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By Petar Bodurov & Vasil Genchev

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IS IT TIME FOR A ROCKET ENGINE FOR PILE DRIVING HAMMERS?

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Is it Time for a Rocket Engine for Pile Driving Hammers?

Petar Bodurov [α] & Vasil Genchev [σ]

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I. Introduction

An important stage in humankind's history is transition to living in pile dwelling. So, about 8 000 years ago, the driving of wooden piles began. The technology included use of an elementary device made of wooden beams upon which a wooden or stone weight was lifted by means of ropes and periodicaly released to drop onto the driven pile. This technology passed without any change through Ancient Egypt, Greece and Rome as well as through the whole Middle Ages. On Figure 1 we see a picture of a 16th Century Dutch painter(History of pile driving) showing a group of men pulling ropes in order to lift and drop a driving weight. In this way the piles of the foundations of Venice, Antwerp, Petersburg and other cities were driven into the soil.

Figure 1 : Driving a pile. Picture by Jan Luyken (1649-1712)

II. Mechanically Powered Pile Driving Hammers

In 1841, the Scottish inventor James Nasmyth built the first steam hammer, raising its ram in the upper position by means of a piston activated by steam in a cylinder. But this was a blacksmith hammer with a falling impact body used for forging metal things. Then, in a consistent manner, he built a steam-powered compactor applied to smooth road surfaces and then, in 1843, a steam-driven hammer for pile driving. We suppose that it was the lack of auto cranes for raising hammer on piles that is the reason why this device did not come into use. Some episodic efforts for using a steam hammer for pile driving were being made in the next years, for example during the construction of railways in USA, but not until 1883 the German company MENCK started to use regularly steam-powered pile driving hammers. The MENCK steam installation raises the ram with a rope and then allowed it to fall freely on the driven piles. But as early as in 1906 it was proposed to raise the hammer ram by explosion in a cylinder with a piston (Otto Ricklefs,1906). In 1923, the German company DELMAG launched an introduction of a simplified diesel engine for raising the impact body to a certain height. Evidences about a regular pile driving by a so called diesel hammer refer to 1936-1940. The diesel hammer proved to be a very convenient pile driving machine and quite soon it turned into the most popular and large-scale hammer for such activity. At the

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moment, more than 65 000 diesel hammers operated worldwide, from which about 40 000 have a ram with a mass of 2 200 kg. One disadvantage of diesel hammers proved to be the limited maximum mass of the impact part. The increased scale of the construction industry imposed the use of even greater piles with a diameter of 5,0 m and even 7,0 m, so their driving into the soil requires even greater mass of the impact parts. The biggest hammer ever built by DELMAG had a ram mass of 20 000 kg. Jet the German company Bauer succeeded in increasing the ram mass initially to 24 000 kg, and then - to 27 000 kg, which for the present seems to be the maximum possible for diesel hammers. In 1963, to meet the new demand of hammers with a greater ram, the German company KRUPP developed a concept for a so called hydraulic hammer for pile driving which used a hydraulic cylinder for raising the ram. In this way it became possible to built hydraulic driving hammers having rams with a mass of 50 000 kg, 97 000 kg (MENCK), 115 000 kg (IHC, Netherland) and 125 000 kg (MENCK). This sheer gigantism continues and at the beginning of 2012 the Dutch company Heerema Hammers & MENCK conducted tests of driving hammer with a ram mass of 192 000 kg. The tendency for increase in the ram mass is also observed in forging hammers. The Russians built in 1983 the world's largest forging hammer with two rams – each with a mass of 150 000 kg, and for several years now, the German company MÜLLER WEINGARTEN (MÜLLER WEINGARTEN, 2007) has been building even greater forging hammer with two rams – an upper body with a mass of 218 000 kg and a lower body with a mass of 230 000 kg.

