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Title:

HYDRAULIC HAMMER DRILLING TECHNOLOGY: DEVELOPMENTS AND CAPABILITIES

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HYDRAULIC HAMMER DRILLING TECHNOLOGY: DEVELOPMENTS AND CAPABILITIES

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ABSTRACT

Percussion drilling technology was considered many years ago as one of the best approaches for hard rock drilling. Unfortunately the efficiency of most hydraulic hammer (HH) designs was very low (8% maximum), so they were successfully used in shallow boreholes only. Thirty years of research and field drilling experience with HH application in Former Soviet Union (FSU) countries led to the development of a new generation of HH designs with a proven efficiency of 40%. That advance achieved good operational results in hard rock at depths up to 2,000 m and more. The most recent research has shown that there are opportunities to increase HH efficiency up to 70%. This paper presents HH basic design principles and operational features. The advantages of HH technology for coiled-tubing drilling is shown on the basis of test results recently conducted in the USA.

R&D AND FIELD APPLICATION BACKGROUND

General

The application of percussion drilling methods to hard rock results in the following advantages as compared to rotary drilling: (1) the impact loads at the bit inserts in percussion drilling are much higher than the load levels typically achieved in rotary drilling; and (2) the time of total contact of inserts with the rock is substantially less than during rotary drilling. Contact time in percussion drilling is typically 2% of the total operational time. This provides high efficiency rock destruction and decreases the abrasive wear of the drilling tool.

The major feature of the percussion drilling is creation of a crushed zone directly beneath the area of impact. Fractures are initiated which allow shearing processes to remove the cuttings easily and increase the rate of penetration. The most productive method of rock destruction in this respect is percussion-rotary. This method optimizes the amount of impact load in relation to standard rotary drilling compressive and shear loads.

At present, some institutions and companies involved in the drilling business are vigorously considering hydraulic hammers for a variety of purposes, such as: coiled-tubing drilling; exploratory drilling for oil and gas, including extended reach boreholes; geothermal drilling; exploratory drilling for hard minerals; and offshore scientific and geotechnical drilling, coring and sampling of soft, unconsolidated soils and formations at sea and lake bottoms. (OGJ, 1996; PEI, 1996; Gelfgat et al. 1994; JPT, 1984).

FSU Experience

The start of hydro-percussion drilling development in the USSR dates from the late 1940s. The main objective was to increase rates of penetration and drill bit performance both in geological prospecting, or "mining," and slimhole oil field drilling in hard formations. R & D work, including investigation of hydraulic machine operational processes and introduction of percussion drilling to the industry, were implemented in several scientific research institutes and mechanical design bureaus. This work has resulted in a great improvement in the performance of percussion drilling systems (Graf and Kogan, 1972).

The All-Union Scientific Research Institute of Drilling Techniques (VNIIBT) made the major contributions in theoretical and experimental studies of hydraulic percussion tools for oil field application. Several designs of the reverse action type hydraulic hammers, VVO-5A with 130 mm outside diameter and VVO 6-5/8 with 168 mm diameter, were developed and field tested. Field testing of these hammers started in 1960 in Bashkiria, West Ukraine and the Belgorod region. In 1963, testing started in the Perm region as well. During the tests more than 10,000 m of hard formations were drilled as deep as 1,400 m. The rate of penetration in medium hard rock, like limestone, sandstone with siliceous inter-layers, was in the range of 4-10 m/hr. That rate was two to three times more than rotary drilling results in the same conditions. During the field and bench tests the application of percussion-rotary drilling in oil and gas wells using different types of bits (cone, drag and combined), was studied (Kichigin et al., 1965).

The Special Design Bureau (SKB) "Geotechnika" commenced hydraulic hammer development in 1957, and at present, is the only enterprise in Russia continuing R & D work in that area of drilling technology. The hydraulic hammers of direct action, double action, diffuser types, and hydro-vibrators of different types including ones without moving parts, have been developed. More than 70 HH prototypes have been fabricated and tested both in the laboratory and in boreholes. These include tools with outside diameters from 42 to 145 mm. Twenty types went into batch production. During that time the theory, bench test facilities and measuring systems were improving continuously. Experience in design, manufacture and application was gained. The latest designs provided wireline coring techniques, soil investigation, and a core-type hammer for the continuous, reverse-circulation coring system (Kiselev and Krusir, 1982; Melamed, 1993).

The advantages of percussion drilling were confirmed by numerous comparative tests and jobs performed in different geological conditions. In 1988, the percussion-rotary and rotary-percussion methods were used to drill over 3,000,000 m. The latter amounted to 15% of the total drilling for hard mineral deposit exploration by the USSR Ministry of Geology.

