Overview about rock drilling

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1 Introduction

Drilling is an important technique in rock engineering and can fulfill quite different tasks, like:

- Blast boreholes in mining, tunneling, rock slope engineering etc.,
- Boreholes for anchors, bolts, nails etc.,
- Boreholes for extraction of liquids and gases (water, oil, gas etc.),
- Injection boreholes (fluids, gases, resins etc.),
- Exploration boreholes to get cores or to perform borehole logging,
- Boreholes to perform rock mechanical or hydraulic testing (dilatometer tests, stress measurements etc.),
- Drilling resistance measurements to estimate rock properties
- Drill holes for special foundations (piles etc.).

In terms of diameter and length of boreholes, drilling operations in rock engineering cover a huge spectrum:

- Borehole diameters: few millimeters to several decimeters,
- Borehole length: several centimeters to several kilometers.

Most typical and standardized borehole sizes used in tunneling, mining and roc slope engineering are shown in Table 1.

Table 1: Standardized borehole and drill bit size values (mining and tunneling)

Core and Drill Hole Diameters Bit Size	Core Diameter In mm	Hole Diameter In mm
AQ	27.0	48.0
BQ	36.5	60.0
NQ	47.6	75.7
HQ	63.5	96.0
PQ	84.0	122.6
CHD 76	43.5	75.7
CHD 101	63.5	101.3
CHD 134	85.0	134.0

Table 2 shows standardized casing and hole diameter, respectively, and corresponding bit sizes used for water and geothermal wells as well as applied in petroleum engineering.

Table 2: Standardized hole, casing and corresponding bit size (deep wells)

Dimensions						Bit Size and Diameter Clearance		
Size OD	Weight per Foot Nominal	Wall	Nominal ID	Coupling OD	Drift	Nominal Bit Size		Clearance From Drift Dia.
Inches	Pounds	Inches				Inches	Decimal	Inches
4½	9.50	0.205	4.090	5.000	3.965	3 7/8	3.875	0.090
	11.60	0.250	4.000	5.000	3.875	3 7/8	3.875	0.000
	13.50	0.290	3.920	5.000	3.795	3 3/4	3.750	0.045
	15.10	0.337	3.826	5.000	3.701	3 5/8	3.625	0.076
5	11.50	0.220	4.560	5.563	4.435	4 1/4	4.250	0.185
	13.00	0.253	4.494	5.563	4.369	4 1/4	4.250	0.119
	15.00	0.296	4.408	5.563	4.283	4 1/4	4.250	0.033
	18.00	0.362	4.276	5.563	4.151	4 1/8	4.125	0.026
5½	13.00	0.228	5.044	6.050	4.919	4 3/4	4.750	0.169
	14.00	0.244	5.012	6.050	4.887	4 3/4	4.750	0.137
	15.50	0.275	4.950	6.050	4.825	4 3/4	4.758	0.075
	17.00	0.304	4.892	6.050	7.767	4 3/4	4.750	0.017
	20.00	0.361	4.778	6.050	4.653	4 5/8	4.625	0.028
	23.00	0.415	4.670	6.050	4.545	4 1/2	4.500	0.045
6	15.00	0.238	5.524	6.625	5.399	5 3/8	5.375	0.024
	18.00	0.288	5.424	6.625	5.299	5 1/8	5.125	0.174
	20.00	0.324	5.352	6.625	5.227	5 1/8	5.125	0.102
	23.00	0.380	5.240	6.625	5.115	4 7/8	4.875	0.240
	26.00	0.434	5.132	6.625	5.007	4 7/8	4.875	0.132
6 5/8	17.00	0.245	6.135	7.390	6.010	6	6.000	0.010
	20.00	0.288	6.049	7.390	5.924	5 7/8	5.875	0.049
	24.00	0.352	5.921	7.390	5.796	5 3/4	5.750	0.046
	28.00	0.417	5.791	7.390	5.666	5 5/8	5.625	0.041
	32.00	0.475	5.675	7.390	5.550	5 3/8	5.375	0.175
7	17.00	0.231	6.538	7.656	6.413	6 3/8	6.375	0.038
	20.00	0.272	6.456	7.656	6.331	6 1/4	6.250	0.081
	23.00	0.317	6.366	7.656	6.241	6 1/8	6.125	0.116
	26.00	0.362	6.276	7.656	6.151	6 1/8	6.125	0.026
	29.00	0.408	6.184	7.656	6.059	6	6.000	0.059
	32.00	0.453	6.094	7.656	5.969	5 7/8	5.875	0.094
	35.00	0.498	6.004	7.656	5.879	5 7/8	5.875	0.004
	38.00	0.540	5.920	7.656	5.795	5 3/4	5.750	0.045
7 5/8	20.00	0.250	4.125	8.500	7.000	6 3/4	6.750	0.250
	24.00	0.300	7.025	8.500	6.900	6 3/4	6.750	0.150
	26.40	0.328	6.969	8.500	6.844	6 3/4	6.785	0.094
	29.70	0.375	6.875	8.500	6.750	6 3/4	6.750	0.000
	33.70	0.430	6.765	8.500	6.640	6 5/8	6.625	0.015
	39.00	0.500	6.625	8.500	6.500	6 3/8	6.375	0.125

	24.00	0.264	8.097	9.625	7.972	7 7/8	7.875	0.097
	28.00	0.304	8.017	9.625	7.892	7 7/8	7.875	0.017
	32.00	0.352	7.921	9.625	7.796	7 3/4	7.750	0.046
8 5/8	36.00	0.400	7.825	9.625	7.700	7 5/8	7.625	0.075
	40.00	0.450	7.725	9.625	7.600	7 3/8	7.375	0.225
	44.00	0.500	7.625	9.625	7.500	7 3/8	7.375	0.125
	49.00	0.557	7.511	9.625	7.386	7 3/8	7.375	0.011
	29.30	0.281	9.063	10.635	8.907	8 3/4	8.750	0.157
	32.30	0.312	9.001	10.625	8.845	8 3/4	8.750	0.095
	36.00	0.352	8.921	10.625	8.765	8 3/4	8.750	0.015
9 5/8	40.00	0.395	8.835	10.625	8.679	8 5/8	8.625	0.054
	43.50	0.435	8.755	10.625	8.599	8 1/2	8.500	0.099
	47.00	0.472	8.681	10.625	8.525	8 1/2	8.500	0.025
	53.50	0.545	8.535	10.625	8.379	8 3/8	8.375	0.004
	32.75	0.276	10.192	11.750	10.036	9 7/8	9.875	0.161
	40.50	0.350	10.050	11.750	9.894	9 7/8	9.875	0.019
	45.50	0.400	9.950	11.750	9.794	9 3/4	9.875	0.044
10 3/4	51.00	0.450	9.850	11.750	9.694	9 5/8	9.625	0.069
	55.50	0.495	9.760	11.750	6.604	9	9.000	0.604
	60.70	0.545	9.660	11.750	9.504	9	9.000	0.504
	65.70	0.595	9.560	11.750	9.404	9	9.000	0.404
	38.00	0.300	11.150	12.750	10.994	10 5/8	10.625	0.369
	42.00	0.333	11.084	12.750	10.928	10 5/8	10.625	0.303
11 3/4	47.00	0.375	11.000	12.750	10.844	10 5/8	10.625	0.219
	54.00	0.435	10.880	12.750	10.724	10 5/8	10.625	0.099
	60.00	0.489	10.772	12.750	10.616	9 7/8	9.875	0.741
	48.00	0.330	12.715	14.375	12.559	12 1/4	12.250	0.309
	54.50	0.380	12.615	14.375	12.459	12 1/4	12.250	0.209
13 3/8	61.00	0.430	12.515	14.375	12.359	12 1/4	12.250	0.109
	68.00	0.480	12.415	14.375	12.259	12 1/4	12.250	0.009
	72.00	0.514	12.347	14.375	12.171	12	12.000	0.191
	55.00	0.312	15.375	17.000	15.188	15	15.000	0.188
	65.00	0.375	15.250	17.000	15.062	15	15.000	0.062
16	75.00	0.438	15.125	17.000	14.938	14 3/4	14.750	0.188
	84.00	0.495	15.010	17.000	14.823	14 3/4	14.750	0.073
18 5/8	87.50	0.435	17.755	20.000	17.568	17 1/2	17.500	0.068
20	94.00	0.438	19.124	21.000	18.936	17 1/2	17.500	1.436

