WEAR DURING QUARRYING
LITERATURE REVIEW
INGEOKRING
CERTIFICATION - PERMAMENT EDUCATION

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HAUSEN, HEIMBACH, GERMANY; 21 MARCH 2015

(photo: Atlas Copco, 2012)
WEAR DURING QUARRYING

- Quarrying is old as humankind
- Quarrying can be done by any means in any soil or rock
- Time and economics are constraining factors
QUARRYING AS OLD AS HUMANKIND

Roman Quarry, St. Margarethen, Austria
Exploitation started over 2000 years ago with slave labor

Slaves were expensive: they wear, get old, and worse they can die!

Nowadays: opera open-air theatre often performing Verdi’s Nabucco including the “Chorus of the Hebrew Slaves”…… (“Va, pensiero, sull’ali dorate”)

EXCAVATION METHODS

Excavations can be made with any mean in any material !!!

Prisoners made escape tunnels in rock with just using their hands and a “spoon”.

Economics and time determine what method is most viable.
## EXCAVATION METHODS IN QUARRIES

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<td>Hammer &amp; chisel</td>
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<td>Mechanical</td>
<td>Digging &amp; ripping</td>
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<td>Ripper</td>
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<td>Cutting &amp; grinding</td>
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<td></td>
<td>Road header</td>
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<td>Trench cutter</td>
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<td>Hammering</td>
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<td>Jack hammer</td>
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<td>Hydraulic/pneumatic hammer</td>
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<td>Blasting</td>
<td>Drill &amp; blast</td>
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<td>Specials</td>
<td>Wood</td>
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<td>Chemical expansion</td>
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<td>Water (high pressure breaking or jetting)</td>
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<td></td>
<td>Sawing (blade or steel cable)</td>
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<tr>
<td>Very special</td>
<td>Laser, plasma, and millimeter wave techniques</td>
</tr>
<tr>
<td></td>
<td>Nuclear</td>
</tr>
</tbody>
</table>
EXCAVATION & DRILLING MECHANISMS

Drilling & excavation by:
- Spalling
- Fusion and vaporization
- Mechanical stresses
- Chemical

(source: Committee on Advanced Drilling Technologies, 1994)
FIRE SETTING

- heat the stone
- cool rapidly with water
- rock breaks

Wear?

(source: Agricolae, 1556)
HYDRAULIC/PNEUMATIC HAMMER/BREAKER

Deawoo excavator with HK380 (photo: http://www.besthammers.com/)

Wear during quarrying – Hack

Yen Bai, Vietnam (photo: Hack, 2013)
To avoid (excessive) wear of tool and equipment:

- **Reposition** often; the hammer should not be used as “a drilling tool” in the same hole as this produces extreme heat and melting wear of the tool.
- **Breakdown force** on hammer should be sufficient; i.e. hammer should be kept in contact with rock rather than jumping up and down.
- **Correct tool**: use correct size and sharpness; often a blunt tool is better for large blocks as the shockwave is better transmitted.
- **No hammering** in air or so-called “blank” firing; for example, avoid shooting through the rock at the end of a rock block; this causes a (backwards) shockwave in the hammer and excavator.
- **Grease** the tool and bushings frequently or use an automatic greasing system.

(partially from: http://www.pitandquarry.com/tips-and-technologies-for-hydraulic-breaking/)
WEAR OF EXCAVATORS

Backhoe (excavator)

Backhoe (excavator)

Komatsu PC2000-8 Hydraulic Excavator (photo: http://www.komatsuamerica.com/)

http://www.eddiepatin.com/HEO/nsc.html
WEAR OF EXCAVATORS

Excavator bucket – seems something simple but…..

(1) Dual wear plates
(2) Reinforced bucket corners
(3) Large bucket teeth for rock excavation
(4) Dual side shrouds
(5) Cutting edge shrouds


IMPORTANCE OF HARD ALLOY COVERING OF BUCKET PARTS IN LABORATORY TESTS

Note the large decrease in wear with increasing Chrome content.
Note the large decrease in length reduction of teeth with increasing Chrome content.

Wear of steel teeth covered with alloy with varying Chrome content: 33, 23, 6.25, and 2 % Chrome (steel of EN-14B high-tensile steel and treated to obtain hardness 508 HV).