Let us return to the pile driving hammer (PDH). The above mentioned types of PDH strike a blow at a maximum ram speed of up to 7 m/s. This is necessary for the sake of structural convenience-in order to conduct the fall from a smaller height and also to reduce the risk of destroying rams and driven piles. An additional restriction of the maximum impact speed probably imposes the use of rams which are castings or hollow bodies filled with metallurgical slag or metal small shot – this was introduced by some companies like MENCK. Due to the free fall of the ram, the most convenient is the vertical pile driving, but technology also enables a tilted pile driving – up to 30˚ towards the vertical. In 1994, we tried to illustrate the development of driving hammers during the last 160 years and the result is shown on Figure 2. Surprisingly, it turned out that every 40 years a new way of powering of PDH appears – for lifting and dropping the ram. So over the course of that development, in succession, after the steam-powered hammers there emerged diesel- and then hydraulically-powered hammers. Will this tendency continue in our days too? The elementary adding of another 40 years to the last date on Figure 2 - 1963 - gives us 2003 as the year when the next new powering of PDH ram should appear.

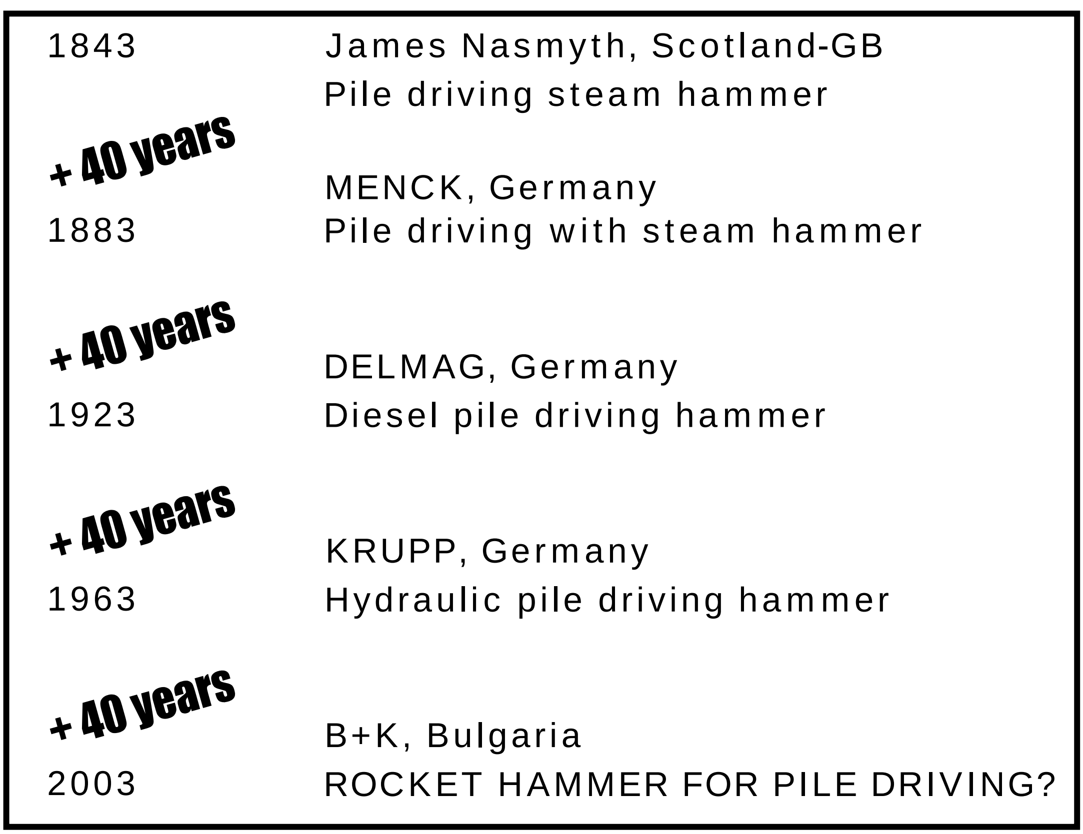

Figure 2 : Evolution of mechanically powered lifting of PDH ram in the last 160 years

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III. What is the Next Ram Powering Engine?