NOTE**:** Information are valid for API casing. Metric equivalents in millimeters are obtained by multiplication the "inches" with 25.4

The drilling is influenced be several factors:

- Strength of rocks,
- Hardness and abrasiveness of rocks,
- Pressure in rock formation,
- Temperature,
- Depth of borehole,
- Change of conditions along borehole path.

Important aspects for all kind of drilling are:

- Wear or damage due to frictional sliding and heat (see Fig. 1),
- Fluid or air driven transport of cutting and fines.

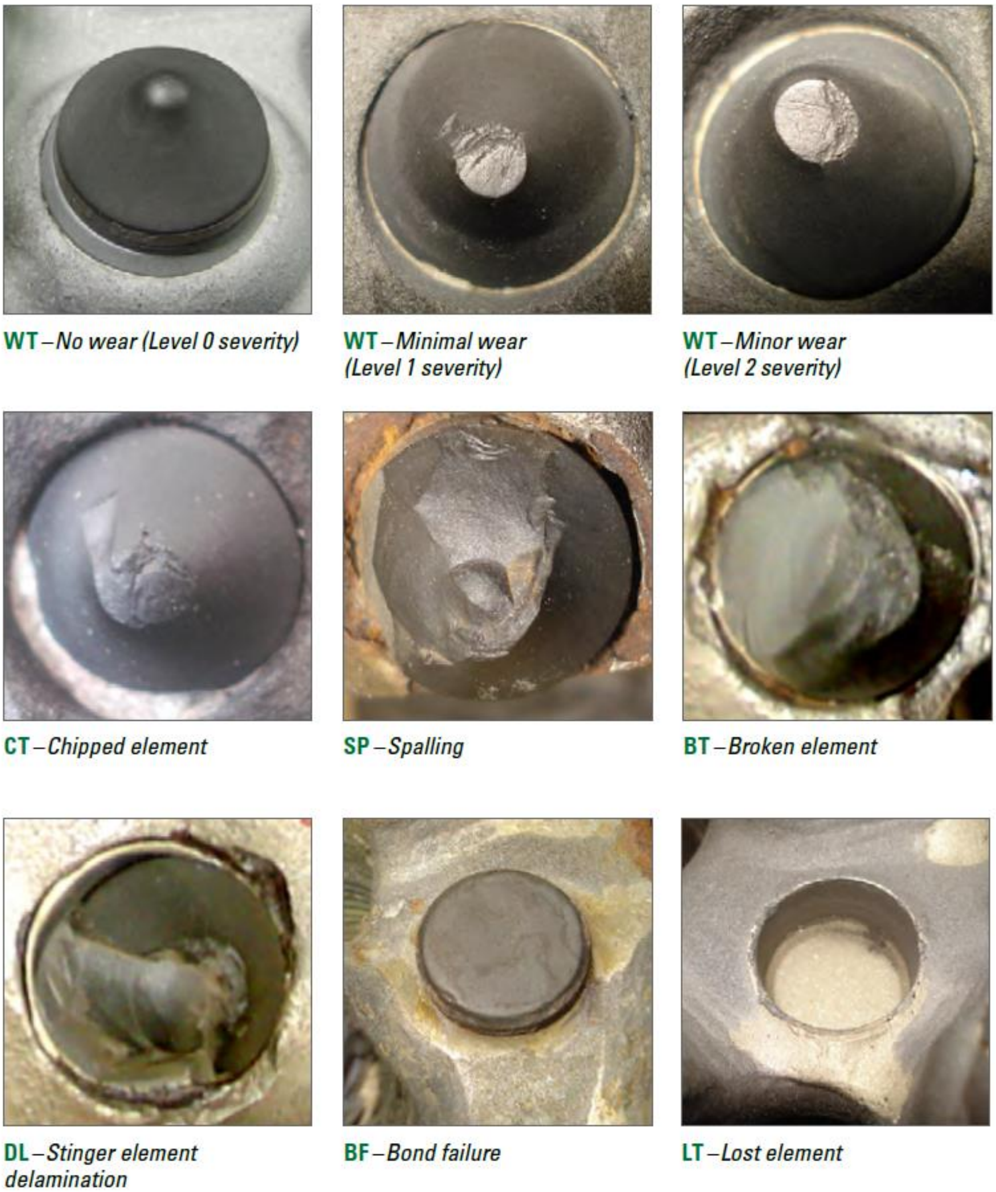


Fig. 1. Typical failure pattern of drill bits (company material)

2 Classification of drilling technologies

Rotary drilling

Rotary drilling is a continuous drilling method based on a rotation bit and suited for most rock types. The inserts on the bit rotate, which leads to slicing and crushing of the rock. The bit contains small nozzles where drilling mud enters the borehole for cooling and lubrication of the bit and cutting transport. Rotary steerable systems (RSS) allow to optimize drilling direction and are needed to perform inclined or horizontal drilling (Fig. 2 - 4).

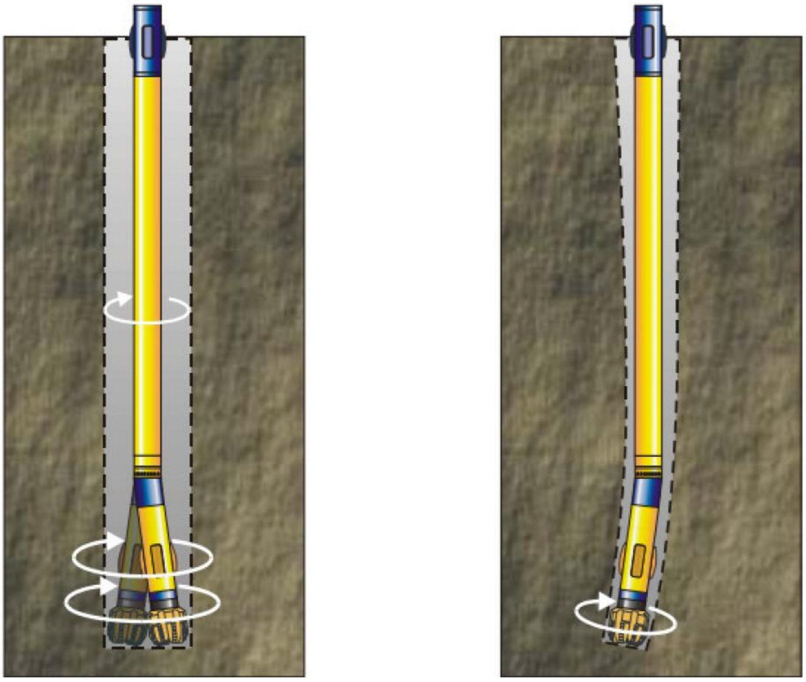


Fig. 2. Principle of rotary steerable systems (company material)