Hydraulic percussion hammers were used for the survey of all types of minerals, from coal and iron to mercury, gold, and water, in boreholes with depths down to 2000 m and diameters from 46 up to 220 mm. Penetration rates, as compared to rotary drilling (depending on geological conditions), was increased 30 to 100%; service life of the drill bit improved - 20 to 200%; and deviation of boreholes and their costs were drastically reduced.

ROCK DESTRUCTION BY IMPACT LOADS

Basic Principles

A downhole hydraulic hammer generates an impact load, which is transmitted to the drilling tool (drill bit, crown etc.) through an anvil. The hammer and bit (Fig. 1) form a mechanical system that consists of the jar-peen (sometimes this part of the hammer is named *"hammer"*) and the intermediate bar (anvil) with a length that is significantly greater than its diameter. The latter is attached to the drill bit. Transmission of load from the jar-peen to the drill is analysed by using stress-wave theory for metal bars undergoing collision. This theory applies for flat parallel impact surfaces. In reality, there are no flat impacts, because of misalignment of jar-peen and anvil, as well as other manufacturing tolerances. An applied theory of collision developed by Alexandrov and Sokolinskyi described the bar with spherical ends and is useful in our case. This theory takes into account the observed impact time increase, in addition to the time predicted by the classical wave theory.

It was established that the amplitude of the stress wave created at the top of a bar decreases along the axis according to an exponential law. The decrement of amplitude dampening depends on the number of thread connections between the components and length of the system. The stress wave has a step change at each change in cross-section of jar-peen and anvil. This wave propagates down to the bit through the anvil and other members, and then divides into two waves at the cutter-rock contact point. The first is the main transmitted wave and the second is the reflected wave. Experimental studies show the reflected wave consists of two parts: tensile wave and compressive wave. The first is smoothly transformed to the second. In the case of rigid bottom connection, the stress in the contact point increases until it is double the magnitude of the down-coming wave. Hydro-percussion drilling in hard rocks is relevant to the latter case with double the contact stress, which was proven both by calculations and experiments (Graf and Kogan, 1972; Yasov, 1977).

Rock Destruction Approaches

Impact energy is the major parameter determining percussion drilling efficiency. This was verified by numerous long term studies of rock destruction by static and dynamic loads. Impact energy can be increased with increased jar-peen mass or increased velocity, once a critical impact speed has been exceeded. In practice, the rate of penetration has a linear dependence on the impact energy. Experiments also show that for complete energy transmission to the rock, the length of an anvil has to be equal to or greater than the length of a jar-peen.

Based on the studies implemented and industrial requirements, two hydro-percussion drilling methods were developed: (1) rotary-percussion with relatively high rotary speed and high frequency impacts and (2) percussion-rotary with lower rotary speed and lower frequency, but with higher impact energy (Kiselev and Melamed, 1984).

The first method was useful for coring with diamond crowns. Relatively low impact energy was very productive in some fractured formations. Problems with core recovery caused by jamming were overcome and the rate of penetration was increased. The efficiency of diamond percussion drilling with more than 50-Hz-impact frequency increased with increased rotary speed. A different approach should be used to match the drilling method with solid bits, tungsten carbide crowns (drag bits) or cone bits. For cone bit drilling, the percussion-rotary method provided the highest penetration rate, but the bit bearing design had to be changed. Tungsten carbide crowns were designed for both methods. It has been demonstrated that core can be effectively fragmented by the formation of discs with the application of high frequency impact loads (Melamed, 1995).

It will be shown below that the Geotechnika Hydraulic Hammers (GHH) provide adequate impact loads and frequencies, so the requirements for the two different methods could be achieved.

HYDRAULIC HAMMER DESIGN CONCEPTS AND OPERATION FEATURES

Design Concept and Classification

Hydraulic impact machines are a mechanical, self-sustained, oscillating system with the following features: (1) robust self-excitation; (2) sharply non-harmonic vibrations; and (3) jar-peen as the only energy accumulator.

Hydraulic hammers can be divided into the three groups determined by the method of energy extraction from the working fluid (Yasov, 1977). The types of hammers are specified as follows:

(1) Direct action hydro-hammers (DAHH): Hydraulic-powered impact stroke with spring-powered return. Energy is extracted from the fluid when the jar-peen accelerates down, before it strikes the anvil. Part of the hydraulic energy is used for impact and the other part accumulated in the spring to provide jar-peen return (cock the peen).