We started to look for the next powering engine in succession. As it happened, one of the authors of this article already has been working for years on end on a new way to activate forging hammers and we assumed that most probably it is he who should be our „usual suspect". In 1976, the dipl. eng. Petar Bodurov, financially supported by the Technical University, Sofia, constructed 3 operating models of: rocket press, rocket hammer and installation for hot sheet metal forming with a rocket jet(Bodurov P.&Genov J., 1976). The Air Force School of the Bulgarian Air Force ensures 57 mm uncontrollable aviation rockets of the type "air-air", model C-5M (made in the ex-USSR) for powering the rocket engines with a solid fuel. All experiments started on 13.10.1976 have been successful and we suppose that those were the first deformations of metal stock material by means of rocket engines. For the present article, the results of the experiments with the rocket hammer are of primary interest.

a)

b)

Figure 3.a) : Dipl. eng. Petar Bodurov with the model of the rocket hammer, minutes before realization of the first rocket impact for deformation of ametal specimen - 22.10.1976, Air Force School, Dolna Mitropolia, Bulgaria

Figure 3. b) : Model of a rocket hammer – left to right: an already used rocket engine, an impact body, formed as a piston with a mounted on it rocket engine charged with a solid fuel, a housing of the hammer with a leading tube and devices for fixing the impact body in the upper (starting) position

The C-5M rocket engine charged with a solid fuel has a total mass of 3,5 kg, develops a thrust of about 350 kg (varying with about 10% depending on the ambient temperature) for 0,75 s. The engine is stationary mounted on a steel ram shaped as a piston, with a mass of 15 kg. The ram is held by fixing devices in a leading tube which ensures acceleration stroke of the ram of 0,9 m, moves under the action of the rocket engine and strikes the stock material. The rocket engine is switched on from a battery with a voltage of 27 V. The ram strikes with a speed of about 19 m/s (calculated). The striking energy of the rocket hammer model corresponds to that of a forging hammer with a falling part of 80 kg at an impact speed of 9 m/s. The first successful strike with a rocket engine was realized on 22 October 1976 on the polygon of the Air Force School. Lead specimens were first deformed and then – specimens from aluminum alloys. Figure 4 shows a matrix, cylindrical stock material of aluminum alloy and a detail forged with a rocket hammer having a mass of 0,053 kg.

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Figure 4 : Matrix, cylindrical stock material of aluminium alloy and detail forged with a rocket hammer model

The experimental results obtained gave us a confidence that the idea to construct a new industrial engine working on the principle of rocket engine is realizible. The rocket engine is the best energy transformer! In addition, it is without any competition in two areas(Barrere M., Jaumotte A. et al, 1960):

1. Space flights.

2. Where it is necessary to have a small-sized engine assembly with a big strength and a brief action.

It is obvious that the impact machines, or, rather, the hammers, are most suitable for powering by a rocket engine, which will be most effective when working at short pulses. The rocket engines used in the first experiments with a rocket hammer model are charged with a solid fuel of the type of colloidal gunpowder pressed in hollow cylinders. However, the solid rocket fuel is about 100 times more expensive than the liquid fuel and is extremely inconvenient for multiple charging – you will need to disassemble the engine after every start, clean it totally and recharge which is unacceptable for an industrial machine. Although the scheme described for multiple charging with a solid fuel was successfully experimentally tested on 21.09.1988, we took up developing a liquid-fuel-charged industrial rocket engine (IRE) which can activate industrial machines. The liquid fuel is cheaper and safer than the solid rocket fuel and allows convenient multiple charging of IRE. Also, the IRE has to endure the dynamic loading generated by the powered impact parts. Another important requirement is that IRE should have a multiple action – not less than 10 000 switching, because at the moment all rocket engines are only single-use machines. All these problems were solved and the first IRE was constructed in 1993 – the model IRE-1, Figure 5a. Technical data of IRE-1 are shown in Table 1, and the exhaust gases composition – in Table 2. It is obvious that the engine creates less contamination than the motorcars and this is due to the assured complete combustion of the fuel. In addition, a removal of the exhaust gases is foreseen, so that the rocket machines can work in production departments of the plants.