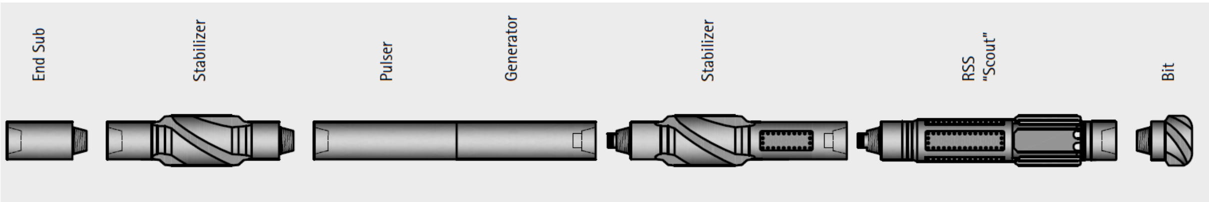


Fig. 3. Principle set-up of RSS (company material)

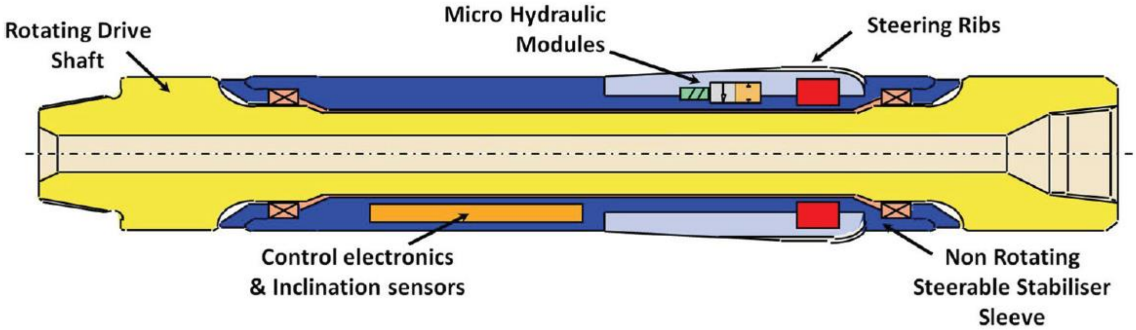


Fig. 4: Sketch of steering mechanism (company material)

Percussive drilling

Percussive drilling is a discontinuous method based on raising and lowering the bit with a high impact force (Fig. 5). Percussive drilling is especially suited for drilling in hard rock formation. The impact energy can be produced either by hydraulic, pneumatic or electrically driven hammers. The hammers can be installed downhole (DTH), at the top (TH) or in the hole (ITH).

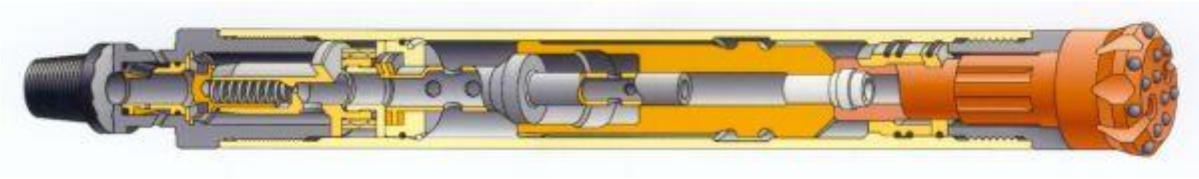


Fig. 5. Drill hammer (company material)

Rotary-Percussive drilling

This technique consists of rotary drilling superimposed by percussive forces.

Cable drilling

This is the oldest drilling technology already applied 5000 years ago in China. It consists of a bit connected to a cable. Repeated lifting and dropping leads to rock destruction at the borehole bottom and creates the drill hole. It is a discontinuous drilling technique with low efficiency.

Jet drilling

Jet drilling is based on high-pressure water jets or abrasive-enhanced water jets like illustrated in Figures 6 and 7. Special nozzles produce directed high-pressure jets. This technique can also be used to perforate casings.

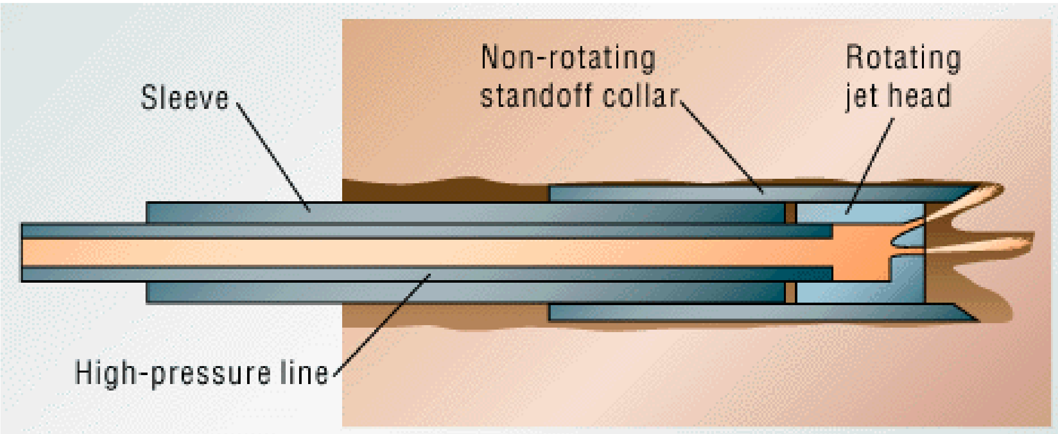


Fig. 6: Water jet drilling (company material)

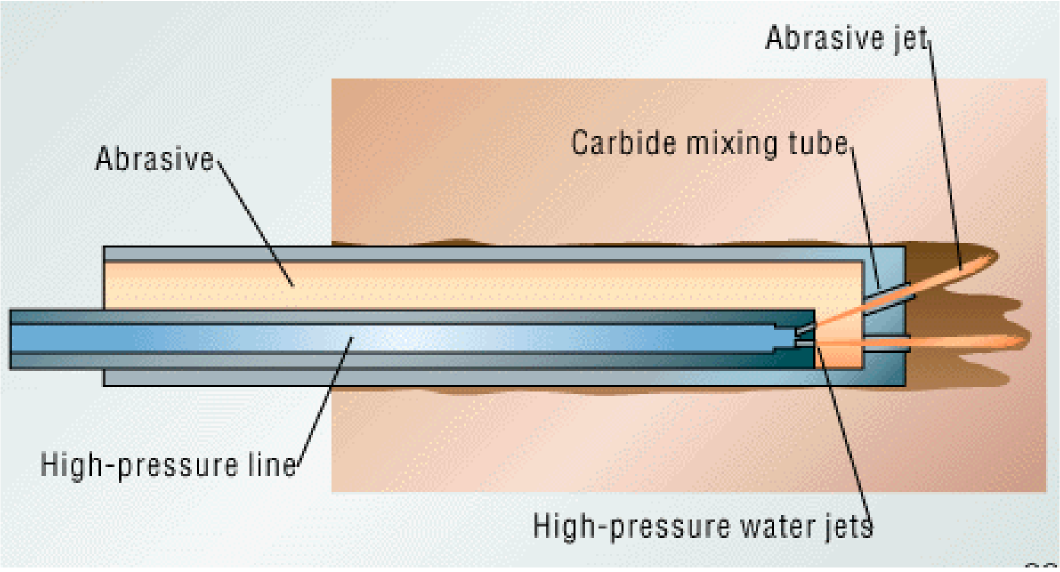


Fig. 7: Abrasive water jet drilling (company material)

