addition to the water supply, there must also be water circulation or water drainage in the mountains,

Approximately 10,000 karst caves are known in Germany

Requirements:
+ Presence of water in the liquid state
+ Solubility of the rock, karst-forming rocks (rock salt, gypsum, limestone, dolomite)
+ Permeability of the rock (underground drainage)
+ Mineralogical purity of the rock

Consequences
+ doline
+ sinkholes
+ caves



Kelle bei Appenrode 2022

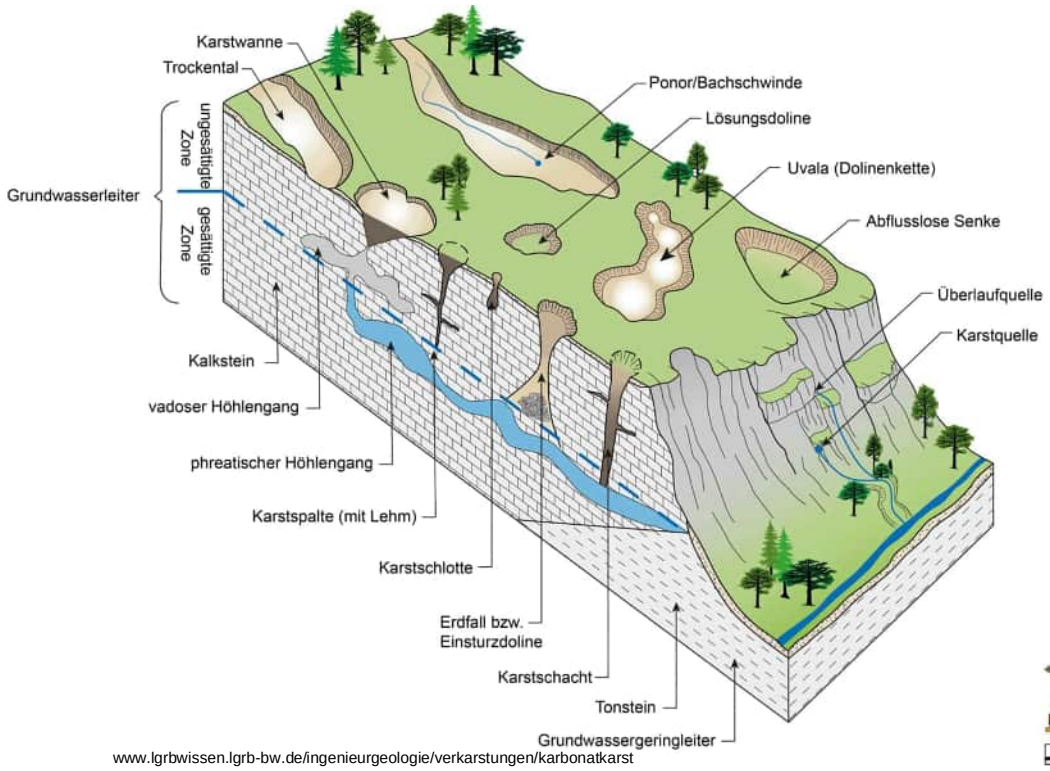


Elisbethschächter-Schlotte, Wettelrode 2015



Heimkehle, Südharz 2008

Karst landforms and karst features



www.lgrbwissen.lgrb-bw.de/ingenieurgeologie/verkarstungen/karbonatkarst

LGRB

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Mansfeld-Südharz, an area with sinkholes everywhere



A sink hole in Riethnordhausen „Rio“



Reithnordhausen, Friday 17.06.2022



Riethnordhausen, Sunday 19.06.2022

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root cause analysis



Yes	No	Maybe	
☐	☒	☐	Structural cause (vibration, sheet piling, blasting, etc.)
☐	☒	☐	Frost
☐	☒	☐	Slope creep
☐	☐	☒	Leaky pipes in the ground (downpipes, waste water, drinking water, drainage) => suffusion, suberosion, etc.
☐	☐	☒	Mining, old foundations, cellars, landfills
☐	☐	☒	Karstification due to lime, gypsum or salt
☐	☐	☒	Groundwater changes due to vegetation
☐	☐	☒	Groundwater changes due to own wells or in the neighbourhood
☐	☐	☒	Groundwater changes due to drinking water or drainage
☐	☒	☐	Drying out of the soil



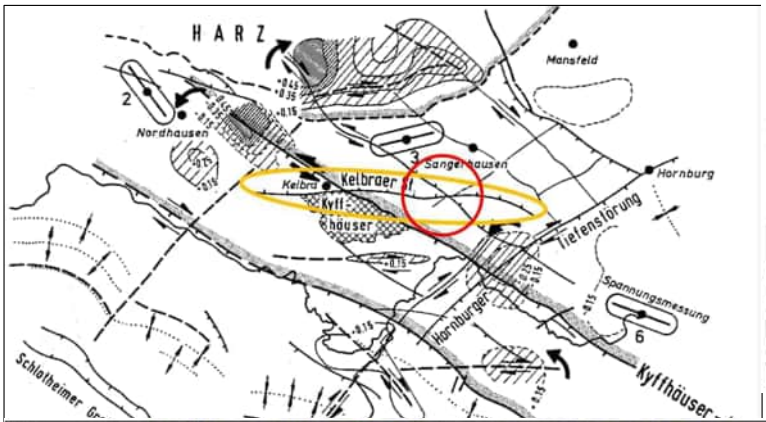
root cause analysis – a first clue

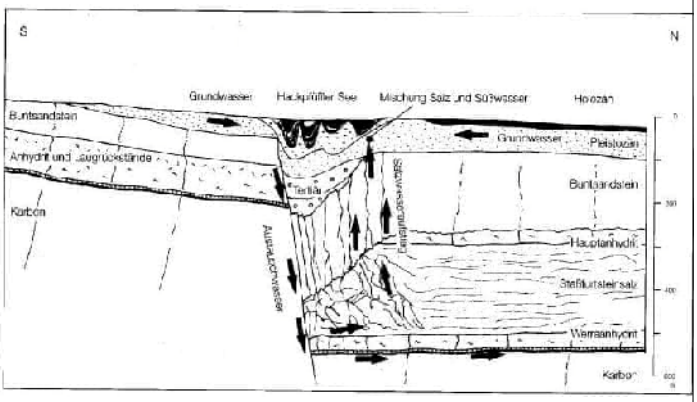




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Geological Situation in Riethnordhausen 2022