Table 1 : Technical Data of Industrial Rocket Engine model IRE-1

Thrust	5 to 20 KN (1 125 to 4 500 lbs)
Pressure in the Combustion Chamber	max 6 MPa (870 lbs/in^2)
Fuel	Kerosene
Oxidizer	Compressed air
Efficiency	0,92
Fuel consumption	max 0,62 kg/s (1,37 lbs/s)
Oxidizer consumption	max 8,90 kg/s (19,62 lbs/s)
Weight	25 kg (55 lbs)

Table 2 : Exhaust Gases of IRE-1 (mol %)

O – 0,0022	H2O – 0,1296	CO – 0,0059
H – 0,0010	N3 – 0,7264	CO2 – 0,1259
OH – 0,0012	NO – 0,0018	Ar – 0,0087

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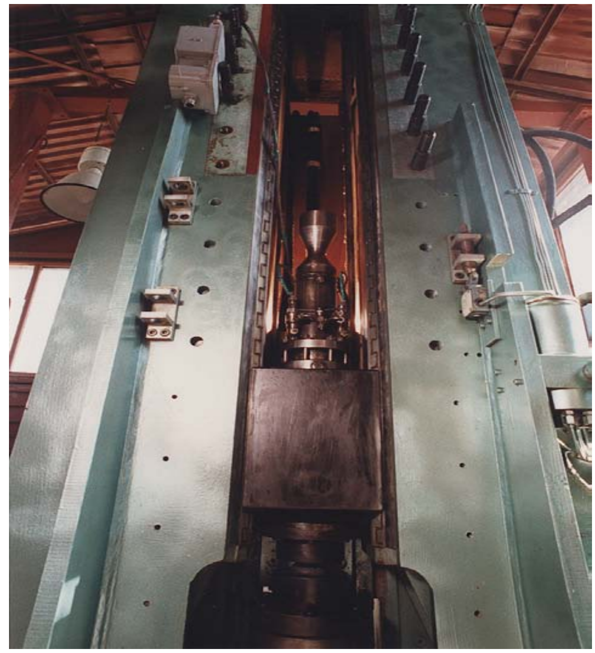
a)



b)

Figure 5.a) : First Industrial Rocket Engine, model IRE-1: hose tubes for air, 2 pieces, 1 hose tube for kerosene (with a smaller d), 2 pieces aviation sparking plugs

Figure 5. b) : Front view of the first Rocket Forging Hammer, model TWS-36 powered by IRE-1 (the front covers are removed): it is seen the impact body with an upper pressure forge mounted on the bottom face and the rocket engine IRE-1 mounted on it

In this way, we added a fifth industrial engine - IRE - to the already existing 4 industrial engines: steam engine, electrical engine, turbine engine and internal combustion engine. According to historians the rocket engine is the first engine made by man as early as about 2 000 years ago. But historically it so happened that it was only used as a transport vehicle rather than as a powering machine. And so is today - the rocket engines are used for transportation of 3 object types – explosion, apparatus and people. We are puzzled why during the past thousand years nobody noticed the ability of the rocket engine to operate also as an impact machine? Perhaps the reason is in the inertia of thinking and the opinion that when something flies it is bound to be light, tender and fragile? The rocket engine has extremely simple structure, can be produced as a single body, without any moving parts, which is a prerequisite for making a product resistant to impacts. Figuratively speaking, the rocket engine is one-profile tube which is closed from one end.

In 1994, we built the first forging rocket hammer model TWS-36 powered by IRE-1 (Figure 5 b, Table 3) (Bodurov P., 1978; Bodurov P. et al., 1999; Bodurov P. & Penchev T., 2005). After its creation it turned out that the mass of the rocket hammer is 35% less than this of an analogous pneumatic hammer – at equal impact energies. We forged on this hammer steel conic gearwheels with a mass of 0,810 kg. Based on the results obtained, we assumed that the rocket engine is the next engine which will gain ground for PDH (see Figure 2).

Table 3 : Technical data of the rocket forging hammer model TWS-36 powered by IRE-1

Maximum Striking Energy	36 KJ
Ram Speed	from 10 to 18 m/s
Stroke of the Ram	max 1 650 mm
Height Above Floor	3 350 mm
Width and Depth	1 250 x 800 mm
Weight (incl. anvil of 22 000 kg)	28 000 kg

IV. Ire-Powered PDH

We propose 3 main schemes for IRE-powered PDH:

A. Lifting the ram with IRE till reaching a set falling height(Bodurov P., 1978).

B. Lifting the ram to a set height (or at a given distance from the pile) by already existing powerings, such as steam, diesel and hydraulic, and striking with the ram under the action of IRE in combination with the earth gravity(Bodurov P., 2008).