Thermal based drilling

There are several thermal based drilling methods (Fig. 8) under development, like:

- Laser drilling,
- Microwave drilling,
- Electric spark drilling,
- Chemical drilling,
- Plasma-bit drilling,
- Hydrothermal spalling drilling.

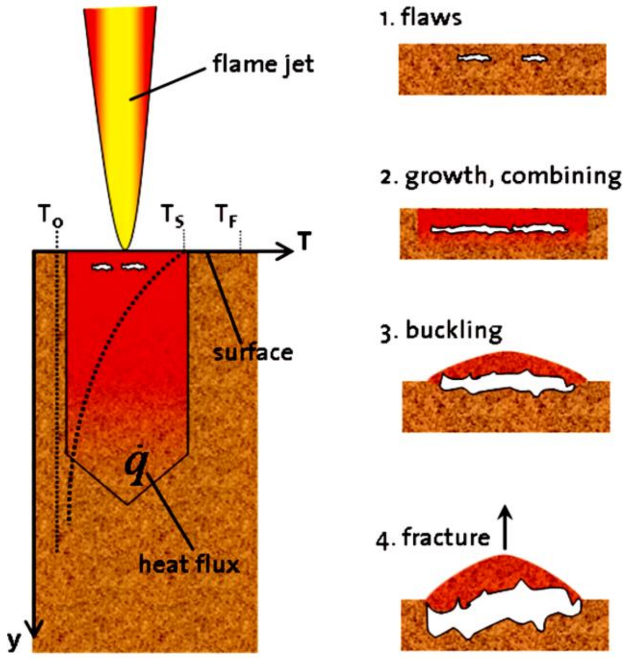


Fig. 8. Principal of hydrothermal spalling drilling (www.transfer.ETH.ch)

Table 2: Typical application range for different classical deep drilling techniques

Depth Interval (m)	Strength Classification	UCS (MPa)	Drilling method
1000-1500	Weak	20-30	Rotary
1500-2000	Medium-Hard	60-80	Rotary/Percussive
2000-3000	Hard	80-120	Percussive

3 Classification of drill bits

For rotary drilling two types of drill bits are used:

- Roller cone bits
  - Milled Tooth (MT)
  - Tungsten Carbide Inserts (TCI)
- Fixed cutter bits
  - Polycrystaline Diamonds Compact (PDC)
  - Impregnated
  - Natural Diomand
  - Bi-Centers

Roller cone bits usually employ three cones to contain the cutting elements. Two main types can be distinguished:

- Steel-tooth bits: have cones that have wedge-shaped teeth milled directly in the cone steel itself. Extremely hard tungsten carbide material is often applied to the surfaces of the teeth by a welding process to improve durability.
- Tungsten carbide insert (TCI) bits have shaped teeth of sintered tungsten carbide press-fit into drilled holes in the cones. Some types of steel-tooth bits also have TCI elements in addition to the milled teeth.

Fixed cutter bits mostly contain polycrystalline diamond cutter (PDC). This is a sintered tungsten carbide cylinder with one flat surface coated with a synthetic diamond material. Other types use natural industrial-grade diamonds or thermal stable polycrystalline diamond (TSP) cutting elements. For hard rocks, where percussive or rotary-percussive drilling is applied, fixed cutter bits are used.

Fig. 9: Typical fixed cutter drill bits for small scale drilling in mining, tunneling etc. (company material)

Fig. 10: Drill bits for core drilling (company material)

Fig. 11: Hybrid drill bit with PDC cutters for large holes and deep drilling (company material)

Fig. 12: Roller cone bits: PDC (left), TCI (middle) and MT (right) tools (company material)

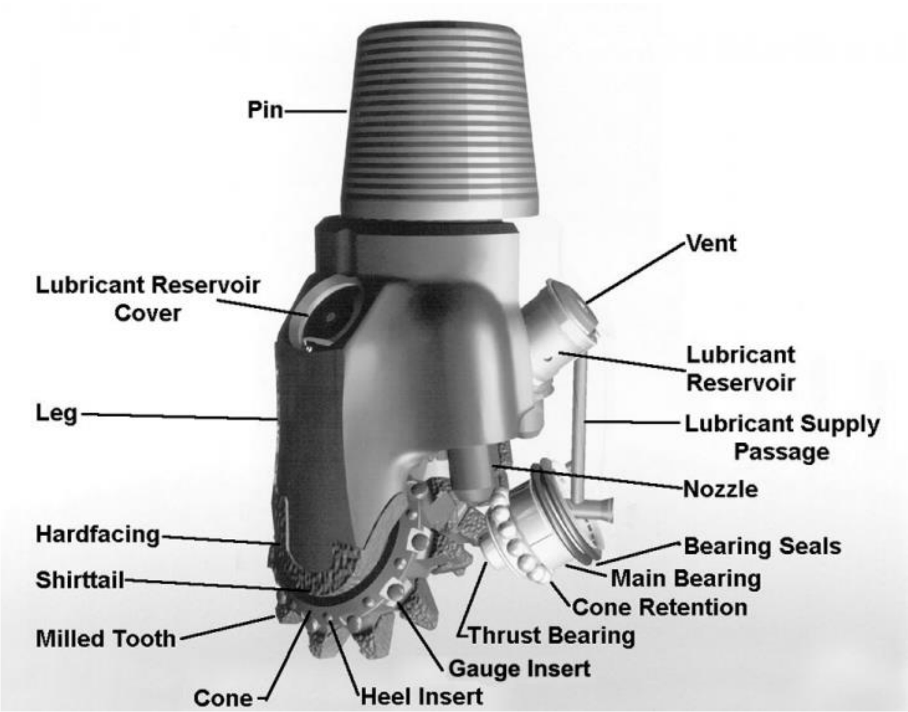


Fig. 13. Principle design of roller cone bits (company material)