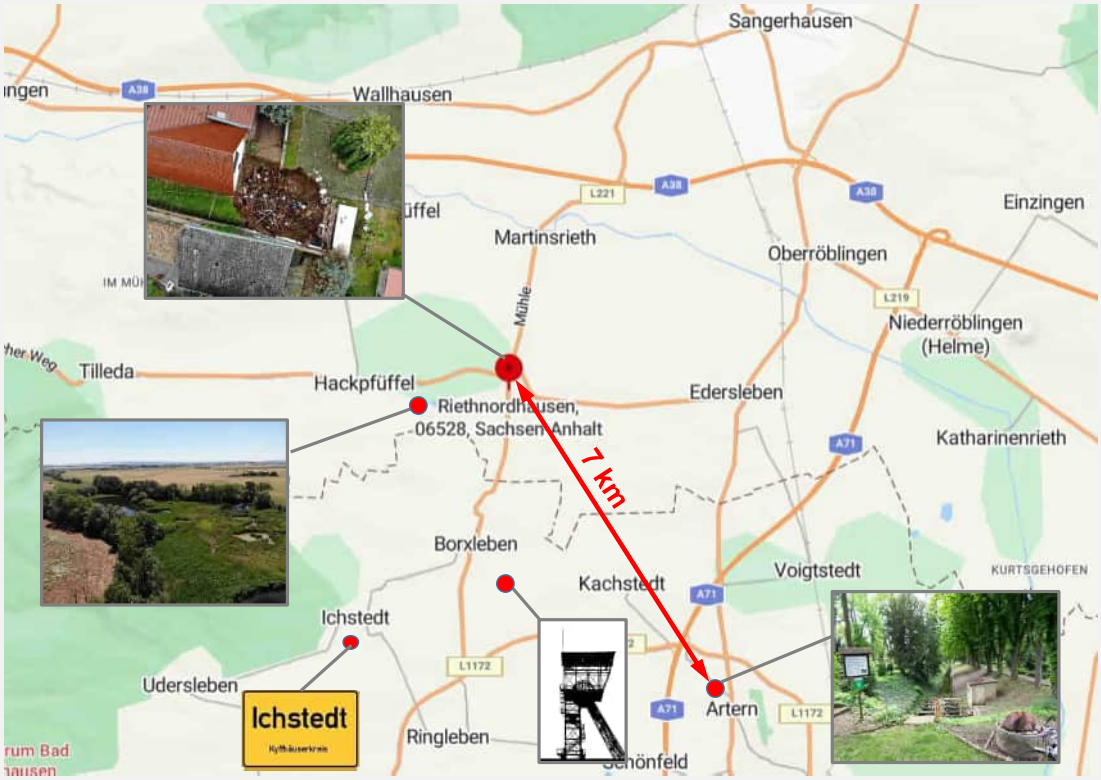
Model of recent horizontal movements in the southern Harz region



Section through the Kelbra fault zone in the area of Lake Hackpfüffler (schematic) and movement of the groundwater in the fault zone

[Völker, R. (1997): Karsterscheinungen am Nordkyffhäuserrand – Das Auftreten von Salzwasser im Bereich des Hackpfüffler Sees. – Gipskarst im Landkreis Sangerhausen, S. 85-95]

The history of the Hackpfüffler lakes



27 July 1890:
a small pond measuring 4 square rods (60 m²) suddenly expands to 1,100 m² and a depth of 30 feet.

It is suspected that this is due to a drop in the water table caused by the Borxleben brown coal mine.

Wells have to be re-drilled and meadows are cracked from dryness.

The water level in the Kringlingsloch (a sinkhole caused by sulphate karst) near Ichstedt rises significantly on the same day.

The brine trench of the spring in Artern overflows its banks and the water turns black. Hours later, the water turns yellow. [Poppe, 1894]

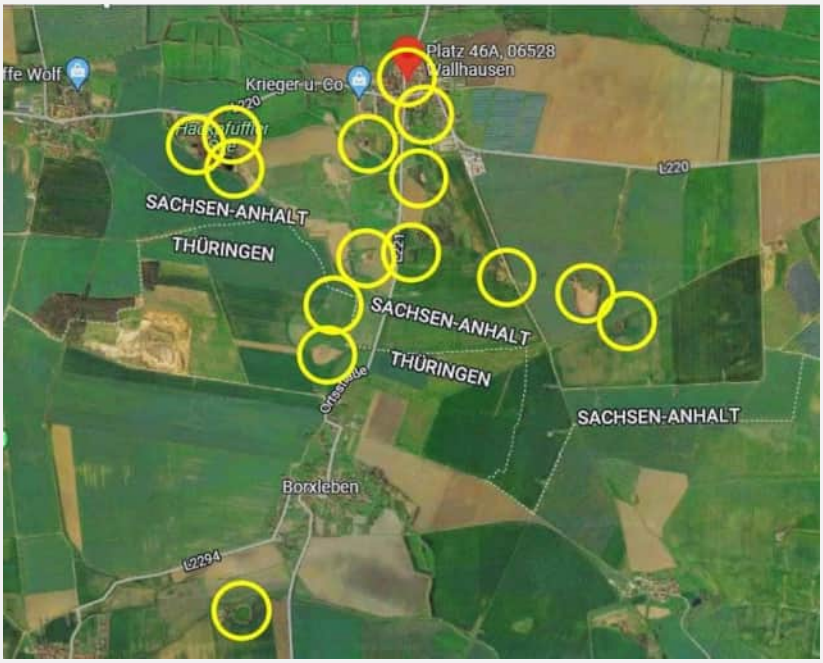
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sink holes close to Riethnordhausen















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First measurements

- Evacuation of residents
- Extensive road closures
- Disconnect supply lines (gas, electricity, water, etc.)

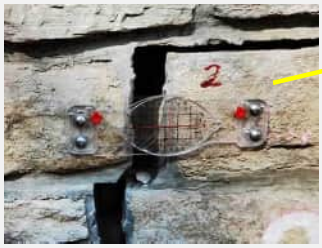




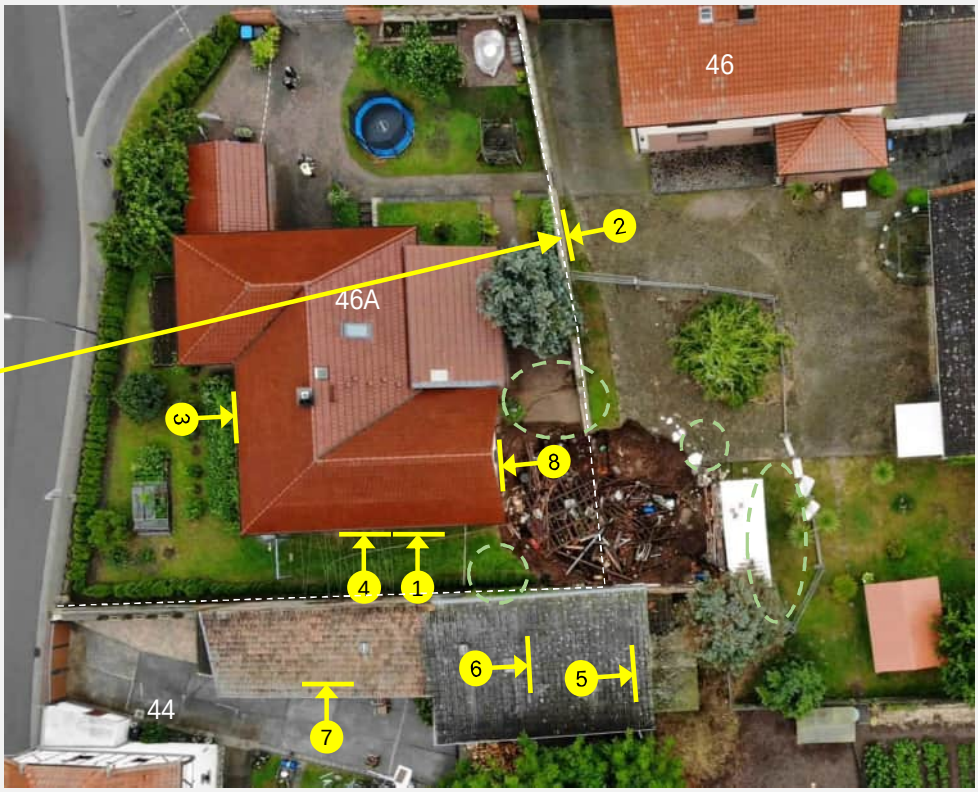
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Next step

- Evacuation of residents
- Extensive road closures
- Disconnect supply lines (gas, electricity, water, etc.)
- **Inventory**
- **Installation of crack monitors**