C. Lifting the ram to a certain height (or at a given distance from the pile), as well as moving the ram for striking – and both movements are realized exceptionally by the action of IRE and the earth gravity(Bodurov P.&Genchev V., 2011).

A characteristic feature of **the First scheme (A)** is the condition that the IRE thrust should be higher with 20-30% than the mass of the ram. Otherwise it cannot be realized. This condition only restricts the pile driving vertically or with a slope up to 30˚ and does not have

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any special advantages over the now operating hammers. For the present, construction of an IRE with a thrust higher than 6 000 kg is still a serious technical problem and this restricts the mass of the ram to max 5 000 kg, if only one IRE is used. However, there is no technical problem to activate the ram with more than one IRE.

The second scheme (B) is more prospective and allows not only to replace the now existing PDH, but also to improve them (see Figure 6), retaining the device for lifting the ram - steam, diesel or hydraulic - and introducing an active powering of the ram for striking a blow. In this way, the effect of the earth gravity is eliminated to a great extent – it is no more a determining factor for the impact speed of the ram and now there is a possibility that PDH can strike at any angle in the space. Another advantage is the possibility to obtain an equivalent increase in the ram mass and therefore – increase in the impact energy. The masses of the equivalent rams are given in Table 4 – they are calculated when the engine IRE-2 is mounted to the masses of three type sizes PDH, according to the scheme of Figure 6. The IRE-2 engine(Raketenantriebe, 2009) has the same parameters as the IRE-1engine, but it is structurally adjusted to the modernized PDH with a ram to 2 200 kg. It is well known that the piles driven at a higher speed have a higher bearing capacity – because of the better soil consolidation around the piles. The active effect of the IRE which is added to that of the earth gravity allows an alteration of the strike energy without any change of the falling height or the ram mass, and so larger piles will be driven with a smaller mass. Another advantage is the unique ability of the IRE to exert so called complex or combined impact and thus at the moment of impact the operating IRE exerts also a press effort (Bodurov P. & Penchev T., 2005). It is imminent to conduct a study of the new possibilities of the combined impact which will totally change the impact and turn it to a “controllable” impact. It is obvious that the so far used “simple impact” does not respond to the already changed requirements for pile driving. What is more, we should note that the introduction of mechanically powered lifting of the impact body 160 years ago resulted in certain change of the impact by which the piles are driven. The reason is that when moving down for striking, the shaped as a piston activation element pushes the respective fluid (water steam or hydraulic liquid) or compresses the air, which leads to striking at a decreasing speed. When the impact body of the elementary gravity hammers makes a free fall, it only encounters the air resistance which is insignificant because of the comparatively small speed of the free fall. So during the gravity fall the impact is carried out at a constantly growing speed. For the sake of mechanization and efficiency, we have made the impact “softer” thanks to introducing mechanically powered lifting of the impact part. Energy expenses are also increased but on account of this we can reach up to 100 impacts per minute, and also enormous in mass impact parts can be lifted. The IRE will allow, for the short haul, to bring back the advantages of the impact at a growing speed till the realization of the impact itself. Introduction of an active ram will allow also to revolutionize the PDH design and technology of driving. There is a real perspective to change and optimize the thousand-year technology of pile driving, adding to it new possibilities. To answer possible objections to introducing the rocket engine for driving, we will remind that more than 100 years ago the introducing of a steam-driven hammer was also considered a fanciful adventure.