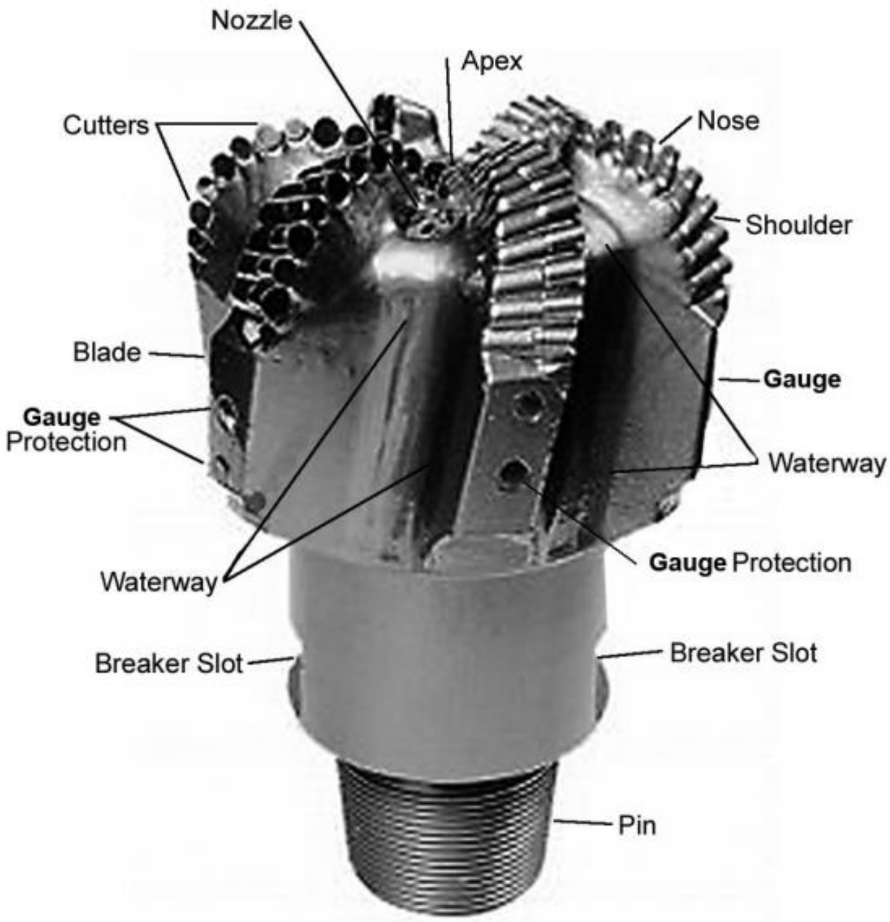


Fig. 14. Principle design of PDC drill bits (company material)

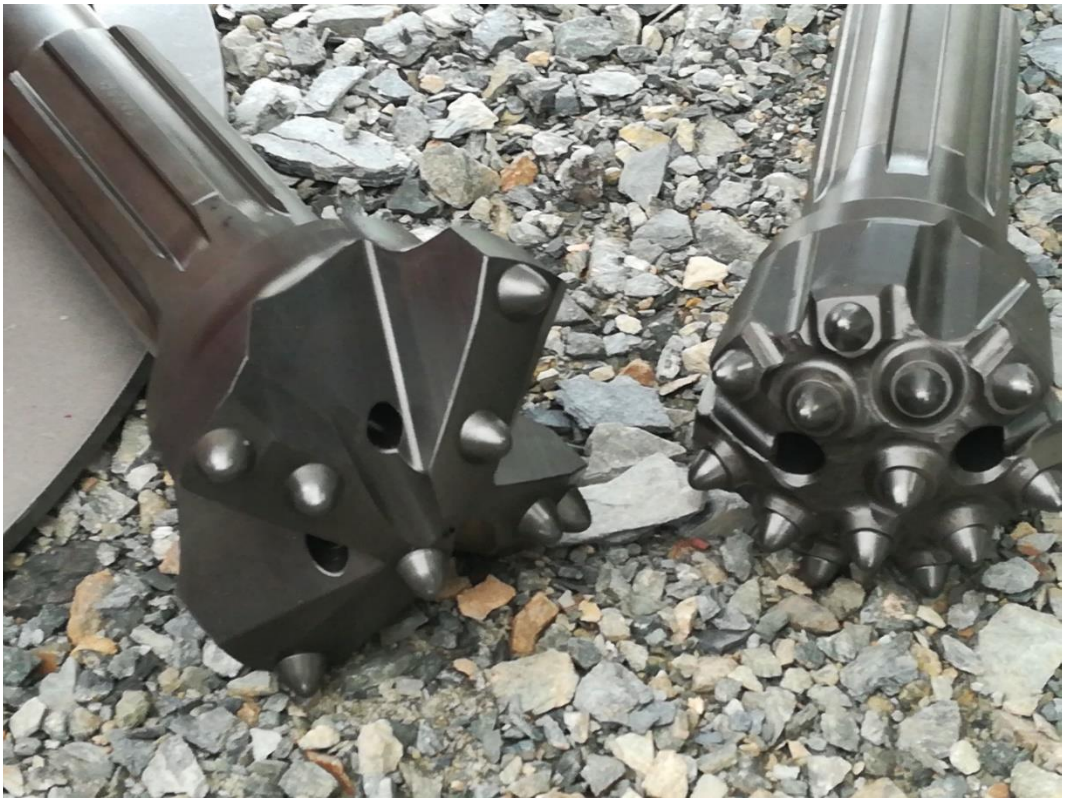


Fig. 15: Drill bits for small scale holes

4 Drilling fluids

Drilling fluids fulfill several tasks:

- Discharge of cuttings
- Cooling
- Reduction of tool abrasion
- Actuation of tools
- Stabilizing of borehole

Potential drilling fluids are:

- Water
- Foam
- Air
- Water-air mixture

5 Drilling parameters

The main control parameters during the drilling process are:

- Contact pressure
- Rotational speed
- Blow count / Blow energy in case of percussion drilling

There is always an optimum in respect to energy consumption and wear on one side and penetration rate on the other side.

6 Drilling rigs

Depending of the purpose drill rigs can be of quite different construction, size and power. Deep drilling rigs are designed for drilling up to depths of several kilometers (Fig. 16). Mobile self-driven rigs are mainly used in civil engineering, for groundwater and for exploration (Fig. 17 and 18), small versions of these are trailer based (Fig. 19). For tunneling and mining special drill jumbos, often with several arms are used (Fig. 20). For small and short boreholes hand-driven drill rigs can be used (Fig. 21 and 22). Special equipped boring machines like shown in Fig. 23 measuring forces, torques and penetration rate are used to evaluate rock, stone or concrete properties (drilling resistance measurement).