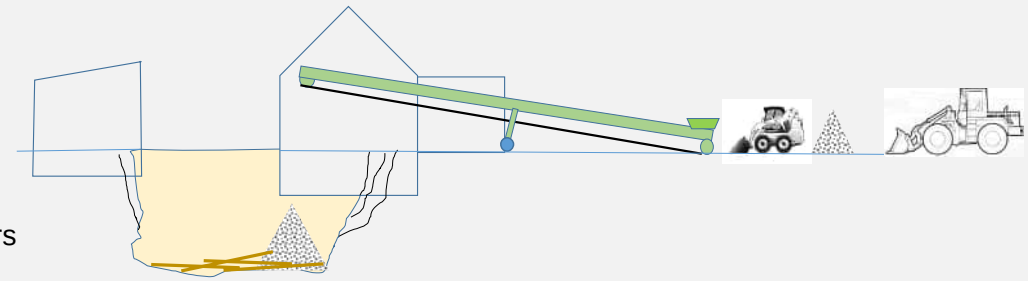






Next steps

- Evacuation of residents
- Extensive road closures
- Disconnect supply lines
- Inventory
- Installation of crack monitors
- **shall we clear out the pit?**
- **backfilling with sand and gravel?**







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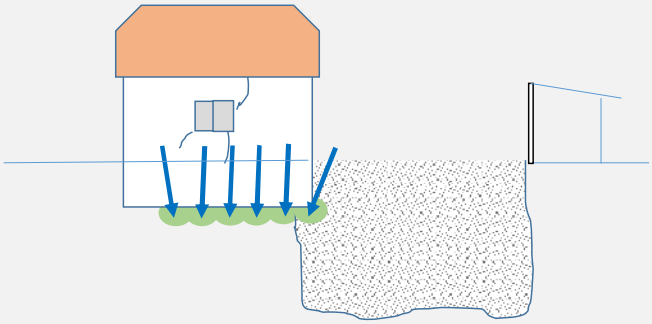
Next step, technical solution

- Evacuation of residents
- Extensive road closures
- Disconnect supply lines
- Inventory
- Installation of crack monitors
- shall we clear out the pit?
- backfilling with sand and gravel?
- **Foundation?**



Next steps

- Evacuation of residents
- Extensive road closures
- Disconnect supply lines
- Inventory
- Installation of crack monitors
- shall we clear out the pit?
- backfilling with sand and gravel
- **Underpinning of foundations**
- **Underpining with ram grouting lances**





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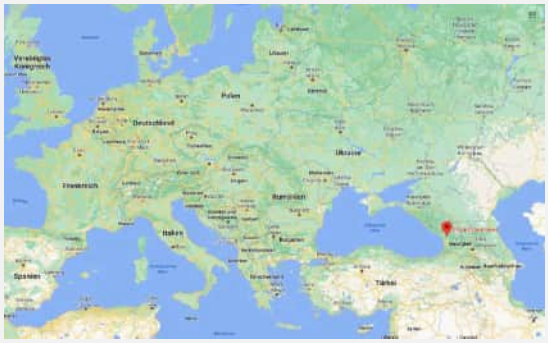
A look beneath a town in my neighbourhood - Sangerhausen

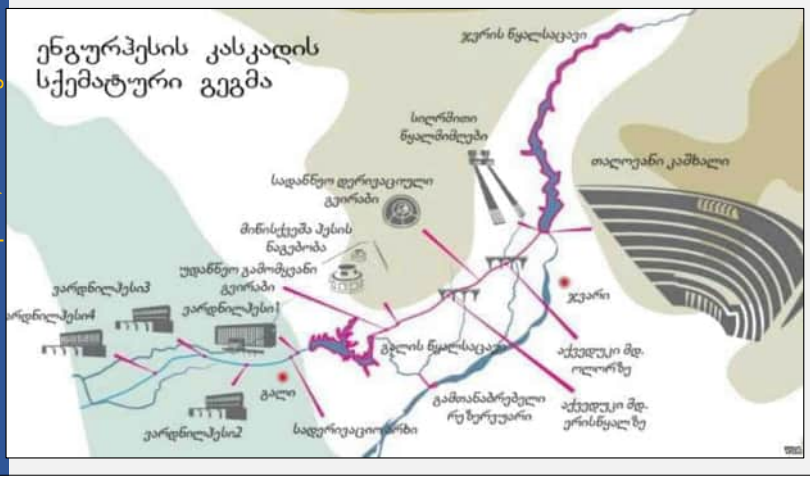


Geologischer Schichtenaufbau.

Diluvium Tertiär Muschelkalk Buntsandstein		5 - 10 Meter 30 - 40 Meter 80 Meter 200 - 70 Meter
Oberer Zechstein	Oberes Jüngeres Steinsalz Roter Salzton Unteres Jüngeres Steinsalz Hauptanhydrit Grauer Salzton Kalilager Älteres Steinsalz	15 Meter 15 Meter 60 Meter 50 Meter 8 Meter 25 Meter bis 300 Meter
Mittlerer Zechstein	Stinkschiefer Oberer Anhydrit Ältestes Steinsalz Unterer Anhydrit	6 Meter 25 Meter 6 Meter 30 Meter
Unterer Zechstein	Zechsteinkalk Fäule mit Dachklotz Kupferschiefer-Flöz Weißliegendes	2 - 5 Meter 1 - 2 Meter 0,4 Meter 1 - 10 Meter
	Rotliegendes	

Pressure tunnel of the Enguri dam (Georgia)