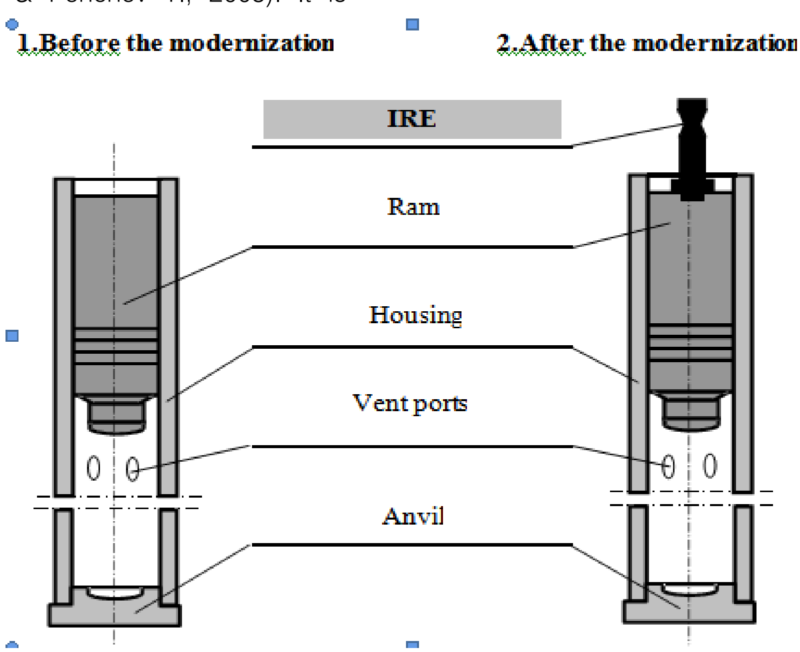

Figure 6 : Modernization of giesel hammer for pile driving

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Table 4

Ram weight [kg] (lbs)	500 (1 102)	1 250 (2 756)	2 200 (4 851)
Power E before modernization [kgm] (ft.lbs)	1250(9 041)	3 120 (22 567)	5 500 (39 782)
Power E after modernization [kgm] (ft.lbs)	4 250(30 740)	6 360 (46 002)	8 800 (63 650)
Equivalent ram weight after modernization [kg] (lbs)	1800 (3 969)	2 540 (5 601)	3 250 (7 166)

Figure 7 : Shows the realized scheme ofthe IRE feeding with a fuel and oxidant(Bodurov P., 2011). Figure 8 b, c demonstrates a modernized tube diesel hammer model УР-2(USSR) with a ram of 500 kg. Possible angles of the pile driving can be seen on Figure 9. The possibility for vertical upward pile driving at an angle of 180˚ can also be used as a technology for removing of an already driven pile

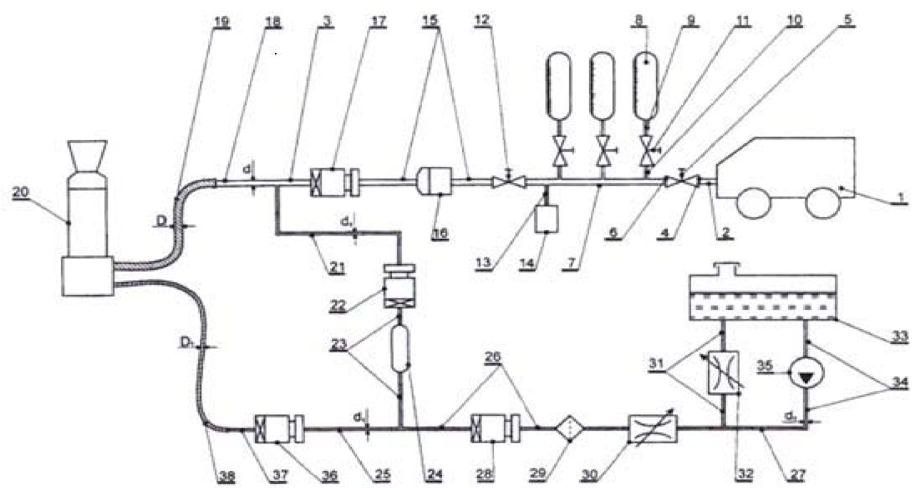
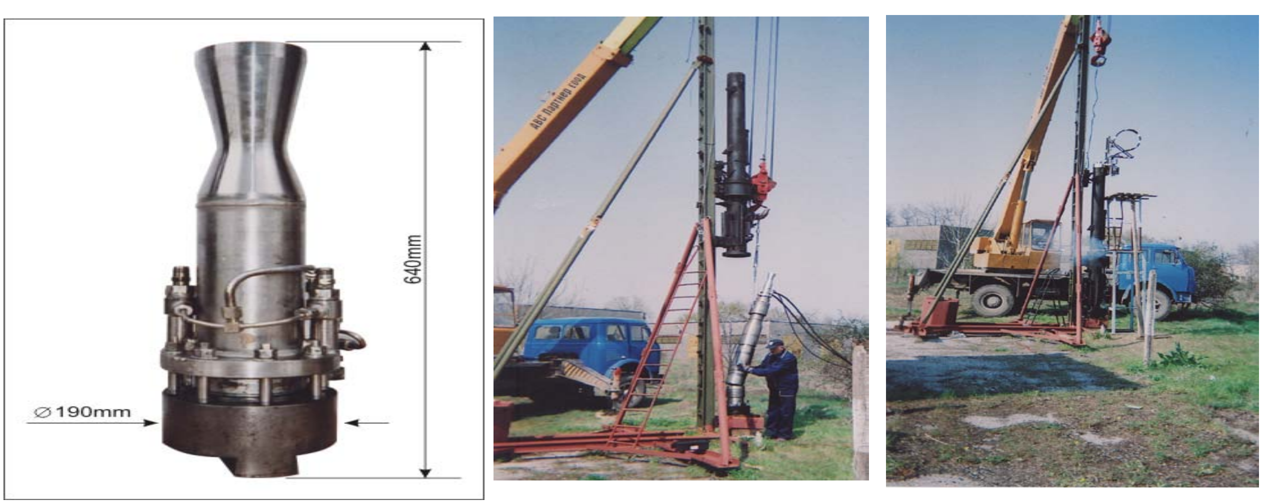