(2) Reverse action hydro-hammer (RAHH): A spring drives the hammer impact stroke with a hydraulic powered return stroke. Energy is extracted during the jar-peen reverse stroke and accumulated in the spring, which is then applied to the impact itself.

(3) Double action hydraulic hammers (DBHH): Impact and return strokes are both hydraulically powered.

The hydraulic hammer as a self-sufficient and self-sustained oscillating system can be operated in resonance. That characteristic is usually observed in machines with a spring-loaded valve: (DAHH) and (RAHH). The forces acting at the jar-peen can be divided into regular and irregular (stochastic) forces. The latter includes: (1) jar-peen rebound force, which depends on the bottom hole conditions; (2) drag forces; (3) forces activated by drill string vibrations; and (4) forces induced by the reflecting hydraulic waves coming into the working chamber. Reduction of the number of moving parts reduces the irregularity of jar-peen operation. Simplification of design provides increased operating stability. This approach, applied to the DAHH, has been the main trend of GHH development.

DAHH Operational Concept

A schematic of the DAHH is shown in Figure 2 (Yasov, 1977). The hammer is shown at the moment when the drill bit is set on the borehole bottom. The housing together with the valve is moving down and closes the hole in the jar-peen. That action creates the hydraulic shock, and the pressure inside the chamber above the valve increases rapidly. The pressure below the valve is: (1) the same as that in the annulus, or (2) less than the annulus pressure if a rarefaction is induced by deceleration of the flow stream with valve closure when the jar-peen has not yet started to move down. If the absolute pressure is insufficient, cavitation occurs and results in increased differential pressure. The differential pressure acts against the piston (top of the jar-peen) to accelerate downward the jar-peen, together with the valve. During this movement both valve spring and jar-peen spring are compresses. When the stroke exceeds "Xk", the valve movement is stopped by the top shoulder. This latter event is named "valve cut-off." The previous operational phase is named the "acceleration phase." The jar-peen continues its movement down to strike against the anvil. That distance is "Xb," and the operational phase name is "free jar-peen stroke." During this phase the valve moves to the upper position, as flow balances the pressure on the valve.

During the accelerating phase, the energy extracted from the flow is consumed to accelerate the jar-peen, compress the jar-peen spring, and overcome both mechanical and hydraulic drag forces. The external force stops acting on the jar-peen after "valve cut-off" occurs, and the jar-peen continues moving down by inertia. During this phase the jar-peen compressed. The phase of impact starts at the end of the free jar-peen stroke. At this time the jar-peen kinetic energy is transferred to the anvil and distributed as follows: One part propels the jar-peen rebound and the other drives the drill bit to impact against the rock, with the reflected and transmitted waves originating as explained above.

At the end of the impact the jar-peen starts moving up by the forces of the spring and reflecting wave, which defines the rebound. The jar-peen accelerates upward until it makes contact with the valve piston thus closing the valve. This is the "idle stroke" phase. Drag forces during this phase have to be overcome as well. The speed of the jar-peen and valve interaction determines the time of build up of the hydraulic shock pressure. As the jar-peen has some inertia and the pressure build-up requires some time, so the jar-peen and valve continue to move up together until the forces are balanced. This phase is called the "floating phase." At this time the rarefaction occurs and cavitation bubbles possibly form. Then the cycle repeats.

GHH Operational Features and Parameter Calculations

The hydraulic shock generates the pressure wave with specific shape, amplitude and duration. The wave propagates up the inside of the drill string with dissipation and reflection at each point where the cross-section area or slope varies (at each joint, for example), to the mud pumps, valves and pulsation dampeners. During percussion drilling in shallow boreholes without a dampener, wave interaction with the mud pump can cause damage to the pump. A hydraulic wave reflector can eliminate substantial dissipation of wave energy. The reflector has the added advantage that the hydraulic energy reflected back toward the drill bit (and away from the string and mud pumps), may increase the efficiency of the rock destruction produced by the hammer (Yasov, 1977; Kiselev and Melamed, 1984). Elastic and hard reflectors were developed as shown in Figures 3 and 4 respectively. The use of hard reflectors doubles the machine efficiency from 8-10% to 16-18%, with a twofold reduction of flow rate. Similar results were obtained for elastic reflectors.

These designs had definite drawbacks and did not solve the basic problem of increasing the efficiency of percussion drilling. SKB "Geotechnika" developed a new design for the reflector, which was based on long-term studies at special test facilities. This reflector provides significant reduction of the mud flow required for rock destruction, and the machine efficiency increased 40% (Melamed, 1993).