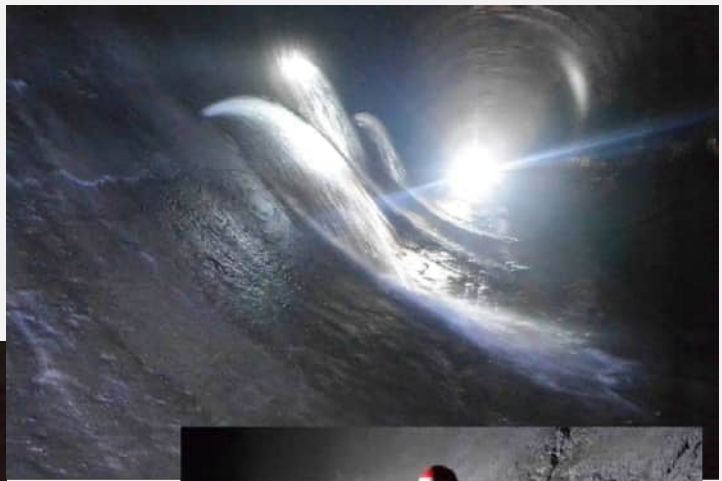


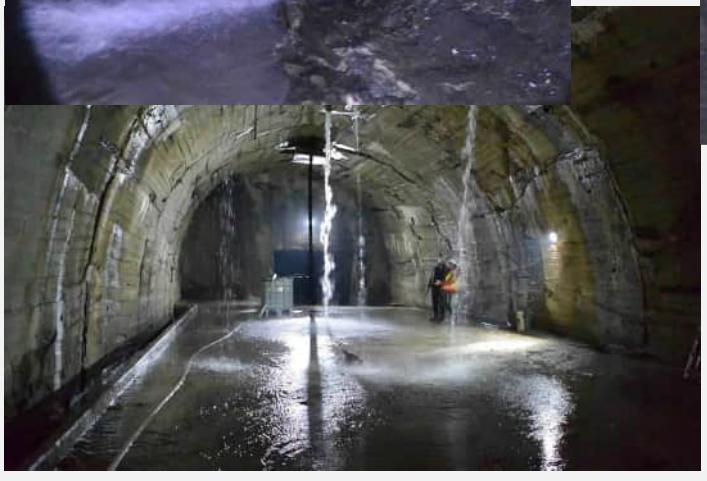




Water in the tunnel



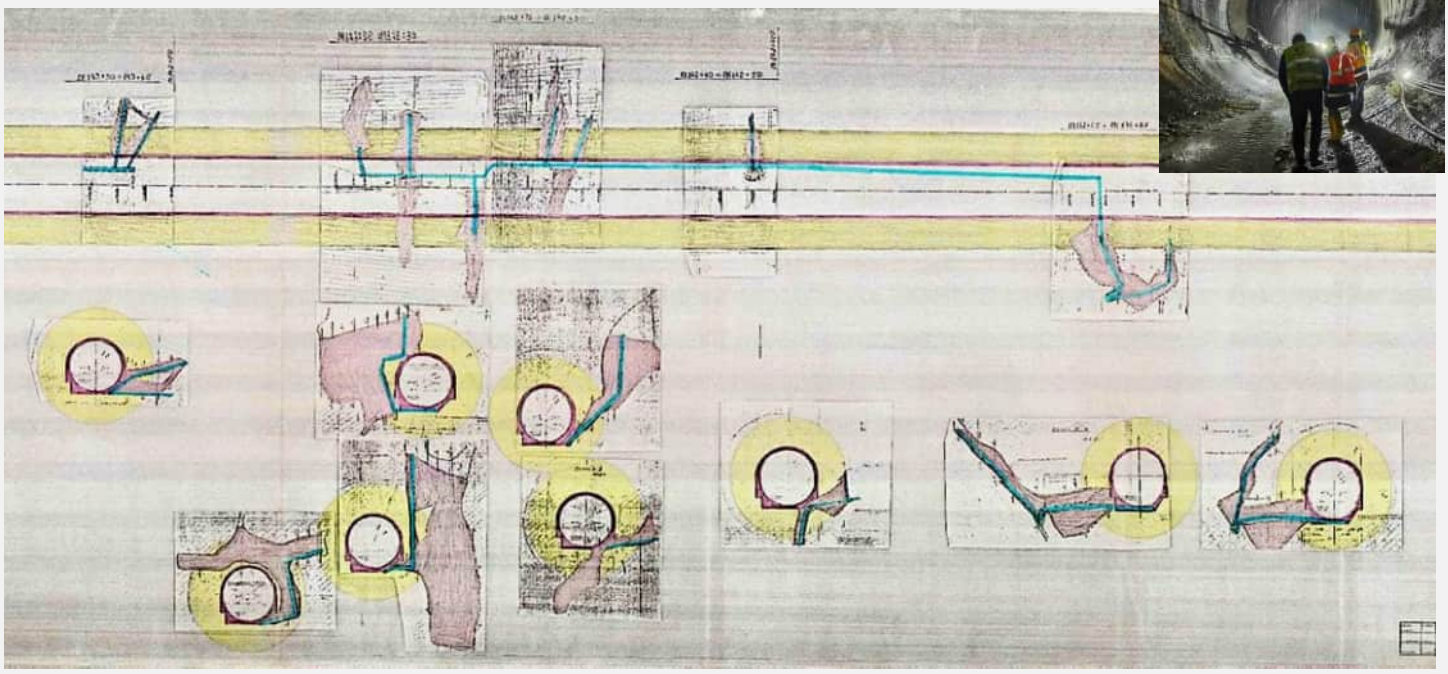






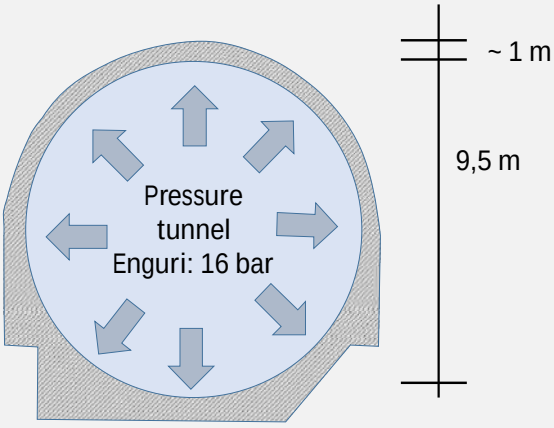
Where does the water in the pressure tunnel come from?



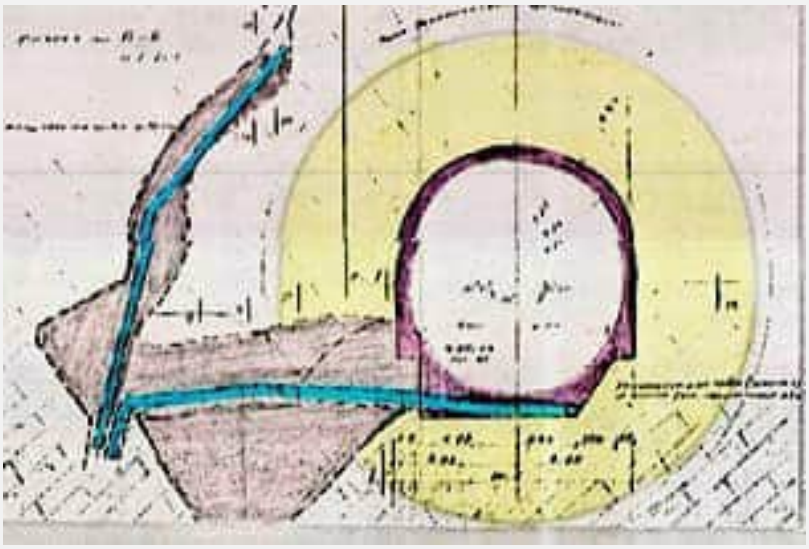


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Pressure tunnel in karstic rock



For concrete linings that are not prestressed, no static dimensioning is usual, as it is assumed that the concrete shell is sufficiently permeable to mountain water, that the concrete cracks under internal pressure loading and that the pressure is absorbed by the primarily dense rock mass.



Sketch from the construction period: Cave-like cavities were filled with cement. In addition, a drainage system was installed (blue line).

Construction joint +13,700, left side (down stream)

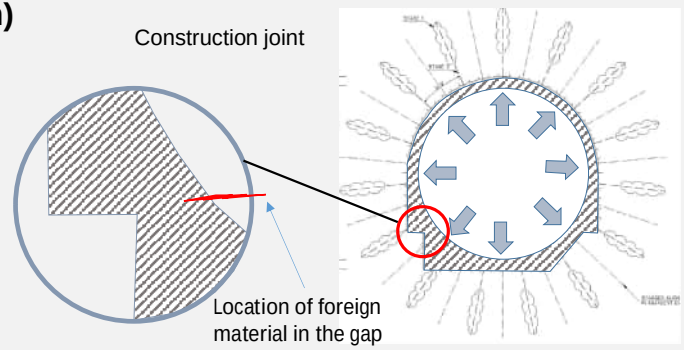
During our first inspection on 25.01.2021, and a closer look on 28.01.2021 we saw a construction joint filled with
- Fresh organic material (leaves, branches, wood)
- Rubbish like plastic bottles, cable ties,
- Dead fishes to size of 8 cm

The material was not only stocked inside, but squeezed between the upper and under part of Concrete lining.

A further inspection on 30.01.2021 with a camera has confirmed this first impression. Measurement shows a gaping joint between 0 and 30 mm. The gap had a deepth a least of 200 mm. The problem shows up on a length of 40 m.

It is obvious that a huge amount of water is lost in this area of the tunnel by the gap. According to the owner, the tunnel has lost more than 2 m³/ sec water at that spot.
Due to the squeezed material, it is to be feared that the gap will open further at high water pressure and close again when emptying the tunnel.