Fig. 16: Deep drilling rig (company material)

Fig. 17: Portable drill rigs for small scale holes

Fig. 18: Mobile self-driven drill rigs (company material)

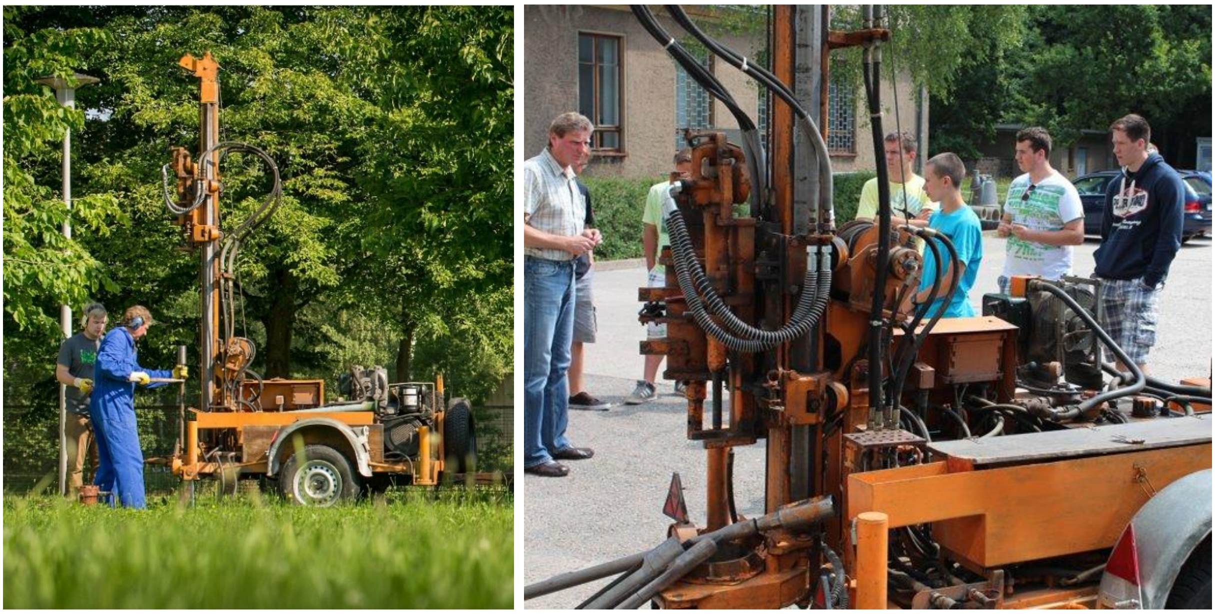


Fig. 19: Mobile trailer drill rig (RML 2016)

Fig. 20: Drill jumbo in operation (company material)

Fig. 21: Hammer-assisted hand drill with core drilling (RML 2016)

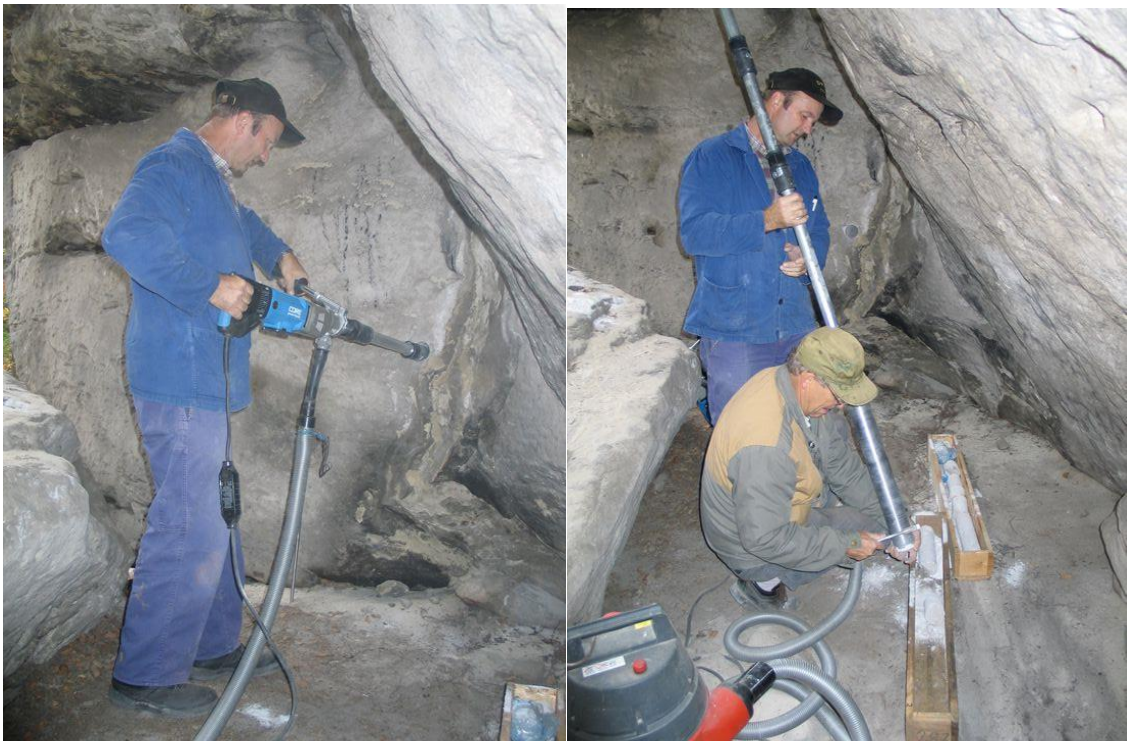


Fig. 22: Hammer-assisted hand drill with core drilling (RML 2016)

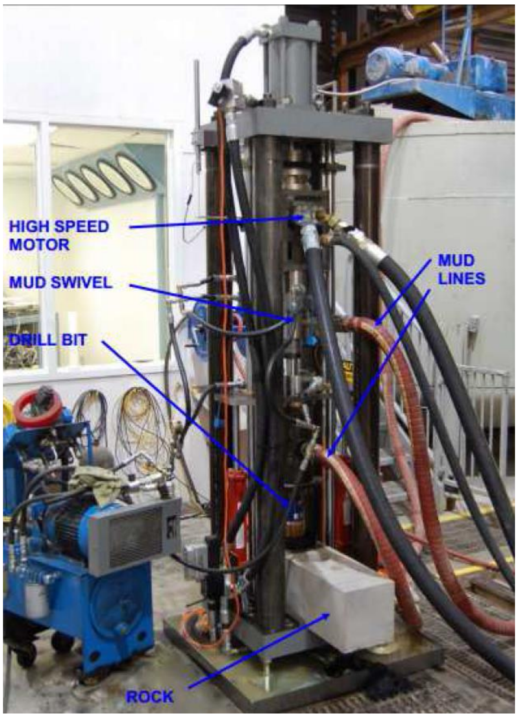
Fig. 23: Drilling resistance measuring device (company material)

7 Lab drilling rigs

Research departments for rock mechanics, petroleum engineering, deep geothermal energy or deep drilling have usually two different types of drill rigs:

- Drill rigs to extract cores (samples) from big rock blocks (Fig. 24),
- Comprehensive drill rigs with sophisticated measuring devices to simulate the drilling process under certain conditions and to test new tools (Fig. 25).