Cavitation is the other element that has to be considered when developing hydraulic hammers. The jar-peen acceleration increases when cavitation occurs, but with increase of the borehole depth and hydrostatic pressure, the enhancement of the acceleration stroke is diminished and eventually eliminated. In this case, the premature valve cut-off results in a short stroke, non-impact operating cycle. There are two ways to solve the problem. The first, is to eliminate the conditions for the cavitation. The second, is to control the duration of cavitation by adjusting parameters of the hammer. The present GHH design eliminates cavitation. Some preliminary experimental data supports the possibility of controlling cavitation.

With all the above considerations, and accounting for the drag forces in the valve motion, performance of GHH designs was modeled. For each case, a model is developed with a system of differential equations. The solutions are derived for each of the operational phases described above.

The current GHH designs are tailored to operate in both percussion-rotary and rotary-percussion modes of drilling. GHH designs are easily adjusted to operated in resonance, and have 25-40% efficiencies in borehole operations. Recent experimental studies have shown the opportunity for a significant increase in power for the GHH, and efficiency should approach 70%.

Drill Bits for Hydro-percussion Drilling

Several types of rock destruction tools have been developed in conjunction with percussion drilling. First there were solid bits and drag type bits, with tungsten carbide cutting structures. In these tools, both bits and crowns are used, mainly for percussion-rotary drilling at relatively shallow depths in medium and medium-hard rock. Impregnated and surface-set diamond bits and crowns (core drilling bits) were developed as well. These bits are best suited to the rotary-percussion method in deep mining boreholes with hard, abrasive, fractured formations. The cone-type bit was the main subject of studies for percussion drilling.

During the percussion-drilling system development for oil and gas field application, VNIIBT did some special studies of three-cone bit performance. The experiments were conducted with a 6-in-diameter, milled-tooth bit while drilling blocks of granite and Vuselemovsky Limestone. Rotary drilling tests were conducted to compare with the percussion drilling results. Some major trends were observed:

(1) Rate of penetration varied linearly with the impact power.

(2) Above the minimum threshold WOB, a lower WOB resulted in a higher percussion drilling rate. For example, in the rotary-percussion mode of drilling ROP of 3.3 m/hr was achieved with the 8-3/4-in. bit when the WOB was 4.5 tonne. To achieve the same ROP in rotary mode required 18.5 tonne.

During the field tests in Bashkiria in hard limestone and dolomites, it was found that the effect of WOB is less important for percussion drilling (Kichigin et al., 1965).

SKB "Geotechnika" developed a range of three- and two-cone bits for rotary and rotary-percussion drilling for 46-, 59-76-, 112- and 132-mm-diameter boreholes in hard and super hard abrasive formations. In the early 1980s, R & D projects were conducted on the bearing assemblies. Several designs of the sleeve bearings for the small diameter cone bits were tested. The main problem with sleeve bearing is to develop a lock mechanism to prevent loss of the cones in the hole. Five batches of 76 mm bits were prepared with five types of lock units. The tests were conducted in granite blocks. The segment lock was found to be the best one in terms of bit life. This type of bit was field tested in the Krasnoyarsk city region at 300-450 m depth in granite with quartzite layers. Average penetration per bit was 11.8 m at an average ROP of 1.15 m/hr. Some additional modifications in bearing lock design (Fig. 5) and drill tests were performed before these bits (III76K-TsA) were introduced for percussion-rotary drilling with GHH G-76U hammer. Tests achieved 17.8 m per bit (80% more than standard), and 2.7 m/hr ROP (34% more than standard) when drilling very hard, fractured basalt. The important point was that the magnitude of drilling parameters, WOB and flow rate in percussion-rotary, were 40-50% less than for rotary drilling (Smirnov, 1983). The results of this R & D work have been applied to other bit sizes (i.e., 46 and 59 mm).

SKB "Geotechnika" completed the development of III59K-TsA and III46K-TsA bits in 1987 (Fig. 6). Both bit sizes have never been manufactured outside of Russia. The 46 mm cone is the only commercial bit this size in the world. Field tests in hard and super-hard abrasive granites included more than 800 m with 59 mm bits, and 350 m with 46 mm bits. The average penetration per bit was: 12-21 m with 4-5 m/hr ROP for 59 mm and 7-8 m with 1.5-2.3 m/hr for 46 mm bits respectively. These tests were for the rotary mode of drilling only (Bodrov et el., 1991).