(source: Singla et al., 2014)
WEAR OF RIPPER

A ripper is a bulldozer with a claw-like device on the back with rips the ground (the device is normally equipped with tungsten steel alloy tips)
WEAR OF RIPPER (2)

(source: Van Buren, AR)

Ripper tip:
- No 1: untreated: forged alloy steel with Silicon, Chrome, and Molybdenum
- No 2: coated with sprayed metal II
- No 3: coated with sprayed metal III
- No 4: coated with sprayed metal IV
- No 5: coated with sprayed metal V (but is self sharpening)
- No 6: coated by welded metal

Table 1. Metal properties of ripper tip and the surface coatings

<table>
<thead>
<tr>
<th>Metal No.</th>
<th>Hpa (MPa)</th>
<th>Hgb (MPa)</th>
<th>Hgb (MPa)</th>
<th>Chemical Composition (%)</th>
<th>%</th>
<th>Surface Coating</th>
<th>Tip No.</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>582</td>
<td>4920</td>
<td>69.3</td>
<td>65.4</td>
<td>2.3</td>
<td>1.7</td>
<td>93.5</td>
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<tr>
<td>II</td>
<td>657</td>
<td>6439</td>
<td>58.1</td>
<td>76.8</td>
<td>17.0</td>
<td>0.0</td>
<td>4.0</td>
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<tr>
<td>III</td>
<td>645</td>
<td>6322</td>
<td>57.7</td>
<td>77.6</td>
<td>14.0</td>
<td>0.5</td>
<td>4.5</td>
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<tr>
<td>IV</td>
<td>663</td>
<td>6497</td>
<td>58.0</td>
<td>78.9</td>
<td>16.0</td>
<td>0.0</td>
<td>4.0</td>
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<tr>
<td>V</td>
<td>677</td>
<td>6635</td>
<td>59.2</td>
<td>79.0</td>
<td>11.0</td>
<td>2.5</td>
<td>2.5</td>
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<tr>
<td>VI</td>
<td>880</td>
<td>8624</td>
<td>66.4</td>
<td>93.6</td>
<td>21.0</td>
<td>0</td>
<td>45.5</td>
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<tr>
<td>VII</td>
<td>737</td>
<td>7223</td>
<td>61.7</td>
<td>84.9</td>
<td>33.0</td>
<td>0</td>
<td>62.0</td>
</tr>
</tbody>
</table>

(source: Muro, 1985)

* R : Softening resistance at tempering

Hack Certification Permanent Education - Ingeokring; Association for Engineering Geology
WEAR FEATURES EXCAVATOR & RIPPER

- Under low contact pressure wear only by abrasion
- Under high contact pressure also melting wear
- Wear of tools in dry excavation larger than in wet excavation because cooling of the bit is better
- Coefficient of friction less for high-surface hardness
**Blasthole Drilling Options**

**Tophole hammer**

- **Hole diameter:** 3/8" - 5 1/2" (22-140 mm)
- **Principle:** In the simplest of terms, the tophammer drilling method goes back to manually hitting the end of a drill steel with a sledge hammer. As recoil makes the rod jump back it is rotated to ensure that the hole is round. In a similar way the impact energy of the rock drill piston is transmitted to the drill bit in the form of shock waves. Drill cuttings are removed from the hole bottom by air or water flushing.

(source: Atlas Copco, 2012)

**Downhole hammer**

- **Hole diameter:** 3 3/8" - 9" (90-229 mm)
- **Principle:** The hammer is situated down the hole in direct contact with the drill bit. The hammer piston strikes the drill bit resulting in an efficient transmission of the impact energy and insignificant power losses with the drill depth. The method is widely used for drilling long holes, not only for blasting, but also for water wells, shallow gas and oil wells, and for geo-thermal wells. In mining it is also developed for sampling using the reverse circulation technique (RC drilling).
Downhole hammer

Hole diameter: 4 1/8" - 6 1/2" (125-165 mm)

**Principle:** The hammer is situated down the hole in direct contact with the drill bit similar to the down-the-hole method. The difference compared to DTH drilling is that the RC-hammer collected the exhaust air and the rock chips through an inner centre tube of the hammer and inside the drill string up to the surface where samples can be collected in bags. Flushing of the cuttings is done up through the chuck sleeve.

Rotary

Hole diameter: 4 3/4" - 16" (120-406 mm)

**Principle:** Rotation is provided by a hydraulic or electric motor driven gearbox, called a rotary head that moves up and down the tower via a feed system, generating the pulldown required to give sufficient weight on the bit. Flushing of drill cuttings between the wall of the hole and the drill rods is normally made with compressed air.