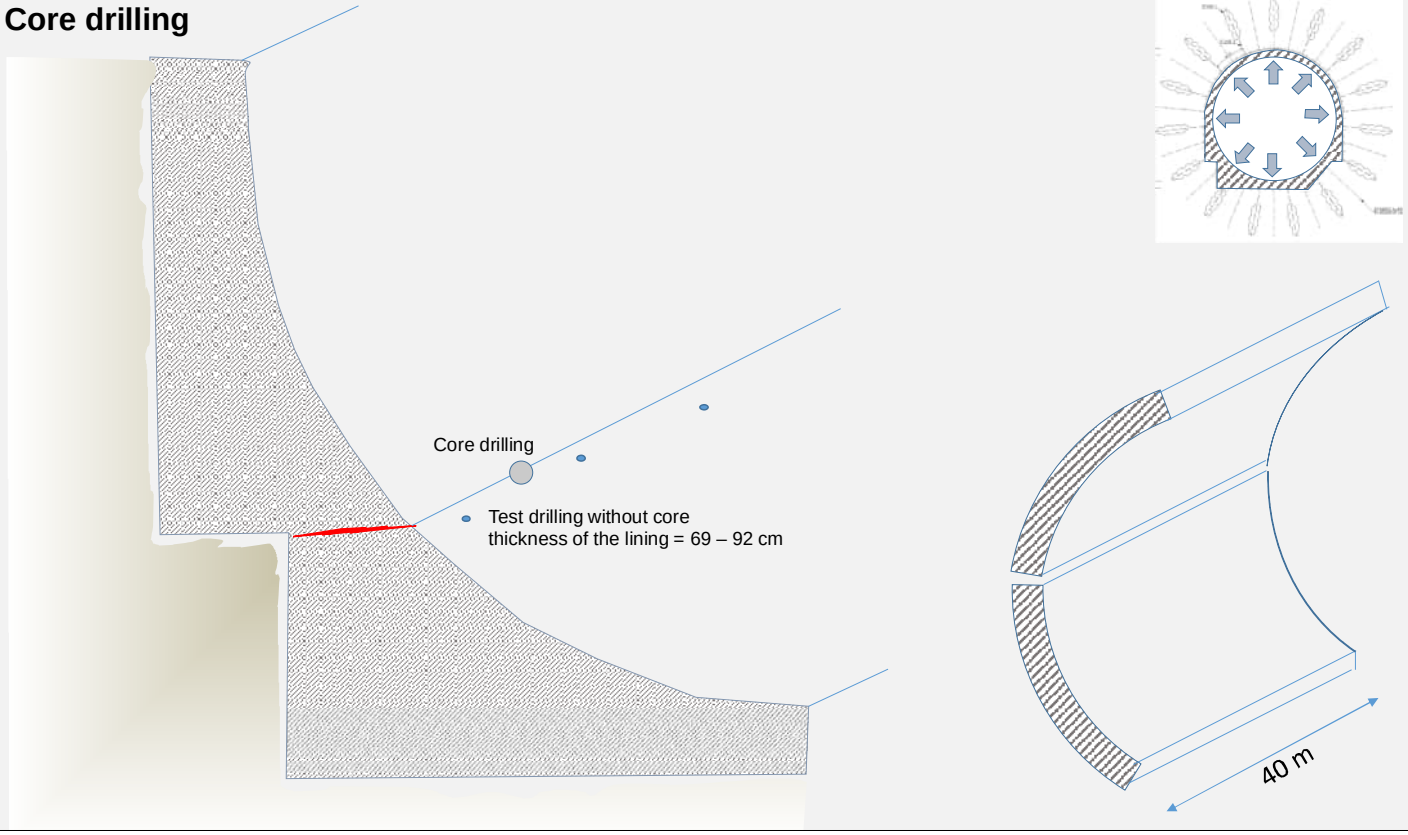
The test holes in the under part of the tunnel lining results a wall thickness of 68, 91 and 92 cm. The distance between the holes: 5 – 7 m
There are cavities behind the concrete.





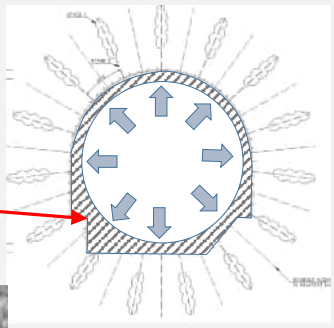
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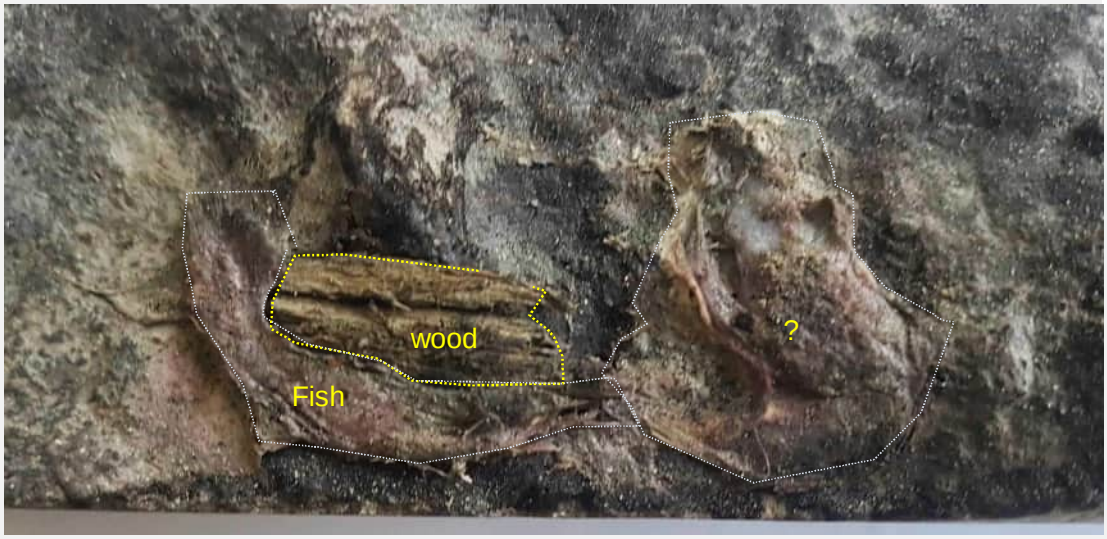
Core drilling



The core

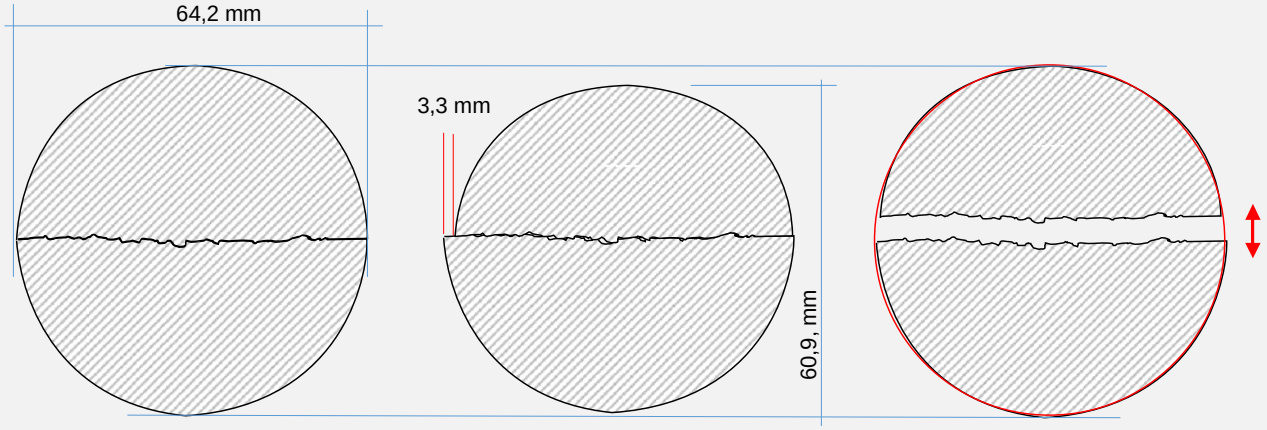






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A result form core drilling



During construction both parts had close contact, and were seperated by a fine line.