TESTING OF EXISTING GHH PROTOTYPE TOOLS

General Concept

To obtain additional information for better evaluation of the proposed microborehole coiled-tubing percussion drilling system components, the following prototypes were recommended for lab testing at the Maurer Engineering Inc. Drilling Research Center (MEI DRC) in Houston.

(1) GHH G-59U(V)O type, 1996 design model: Housing diameter 54 mm, single impact energy exceeding 12 J and frequency range 40-80 Hz.

(2) Three-cone bit, III 59K-TsA type.

(3) Two-cone bit, II 59TK-TsA.

(4) Diamond impregnated bit, 59-mm diameter.

Testing included a series of 1-3-ft boreholes drilled with various assemblies in blocks of granite and marble rocks. Both rotary and percussion-rotary methods would be used over a range of WOB, RPM and flow rates.

The main objectives of the test program were:

(1) Demonstrate rock bit suitability for horizontal coiled-tubing drilling in hard rocks.

(2) Evaluate GHH tool efficiency for horizontal coiled-tubing drilling in hard rocks.

(3). Determine the influence of the percussion drilling parameters on the ROP.

SKB "Geotechnika" prepared a standard G-59U(V)O hammer assembled from components manufactured at the SKB factory in 1994 (Fig. 7). Table 1 shows standard hammers available (Oper. Manuals..., 1988). The smallest hammer was selected for testing, disassembled, checked, adjusted for the expected drilling conditions, and re-assembled. Bench tests at the SKB facilities were performed to check the hammer operating parameters. The assembled tools, the hammer, the reflector and a set of spare parts, were delivered to the DRC. Cone-type drill bits as specified, and a surface-set type diamond bit, were purchased from stock in Russia. The 59-mm impregnated bit was not available from stock, so the surface-set bit (designed for hard formation drilling) was substituted.

For rotary drilling a standard DRC test stand was used. MEI modified a stand for percussion-rotary drilling. The stand was able to record flow rate, pressure, displacement, WOB and ROP. The hydraulic motor used for assembly rotation provided only 150 rpm. The torque was not measured directly, but was estimated by recording the oil pressure at the hydraulic motor. To determine the impact frequency, an accelerometer was installed at the input hydraulic line. An oscilloscope and plotter were used for data processing. The rock blocks were about 35-in. long, so each borehole was 32-33-in.-long, and two or three tests were conducted as each borehole was drilled.

Percussion-Rotary Drilling Testing Performance

Eight boreholes were drilled, but each bore included from two to four tests, where WOB or flow rate were varied. The data are presented in Table 2. Results of each test were presented on three charts. Figure 8 shows the plots for test 527. The measured frequency was 46-74 Hz. The pressure drop was used as the controlled parameter along with the flow rate and the WOB magnitude, which was specified for each test.

The cone bits showed considerable bearing wear during these tests. Some axial play of the cones was clearly observed, and three inserts of the two-cone bit were lost. Nevertheless, that failure did not prevent additional testing.

The hammer start-up was very smooth in each test, but sometimes it was difficult to determine if the best operating conditions were achieved. The reasons for that were: (1) difficulty in setting the desired flow rate with the test stand pumps and control system and (2) the absence of an on-line frequency measurement system. The last series of tests, 527, were performed with a ramping of the pressure drop in an attempt to find the best operating parameters for those conditions. The influence of the flow-rate/pressure-drop increase on the ROP was demonstrated.

Conclusions from the Test Results

(1) The G-59U(V)O type hydraulic hammer results confirmed the expected performance advantages of percussion-rotary drilling in hard rock.

(2) For the coiled-tubing drilling (CTD) application, an efficient method of rotation needs to be developed. The simplest way might be to adapt the existing low-speed PDM for that purpose and conduct additional tests. The power required for the assembly rotation was roughly evaluated on the basis of the hydraulic motor performance data. A 1.6 kW PDM should be sufficient for CTD drilling with GHH assembly.

(3) The modified test stand provided 150 rpm maximum assembly rotation. It is well known from field drilling and laboratory testing experience that ROP is linearly dependent on the rotary speed for rotary drilling. For percussion-rotary drilling this dependency is supposed to be linear as well.

(4) ROP increased noticeably, with increased WOB from zero to 1,500-2,000 lb. Further increases in WOB to 3,000 lb showed different results: in marble 100% improvement, and granite 15% improvement.

(5) The GHH must be operated at the proper flow rate, pressure drop, and frequency; these are more important for this drilling method than appropriate WOB.