Fig. 24: Lab drill rig to extract cores from rock blocks (RML 2017)



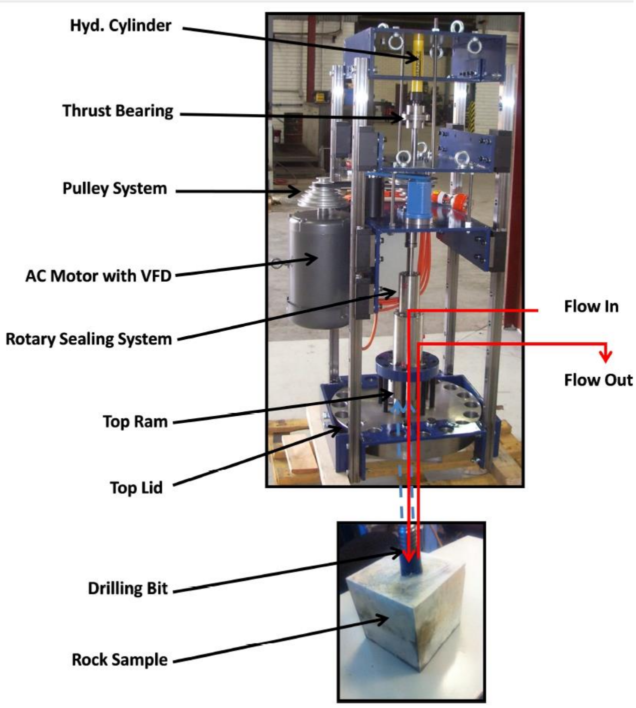


Fig. 25: Lab drill rigs for research (Rasouli & Evans 2013)

8 Principal mechanisms of drilling

Drilling means rock disintegration which implies fracture mechanical processes. Depending on type of drilling massive cursing (domination during percussion drilling) or tensile and shear fracturing (dominating during rotary drilling) occur (Fig. 26).

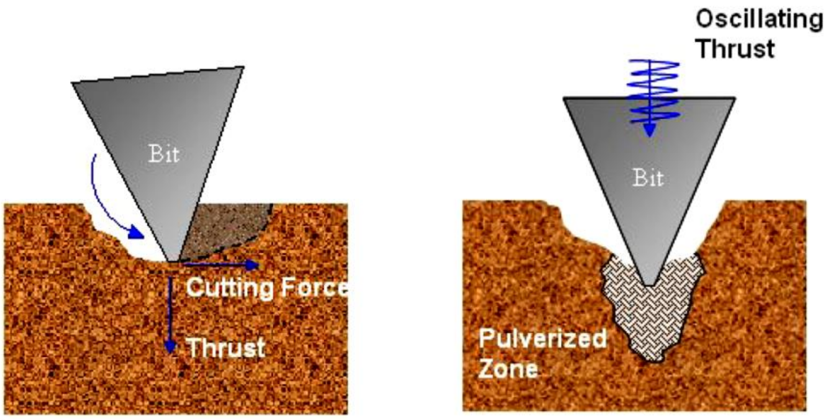
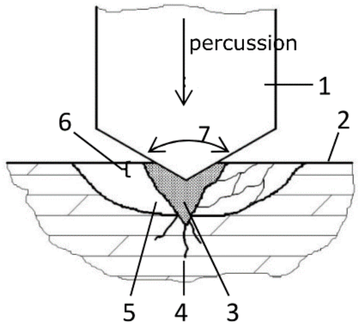


Fig. 26: Principal of rock fragmentation in rotary (left) and percussion (right) drilling (Terralog 2005)

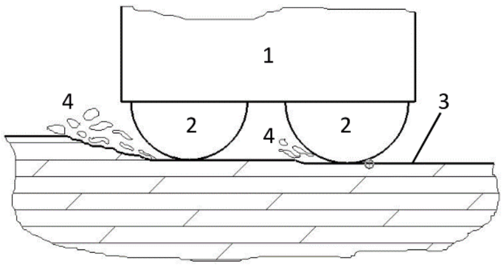
In general, the rock destruction process contains the following 4 elements, which are illustrated below:

(I) Notching:



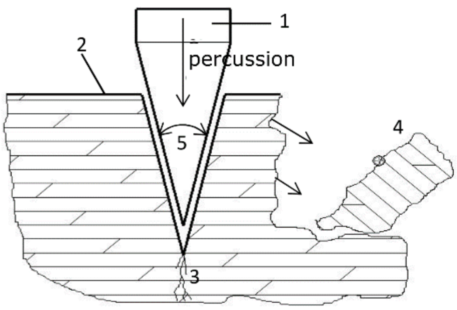
1 - cutting edge
2 - rock surface
3 - cuttings
4 - extension cracks
5 - shearing chip
6 - chip thickness
7 - edge angle

(II) Grinding:



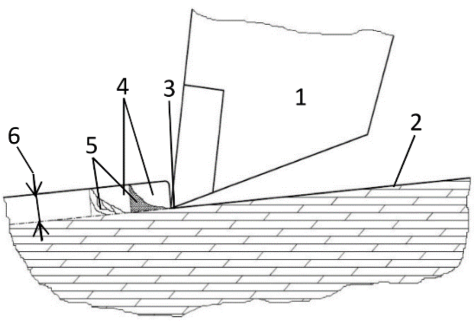
1 - drill matrix
2 - cutting material
3 - borehole bottom
4 - cuttings

(III) Splitting:



1 - splitting tool
2 - rock surface
3 - extension crack
4 - cut-off rock
5 - edge angle

(IV) Cutting:



1 - hard metal cutting edge
2 - borehole bottom
3 - cuttings
4 - shearing chip (large)
5 - shearing chip (small)
6 - chip thickness

9 Numerical simulation of drilling process

The numerical simulation of cutting and drilling processes aims to understand the complex underlying physical processes and is used to optimize cutting and drilling tools and technologies. Because cutting and drilling are disintegration processes, discontinuum based approaches like Distinct Element Methods or Particle Methods are advantageous. Exemplary, the following figures 27-29 illustrate different Distinct element based drilling simulations.

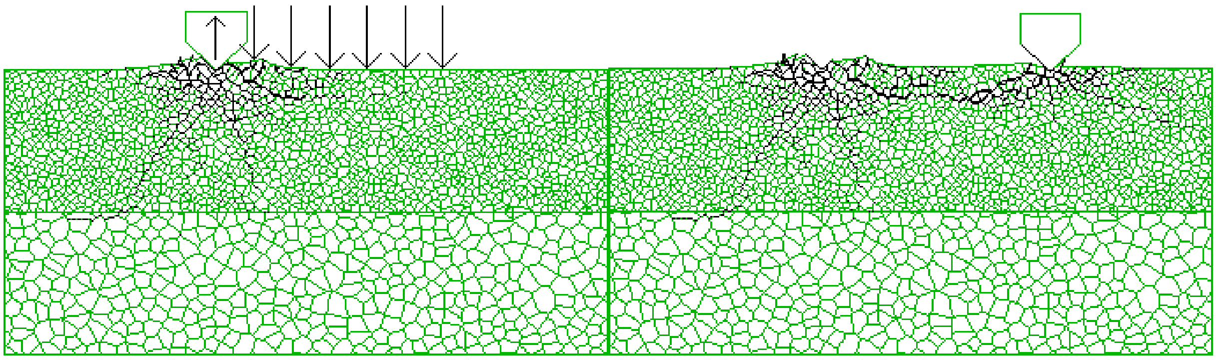


Fig. 27: Simulation of rock fragmentation due to penetration of a single disk cutter (Lunow & Konietzky 2010)