Today, the two halves fit by surface in the joint area, but not in the length of the basic line

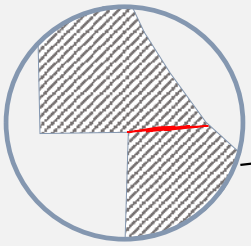
When moving both parts away, both halves will fit

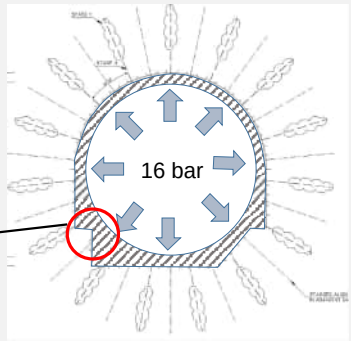
Conclusion:

- There was a crack, but not an open joint in the concrete lining during construction.
- Under pressure the both parts moved away from each other and do not fit in position any more.
- It can be assumed that this effect is more pronounced under pressure, when there is an opening and closing of the gap.
- Otherwise it would not be possible that we found pieces of wood and the remains of a 20 cm long fish in the drill core.
- A larger gap size also explains the numerous foreign objects (branches, fish, plastic) that were clamped in the gap.

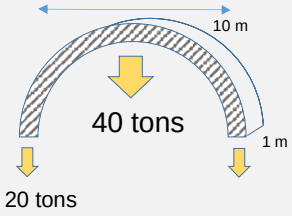
Very simplified calculation for the size ratios

Construction joint

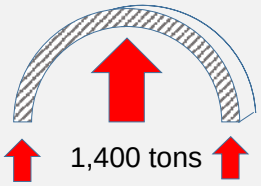




Dead weight of lining
10 * 3,14 / 2 = 15,7 m
15,7 * 2,5 tons = 40 tons



Uplift
16 bars = 160 tons/ m²
160 `* 9 m = 1440 tons



700 tons = 7,000,000 N

tangential stress for internal pressure in thin-walled tubes

$$\sigma_t = P_i * \frac{r_i^2}{r_a^2 - r_i^2} * \left(\frac{r_a^2}{r_x^2} + 1\right)$$

$$x\ [\text{N/mm}^2] = 1.6\ [\text{N/mm}^2] * \frac{4500^2}{5500^2 - 4500^2} * \left(\frac{5500^2}{5000^2} + 1\right)$$

3.9 [N/mm²] = 1.6 * 2.0 * 1.2

Assumptions for the concrete
- lining of 1.0 m, weight: 2.5 tons/m³
- Compresive : tensile stress = 10 : 1
- No force transfer by concrete in joint

- Steel with 420 MPa
- Steel bar with diameter 40 mm = 1,256 mm²

To take the power from uplift, without dead weight or any safety factors

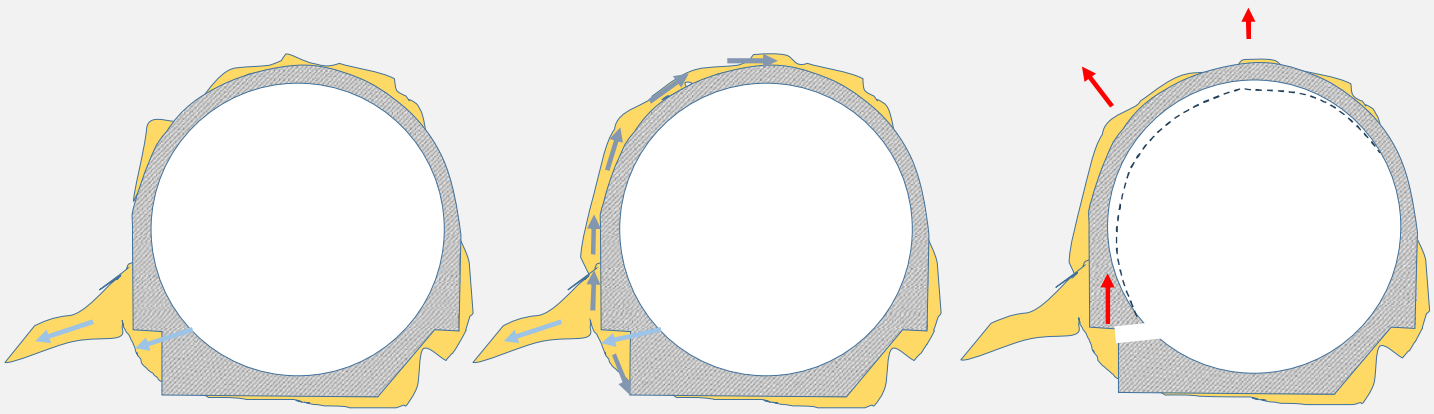
7,000,000 N / 420 MPa = 17,000 mm²

17,000 mm² / 1,256 = 18 steel bars with d = 40 mm for every running meter of tunnel lining



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What will happen in future?



In the beginning
fresh water at high pressure can leave the tunnel through a narrow gap.
Due to water channels in the karst rock, fresh water with a high solution potential can flow in again and again.

Later
The water will preferentially seek its way along the connection between the rock and the tunnel lining. This water will dissolve limestone over time.

Now and in future
New cavities are created in the top area of the tunnel. If the rock cannot provide sufficient abutment, the upper part of the tunnel lining lifts and the gap widens.

Geological risks or geo hazards

Geo hazards are natural hazards caused by geological factors that can lead to damage to buildings and infrastructure, as well as personal injury.

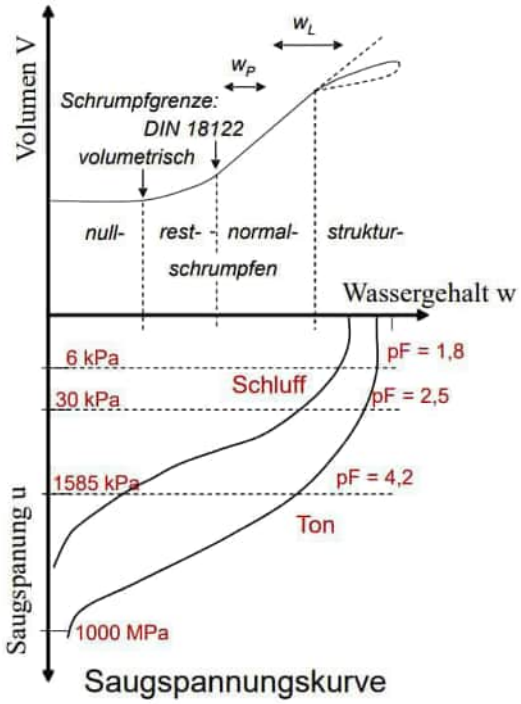
- Settlement
- Subsidence - elevation
- Earthquake - rock burst
- Volcanic eruptions
- Landslide - rock fall
- Sinkhole - collapses
- …