(6) The direct comparison of ROP at the equivalent drilling parameters can be made on the basis of test 527A and the rotary drilling test at the same conditions: 150 rpm and 1500 lb. WOB. The percussion-rotary method shows a 7.3 times higher ROP than rotary. At the best operational conditions for both methods percussion-rotary still has a 2.3 times advantage in ROP over the rotary method.

(7) The major advantage of percussion drilling for CTD application is the possibility of achieving good performance under low thrust conditions.

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Table 1 Geotechnika Hydraulic Hammers specifications

Parameters	G 59 V G 59U(V)O	G 76 V G 76 VO	G 76 U G 76 UO	G 112/300U G 112/200U*	G 134U(V)O	G 151/600U G 151/350U*
Diameter, mm: Borehole/ housing	59/57	76-93/70	76-93/70	132-151/108	151-190/134	190-240/146
Flow rate, l/min (gpm)	60-80 (16-21) 20-40 (5.3-11)	80-120 (21-32) 40-50 (11-13)	180-200 (48-53) 70-90 (18-24)	300 (79) 200 (53)	60-200 (16-53)	600 (158) 350 (92)
Pressure drop, bar (psi)	15-17 (210-240) 25-42 (350-600)	14-18 (200-260) 25-35 (350-500)	16-22 (230-310) 30-40 (420-570)	20 (280) 30 (420)	20-60(280-850)	15 (210) 25 (350)
Single impact energy, J	4.5-6.5 5.5-12	8-12 10-17	22-30 30-45	60	30-200	100
Impact frequency, Hz	30-40 40-80	30-45 50-55	20-22 30-40	15	15-50	15
Length, mm	1635 2820	1845 2985	1955 3095	2010	3590	2520
Mass, kg	23 45	39 74	39 74	95	305	230

V - for rotary-percussion drilling; with fluid flow reduction unit ; U - for percussion rotary drilling; O - with hydrodynamic wave reflector

Table 2 General Results of the Percussion-Rotary Drilling Tests at MEI DRC

Test No.	Rock type	Bit size and type	RPM	Flow rate, gpm	Pressure, psi	WOB, lbs	Average ROP, ft/hr
521A	Marble	59 mm, 2-cone	150	8-11	450-540	2200	16
521B	Marble	59 mm, 2-cone	150	8-10	580-600	3000	15
522A	Marble	59 mm, 3-cone	150	9-16	430-450	500	4.5-5
522B	Marble	59 mm, 3-cone	150	9-18	430-480	1300	9
522C	Marble	59 mm, 3-cone	150	8-13	320-360	2200	8
522D	Maryble	59 mm, 3-cone	150	7-8	500-550	3000	17
523A	Granite	59-mm, 3-cone	150	7-9	580-640	1300	7
523B	Granite	59-mm, 3-cone	150	9-14	320-370	2200	8.5
523C	Granite	59-mm, 3-cone	150	7-9	370-470	3000	8.5
523D	Granite	59-mm, 3-cone	150	7-8	490-530	2200	11
524A	Granite	59-mm diamond	150	7-8	460-500	1300	4.5
524B	Granite	59-mm diamond	150	7-8	590-600	2200	5.5
524C	Granite	59-mm diamond	150	7-8	500-560	3000	5.5
527A	Granite	59-mm, 3-cone	150	10-11	650-700	1500	11
527B	Granite	59-mm, 3-cone	150	12-14	890-980	3000	15
527C	Granite	59-mm, 3-cone	150	10-12	650-670	3000	12

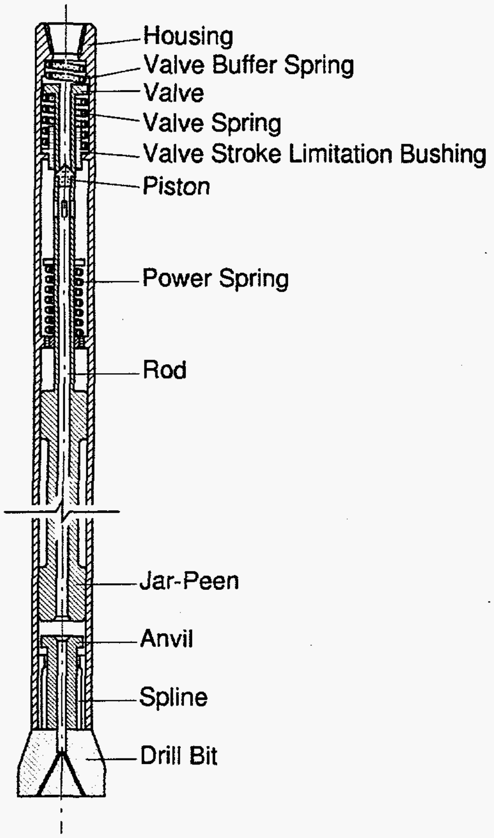

Figure 1. The hydraulic machine of Bassinger, USA, 1948-1957 (Graf and Kogan, 1972).