Rotary & downhole hammer

Hole diameter: 9 7/8" - 12 1/4" (251-311 mm)

**Principle:** By combining a low impact DTH hammer with the high feed pressure and torque of rotary tricone drilling, a higher level of energy can be provided for rock drilling, than what a DTH hammer or rotary drilling can create alone. The lightweight hammer piston strikes the tricone drill bit resulting in a transmission of the impact energy to the drill bit. The impact energy from the hammer is supporting the spalling and rock cutting process and is increasing the penetration rate.

(source: Atlas Copco, 2012)
WEAR OF BLAST HOLE DRILLING BITS

Rotary blast hole drilling
• Continuous contact with bottom borehole
• Rock breaks by spalling and abrasion

Percussion blast hole drilling (top- & downhole hammer)
• Loose contact with bottom borehole
• Rock breaks by spalling
WEAR OF BLAST HOLE DRILLING BITS

Downhole drill hammer & bit

- Conical thread connection to drill rods
- Hammer array powered by borehole flushing medium (mostly compressed air)
- Hardened inserts
- Bit

(source: Atlas Copco, 2012)
ROTARY VERSUS PERCUSSION

Wear during quarrying — Hack Certification Permanent Education - Ingeokring; Association for Engineering Geology

Harder & stronger

(source: Atlas Copco, 2012)
ROTARY DRILLING

- Rock is broken by spalling (not crushing) due to the inserts
- Harder rock needs less rounds per minute (as inserts need time to stress the rock)

Tungsten-carbide (or another hardened steel) inserts
Abrasive phase
insufficient weight on insert (bit)

Fatigue phase
more weight on insert (bit)

Start of spalling
sufficient weight

Spalling phase
optimum weight

Rotary drilling

Superficial abrasion only
- ineffective
- fine dust only

Deeper abrasion
- ineffective
- much fine dust and some small rock chips

Spalling
- effective
- rock chips

note: shell does not touch rock surface;
if shell touches rock surface: dust & chips cannot be removed by air or water flush

Spalling
- most effective
- larger rock chips

(source: Atlas Copco, 2012)
Worn inserts

Worn and broken inserts

Inserts spall the rock:
- no inserts -> no spalling, and
- thus no progress

(Photos: Atlas Copco, 2012)
WEATHERING, EXPLOSIVES, QUARTZ CONTENT, AND BIT LIFE

Left: Excavation is faster in weaker rock masses, demonstrated by drill rate of blasting holes increasing and explosives consumption decreasing in granite rock masses with higher weathering grades (modified after Thuro & Scholz 2004).

Right: lifetime of drilling bits strongly reduces and thus costs increase with increasing abrasiveness (‘equivalent quartz content’) (modified after Thuro & Plinninger 2003).
PENETRATION RATE & DRILLING COSTS

- Penetration rate drops rapidly near end–of-life of bit
- Drilling bits are only part of Total Drilling Costs (TDC)
- Faster exchange of bit may save money
SAWING

Cutting a rock block with a “saw wire”

Blade saw used in the South Limburg chalk mines


Wear of wire saw cable with diamond-impregnated beads in limestone

Note: number of data is rather limited; relations are not very certain (source: Ozcelik et al., 2004)
VARIATION IN ROCK QUALITY

- Intact rock strength and hardness only part of the story of wear
- Varying weak and strong rock (masses) give impact forces on bits and may result in excessive damage and wear to bits
INHOMOGENEOUS & PARTIALLY HARD GROUND

Insert failure if:

- In inhomogeneous (weak & strong) ground masses, or rock masses with high intact rock strength with open discontinuities or discontinuities filled with weak or loose (soil-type) material.
- Soil-type ground with strong components (> approx. 80 MPa) exceeding diameters of about 2 cm in loose matrix, e.g. gravelly ground, conglomerate, and breccia.
- Penetration rate seriously decreases and breaking of (peripheral) inserts may increase, when holes have to be drilled through metal, either natural (e.g., native copper) or man-made (e.g. pieces of old steel drill rods, old foundations, etc.). (“soft metal” winds around drilling bit; drilling bit does not cut anymore, but abrasion causes temperature increase and possible melting wear).
- Wear and drilling bit damage very much dependent on operator (and quality of equipment).

(partially from among others Plinninger et al., 2002)
Future
NEW DRILLING (& EXCAVATION) TECHNIQUES

Many new (and not so new) drilling & excavation techniques are being developed, some based on proven surface industry techniques:

- Water jet cutting/erosion
- Water jet assisted rotary drilling
- Ultrasonic
- Pulsed electron beam
- Laser
- Electro-pulse (spark and discharge, electric arc)
- Microwave
- Plasma (and induction, forced flame explosive)
- Turbine
- High frequency
- Heating/cooling stress
- Electric current
- Spallation

and

- Nuclear drilling
- Nuclear explosions (not practically used at present)

At present not yet for quarry blast holes; but some techniques may be suitable in the future.