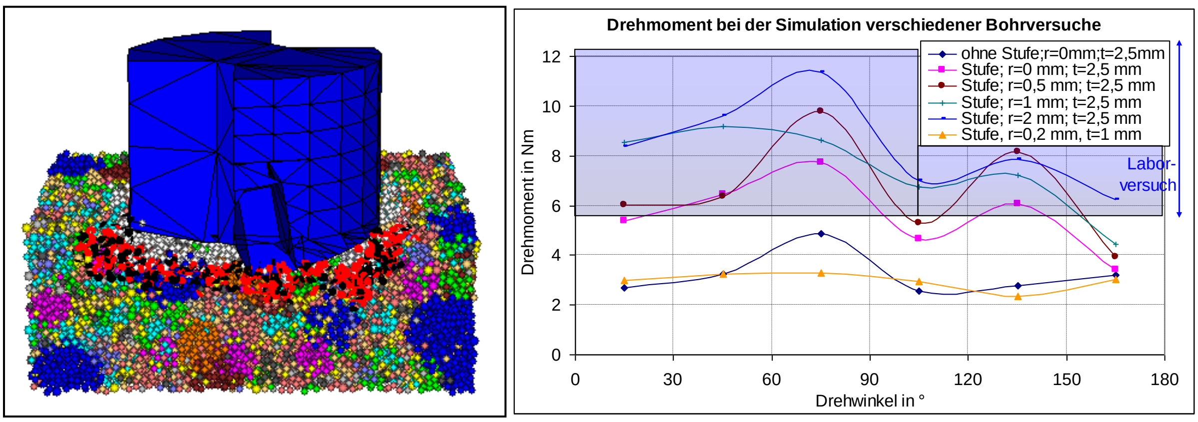


Fig. 28: Simulation of drilling process and comparison with moments measured in the lab (Lunow 2015)

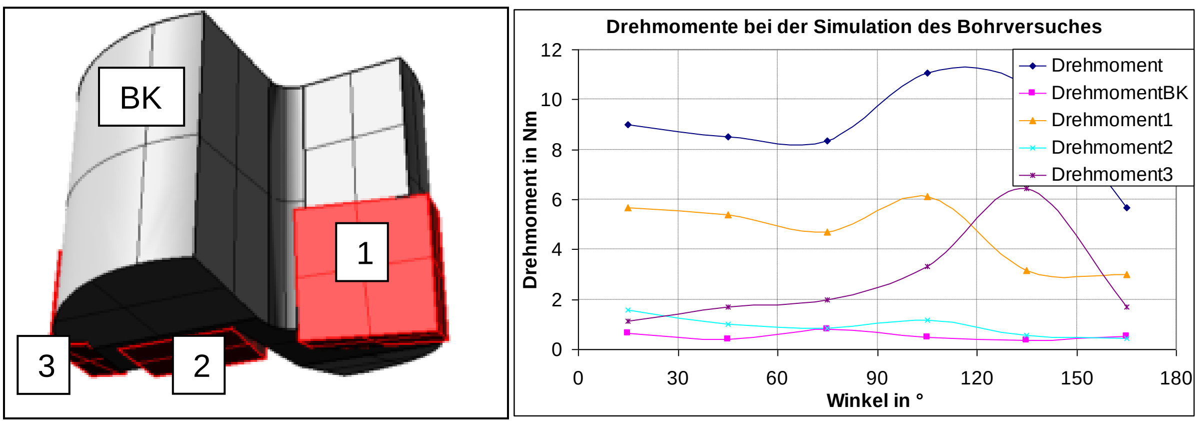


Fig. 29: Drilling head with three inserts and simulated moments acting on these parts (Lunow 2015)

10 New drilling technologies

Especially for deep drilling operations in hard rock the drilling costs are extremely high. Therefore, alternative drilling technologies are under development. At the moment the most promising methods are (Richter, 2019):

- Thermal shock based drilling technique
- Electro Impulse technology (EIT)
- Laser jet drilling
- Hydraulic downhole hammer (percussion drilling)

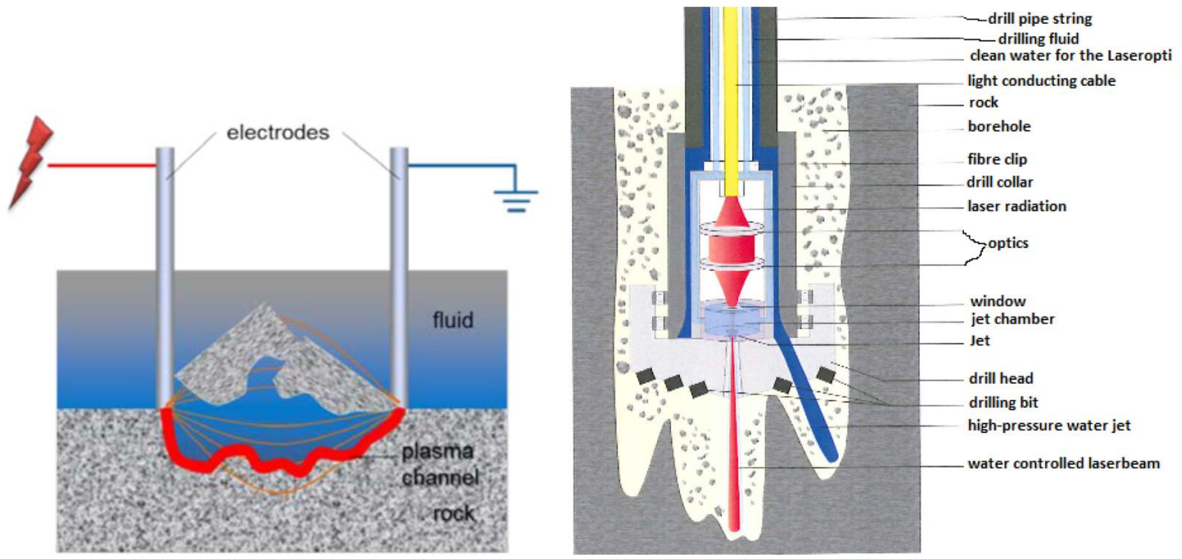


Fig. 30: Scheme of EIT (left) and laser drilling (right) (Richter, 2017)

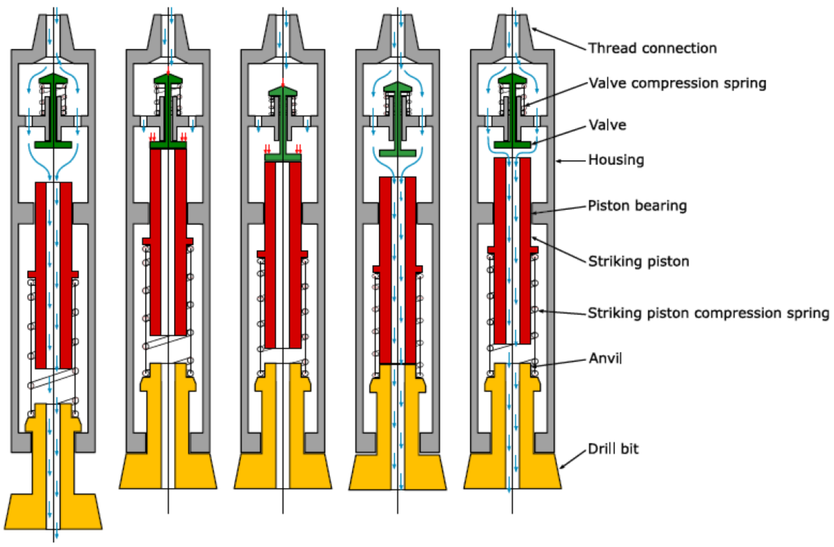


Fig. 31: Scheme of hydraulic downhole hammer (Richter, 2017)

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