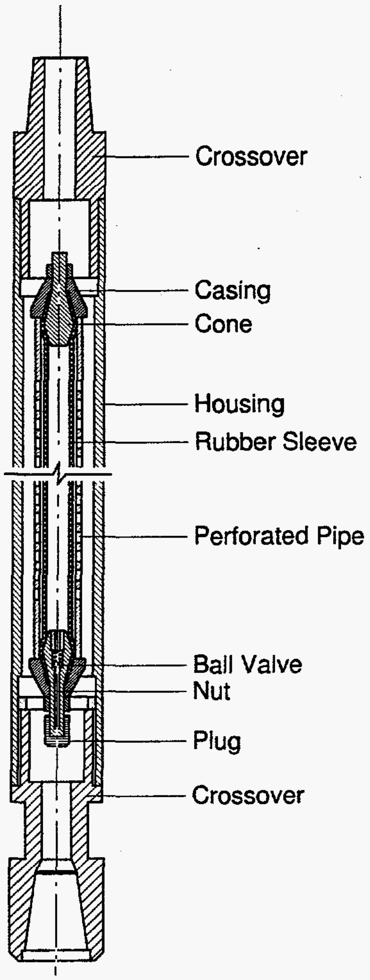

Figure 3. The submerged pneumatic elastic reflector PPO-70, GI, Ukraine (Yasov, 1977).

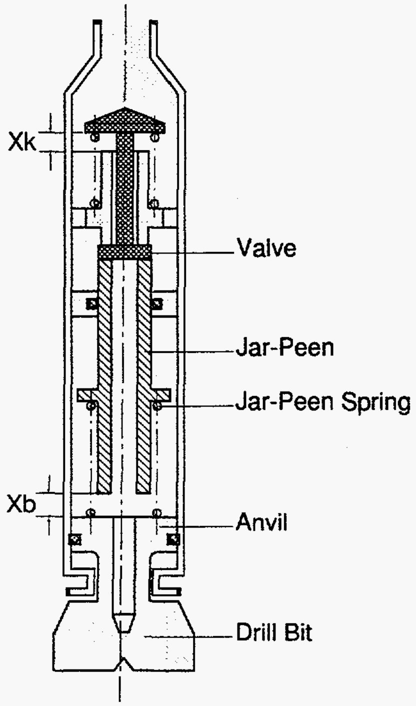

Figure 2. The direct action hydraulic hammer, general scheme (Yasov, 1977).

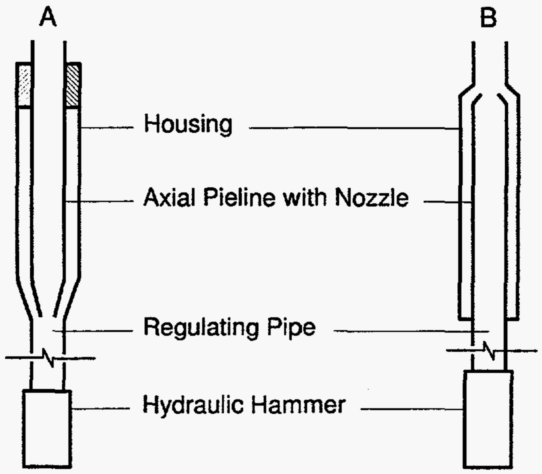

Figure 4. Hydraulic wave hard reflector, SKB Geotechnika, 1984.

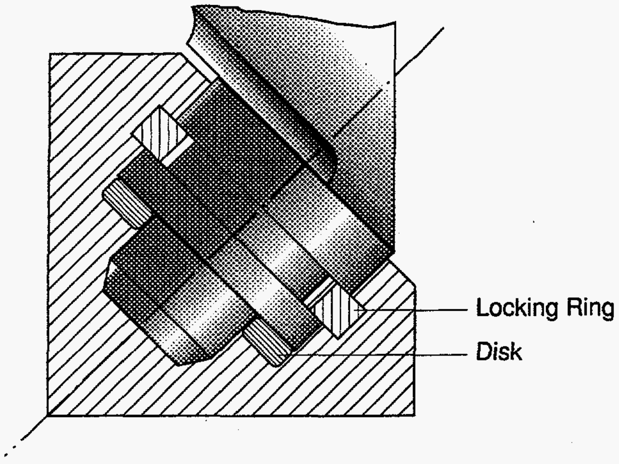

Figure 5. Drill bit bearing design scheme (Smirnov, 1983).