Likely the type of wear as currently occurring in drilling & excavation equipment will be absent, probably replaced by totally different problems....
WATER JET CUTTING/EROSION

- High pressure water stream
- Water may be mixed with abrasive material for more grinding
- Water grinds the rock
- Widely used in (surface) industry as tool for cutting material, e.g. rock, steel, and textile

Advantage:
No wear (in conventional terms); but wear of jet nozzle

Disadvantage:
Thought to be too bulky equipment and too energy consuming to be suitable for drilling holes in rock economically

Water jet cutting of rock (water jet > 400 MPa) (source: http://www.pegasusnw.com/)
WATER JET ASSISTED ROTARY DRILLING

- High pressure water stream
- Water may be mixed with abrasive material for more grinding
- Water grinds the rock

Advantage:
- Reduced wear of drilling bit and inserts

Disadvantage:
- Thought to be too bulky equipment and too energy consuming to be suitable for drilling holes in rock economically
ULTRASONIC

- Ultrasonic and sonic vibrations give drilling action which is transformed into sonic hammering action; impact of the bit on and into the rock performs the drilling
- Drill bit does not require sharpening
- Cryogenic and high temperatures
- Non-round cross section cores
- Used in various rocks including basalt

Advantage:
- ???

(developed for planetary drilling; Mars)

(source: Bao et al., 2006)
**PULSED ELECTRON-BEAM**

Already in the 1970s tests were done to apply “pulsed electron beams” for rock drilling:
- Intense sub-microsecond bursts of energetic electrons
- Pulverize and spall surface of rock
- Debris generally of sand, dust, and small flakes

Advantage:
- Rapid drilling
- No wear (in conventional terms)

Disadvantage:
- Needs vacuum chamber

(source: Schumacher & Holdbrook, 1972)
LASER, ELECTRO-PULSE, MILLIMETER-WAVE, AND PLASMA TECHNIQUES

- Based on creating extreme temperatures that:
  - thermal spall,
  - melt, and/or
  - evaporate
  the ground material.
- Still in testing stage.
- Not yet for blast holes.
LASER

- Laser beam heats the rock; the rock is melted and vaporized.
- Suitable for drilling very small and precise holes
- Widely used in (surface) industry as tool for cutting material, e.g. rock, steel, and textile

Advantage:
No wear (in conventional terms)

Disadvantage:
Thought to be too bulky equipment and too energy consuming to be suitable for drilling holes in rock economically
A shockwave is created by an electrical discharge (sparc due to voltages up to 250,000 Volt) and creates a shockwave.

Voltage rise-time of electro-pulse determines the location of the discharge channel:
- Electro Hydraulic (EHD): the channel (and shockwave) is created in the water
- Plasma Channel (PCD) the shock-wave is created in the rock

Plasma Channel Drilling (PCD)
The electrodes are charged very rapidly to voltages up to 250,000 V. The spark through the rock creates a plasma with very high temperatures and expands rapidly; creating a shockwave.

(source: Höbejögi, 2014)
MILLIMETER-WAVE TECHNIQUES

MICROWAVE DRILL

(source: http://www.scienceinschool.org/sites/default/files/articleContentImages/12/fireballs/issue12fireballs4_large.jpg)
Millimeter-wave drilling

- Waveguide
- Glassy wall
- Exhaust
- Purge gas
- Launched beam

Circular borehole with a metallic waveguide inserted down its center.

A beam of millimeter waves launched from the top travels down through the waveguide and emerges to melt and vaporize the bottom of the borehole.

A purge gas injected through the waveguide solidifies the vapors into nanoparticles and then blows them from the bottom upward along the outside of the waveguide to the surface.

The beam also heats the walls of the borehole, making them glassy ("vitrified") and strong enough to prevent collapse, even under high pressures.

(source: Stauffer, 2012)
MILLIMETER-WAVE TECHNIQUES

Laboratory tests:
A granite specimen with a non-flat surface showing part of the rock ablated away by the 28 GHz gyrotron beam.
(source & photos: Woskov & Michael, 2012)
PLASMA TORCH

(source: http://www.scienceinschool.org/sites/default/files/articleContentImages/12/fireballs/issue1/2fireballs4_large.jpg)
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PLASMABIT

Plasma:
- Water steam heated inside an electrical arc.
- Temperatures > 5,000°C.

Rock fragmentation:
- Thermally processed rock cooled with water in a controlled way.
- Controlled process of fragmentation, 98% of fragments below 1 mm.
- Different physical processes based on rapid cooling of thermally processed rock.