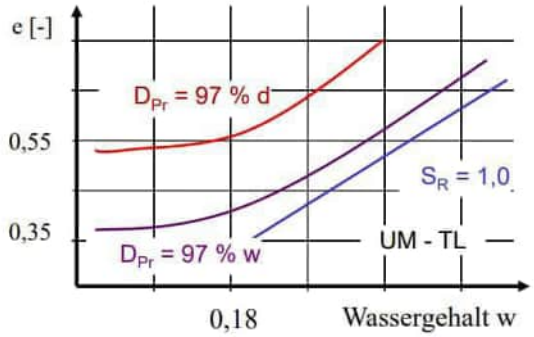




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Shrinking of cohesive ground





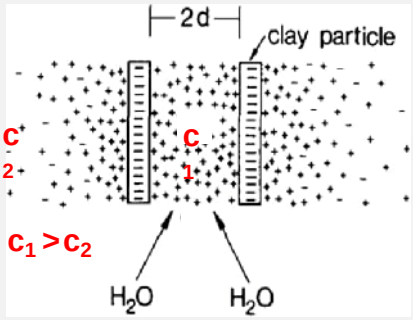


Zeh R., 2007: Die Zugfestigkeit bindiger Böden als Kriterium der Rissgefährdung mineralischer Oberflächenabdichtungen Schriftenreihe Geotechnik Weimar, Heft 16

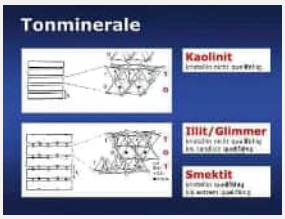
swelling rock

Rocks with a proportion of swelling clay minerals
(e.g. montmorrillonite, correncite), which incorporate water into the crystal lattice Clay mineral swelling can amount to a maximum volume increase of 14 %, the process starts within a few hours

+ osmotic swelling
+ caused by different cation concentrations
+ water is bound to clay particles => volume increase



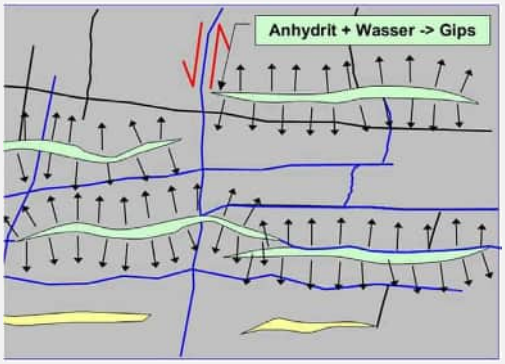
Madsen et al. (1989)



One gram of clay material with a particle size of 2-0.2 µm: 5x1011 particles, 200 m2 surface area

Anhydrite sources
Anhydrite which converts to gypsum when water is added. The volume increase can be max. 61 %, whereby the process is delayed, up to several weeks

+ Chemical reaction of anhydrite + water => Gypsum under ~60% volume increase
+ Gypsum dissolved in pore water
+ crystallisation in existing cracks and macropores



Sass & Burbaum (2009)

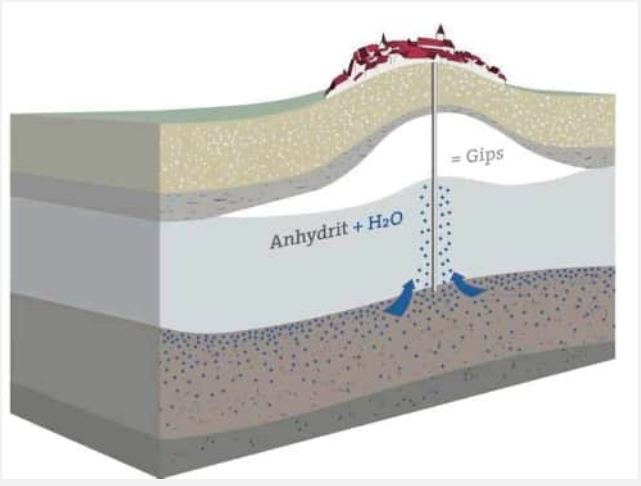
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Swelling underground, impact on the surface

In 2007, 7 geothermal exploratory boreholes were drilled in Staufen. As it later turned out, the boreholes had created a connection between a layer of highly pressurised groundwater and an overlying gypsum keuper layer around 75 m thick. As a result of the water absorption, the anhydrite embedded in the gypsum keuper layer began to transform into gypsum.
The maximum elevation in the centre area was 57 centimetres by March 2016. The horizontal displacement had reached up to 40 centimetres in places by November 2014.
By October 2010, 268 houses had been affected by damage, 127 of which were particularly badly damaged.

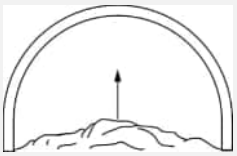






Swelling at the Belchem Tunnel





Swelling of anhydrite

Belchem tunnel: Switzerland
bed elevation: 1.5 m in 3 months
In the literature, swelling pressures of 1.3-4.5 MPa are described for gypsum keuper samples from the Belchen tunnel.

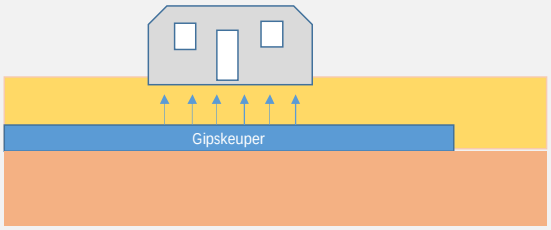




Anhydrite/ Gypsum: what pressures can occur







Is it possible to elevate a house on a layer of gypsum keuper?

swelling pressure of gypsum keuper: 2 MPa
= 4 N/mm²
= 2 MN/m²

<u>single family house</u>

Floor area:	8 x 8 m = 64 m²
Dead weight:	200 tonnes = 2 MN
Load of the house:	<u>2 MN/64 m² = 0,03 MN/m²</u>
	=> 2 MN/m² > 0,03 MN/m²

characteristics of rock

- Parameters
- Density, weight
- Compressive strength
- Splitting ability
- Abrasiveness
- Tension
- Elongation
- Young modulus
- Shear strength
- Transverse strain
- porosity
- Water content
- Water absorption
- Swelling
- Shrinkage
- Solubility
- Radioactivity
- ...

→ Laboratory Testing Pressure tests
Triaxial cell
Vicat needle
...

→ Field Testing
Compression tests
Shear strength
Water pressure test (Lugeon)
Pumping test
Sip test
...

→ Monitoring Convergence measurement
Extensometer
inclinometer
Fissurometer
Pressure cells
Water level
Vibration measurement
...