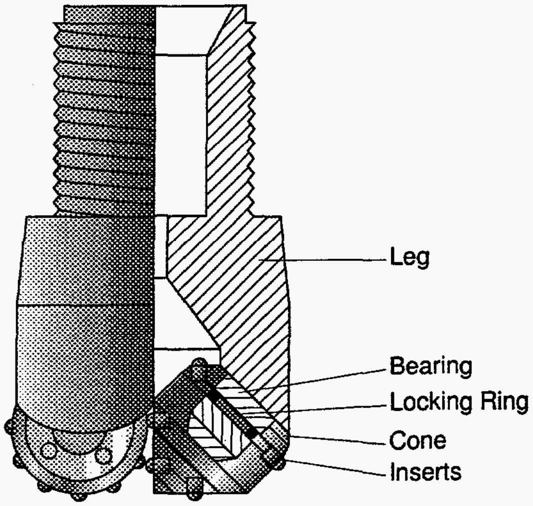

Figure 6. Three-cone 59 and 46 mm diameter drill bit, general scheme (Bodrov, et al., 1991)

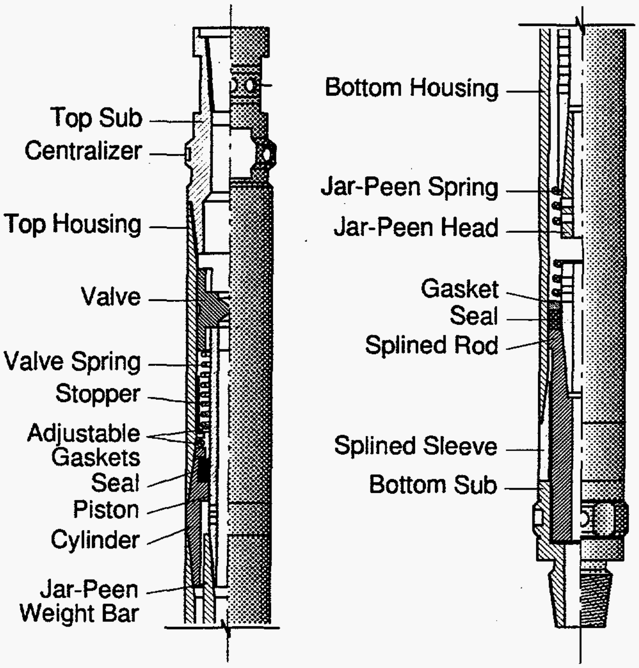

Figure 7. Unified hydraulic hammer, SKB Geotechnika (Operating Manuals, 1988).

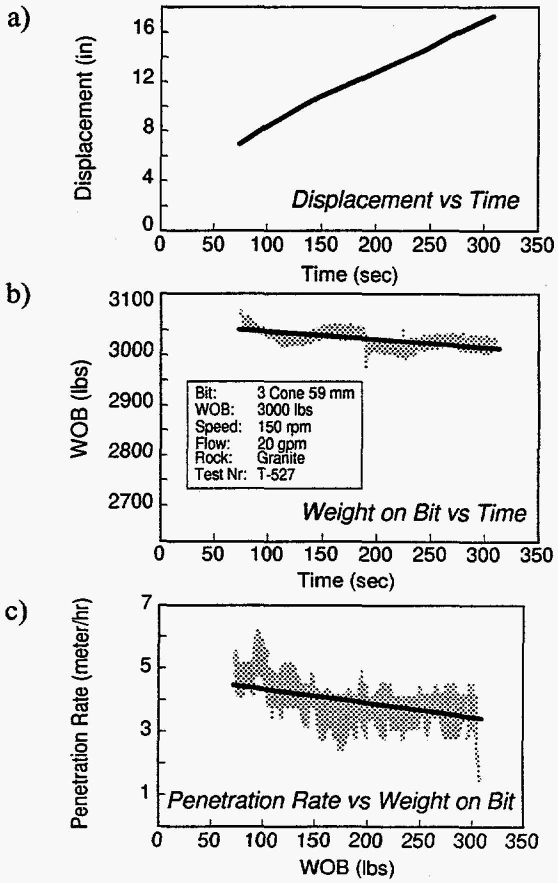

Figure 8. Plots with percussion-rotary test results at the MEI DRC.