Rock fragments removal:
- Water transport of fragments.

Note: Whether the Plasmabit has actually been used in a real situation is not clear; laboratory test results and plenty of marketing information from the firm "GA Drilling" (http://www.gadrilling.com/technology/).
LASER, MILLIMETER-WAVE, AND PLASMA TECHNIQUES

- High temperature plasma torches used for in-situ vitrifying waste disposal sites (temperatures up to 1,000-2,000°C; waste turns in class or evaporates) (Mayne & Elhakim, 2001).
- Very high temperature plasma torches are planned to be used in ultra-deep boreholes (temperatures 6,000 up to 20,000°C).
- Plasmabit expected suitable for drilling 10 km deep geothermal wells with environment temperatures of up to 400°C and 100 MPa ground pressure (Bucala et al., 2014). (water would be “super critical” and “contain” very large energy).
- High production; probably more than with conventional tools (claimed by Plasmabit vendor; GA Drilling; http://www.gadrilling.com/technology).

No wear?
NUCLEAR DRILLING BIT

“The Subterrene” bit concept:
• Powered by a small nuclear reactor.
• The power from the reactor is fed to a ceramic tip on the drill, which melts the rock ahead of it, and
• then the molten rock is squeezed into the surrounding rock by the thrust of the bit as it keeps moving forward.

No wear ??

Information from secret experiments of the 1960-70s at Los Alamos, USA, which now becomes partially public.


Hole drilled based on design of nuclear subterrene bit (but conventionally powered!)
NUCLEAR TUNNEL BORING MACHINE (TBM) 
“THE SUBTERRENE”

Conceptual design of a partially nuclear TBM (the face is conventionally excavated with cutters; the circumference ("annular") is melted and turned into glass as support)
PEACEFUL NUCLEAR EXPLOSIONS

Trials have been done to use nuclear explosions for excavation:

- In the US surface experiments created large craters but also large nuclear fallout and the idea was abandoned.
- In Russia, multiple nuclear test explosions were done for excavation purposes, for example, test explosions for the Pechora-Kama Canal in 1971 (Nordyke, 1998).

Underground nuclear explosions have been done more often. As far as known this never resulted in useful applications probably due to unknown stability of the holes and radian risk.

No wear ??
NUCLEAR TEST EXPLOSION FOR EXCAVATION

Nuclear test explosion of 3 nuclear devices for the excavation of the Pechora-Kama Canal, Russia.
3 devices; total 45 kt on a row at a depth of 128 m; resulting crater: 700 m long, 540 m wide, and 10-15 m deep; radiation in the crater direct after explosion 1 mR/hr (Evseeva et al., 2005). (Nordyke (1998) reports different sizes and radiation at the tip of 30 µR/hr, only slightly above regional background levels and no increase beyond the limits of throw out from the crater.)

just before the explosion

the start

maximum

≈ 300 m

the resulting excavation with lake

≈ 600 m

(source: http://www.atomcentral.com/)
ENERGY CONSUMPTION

Apart from wear also energy consumption is determining economic operation. Differences between energy consumption per volume excavated are very large.

<table>
<thead>
<tr>
<th>Drilling technique</th>
<th>Approximate energy consumption per volume drilled (Joule/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-pulse</td>
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<tr>
<td>Plasma Channel Drilling (PCD)</td>
<td>100 - 200</td>
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<tr>
<td>Electro Hydraulic Drilling (EHD)</td>
<td>400 - 500</td>
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<tr>
<td>Percussion</td>
<td>200 - 650</td>
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<tr>
<td>Explosive (drilling &amp; blasting)</td>
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<tr>
<td>Percussive</td>
<td>200 - 400</td>
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<tr>
<td>Rotary</td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>600 - 800</td>
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<tr>
<td>Crusher</td>
<td>700 - 950</td>
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<tr>
<td>Hydraulic (water jet)</td>
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<tr>
<td>Laser</td>
<td>1,000 - 2,000</td>
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<tr>
<td></td>
<td>5,000 - 12,000</td>
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</tbody>
</table>

(source: Höbejögi, 2014 and Usov & Potokin, 2014)
CONCLUSIONS

- Wear strongly depends on quantity of abrasive materials
- Wear & damage to bits depends on variation in soil and rock strength
- Wear is the determining economical factor in many projects
- Wear is strongly depending on quality operators
- Wear is strongly depending on quality of equipment
- In the (near) future, wear may become an obsolete problem because of developments in plasma and similar drilling techniques
REFERENCES