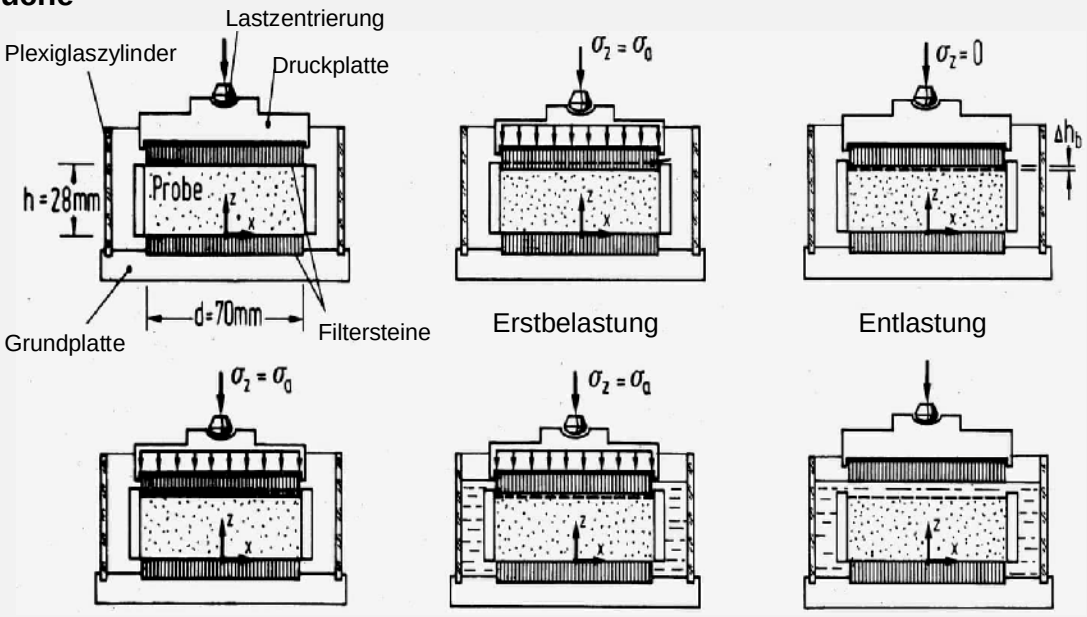
Mrs. Shapua, Monika Ndilimeke



Mr. Mundjele, Elifas

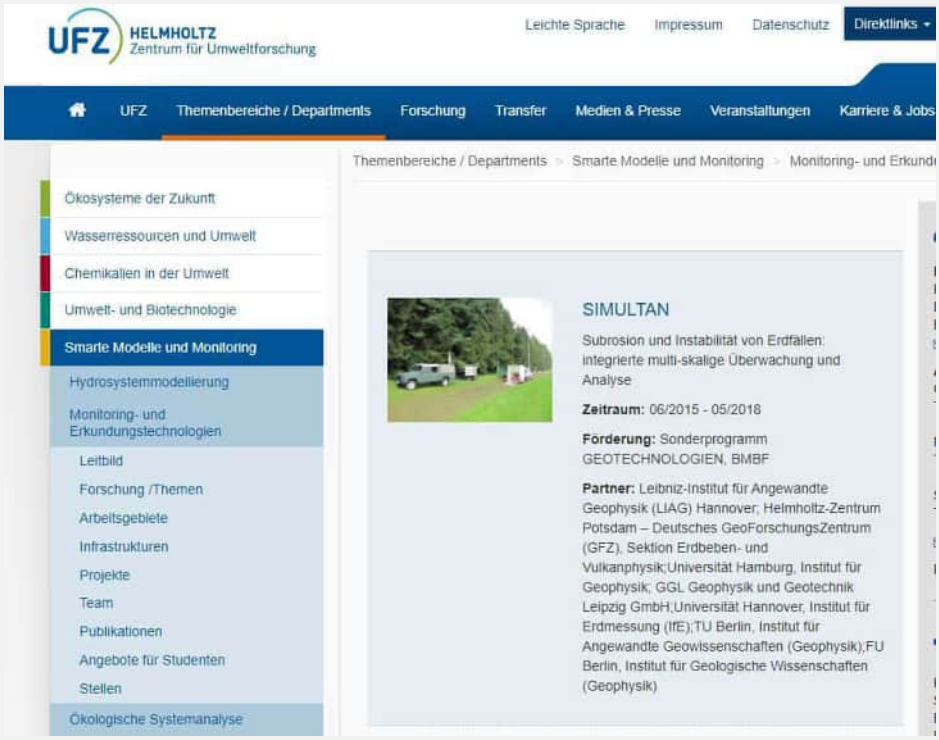
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Quellversuche



⇒ Versuchseinrichtung entspricht dem eines Kompressionsversuchs

Is there are way to predict sinkholes?



Erdsenkungen oder Erdfälle treten

If there is a sinkhole in my area. Will there be a second one?

Yes!

When will it happen?

Who knows?

Is it possible to reduce the conquences and risks?

Yes, asked an expert with a geotechnical background

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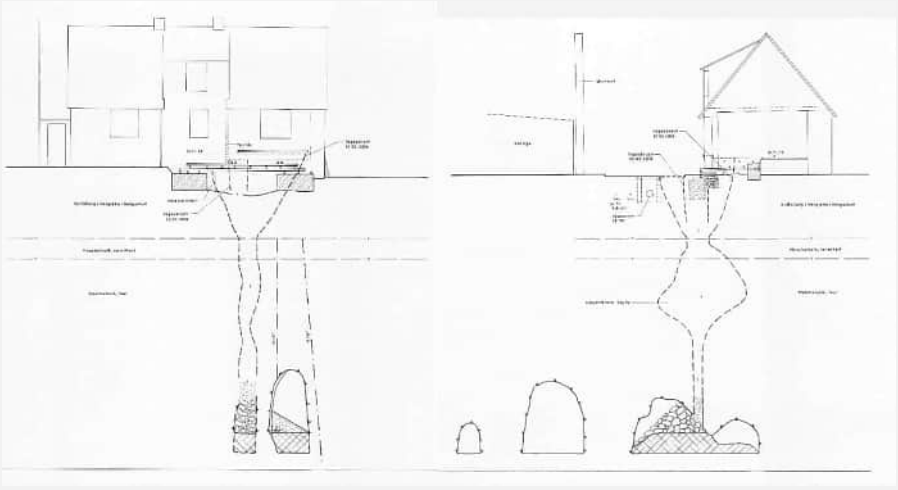
Schraplau 2009, am Kirchberg



In der Praxis….







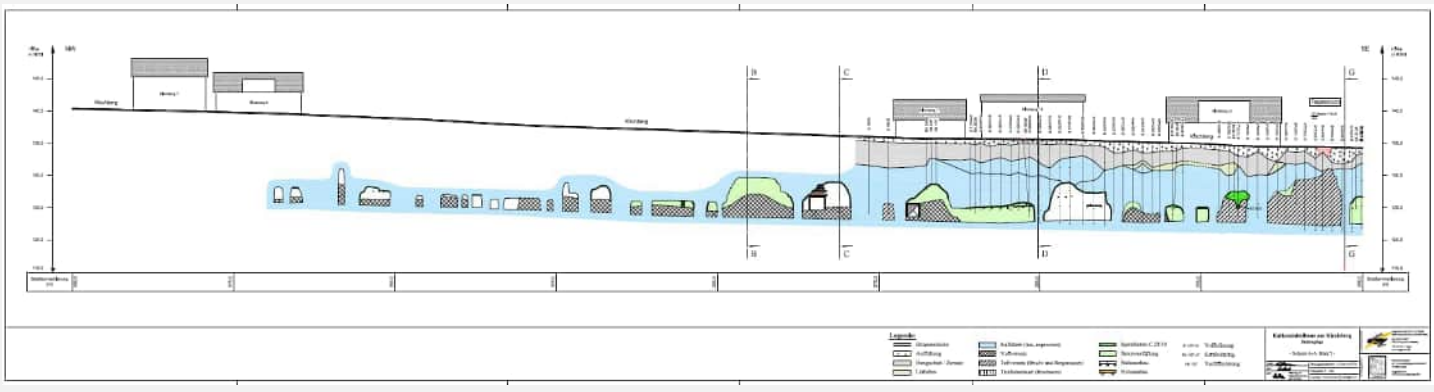
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Schraplau and the movie team









Schraplau





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Arbeitskreis 2.10 „Geomesstechnik" der DGGT und des DVW
Empfehlungen des Arbeitskreises Geomesstechnik