Figure 7 : Scheme of feeding the IRE-2 with fuel and oxidant

1 – compressor, 3 – oxidant (air) line, 5 - crane, 8 - receiver, 14 - safety relief valve, 16 – reductor, 17 – main electromagnetic valve, 19 – flexible hose for oxidant, 20 - rocket engine, 21- tube for air, 22, 28, 36 - electromagnetic valves, 24 –fuel dose, 25 – fuel (kerosene) line, 29 – filter, 30, 32 – throttles, 33 – fuel tank, 35 – pump, 38 – flexible hose for fuel



a) b) c)

Figure 8 : Hammer for pile driving model Ур-2, powered with IRE-2:a) IRE-2

b) Assembling of IRE-2, together with air hoses – 2 pcs. and 1 kerosene hose on the ram with a mass of 500 kg. c) Surface tests of the hammer model УР-2 with a mounted IRE-2.

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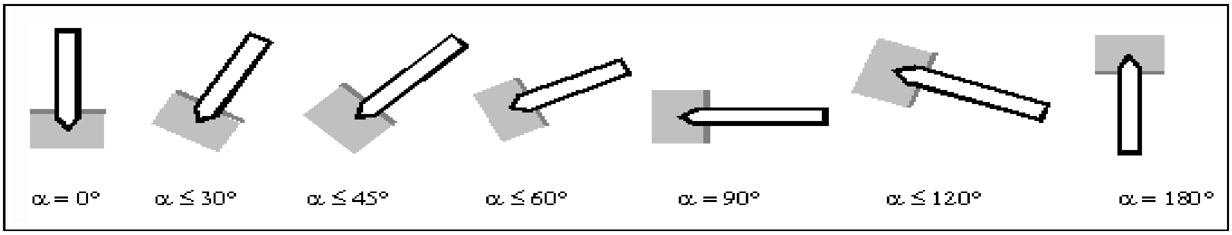
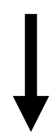
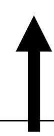
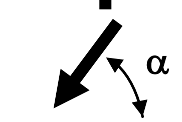
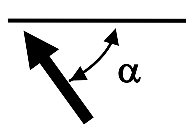


Figure 9 : Angles of pile driving with a rocket-powered hammer

Formulas for determination of the ram speed when striking on the pile are given in Table 5, with the basic 5 pile positions (Bodurov P. & Radev S., 191979). Speed V is given in *m/s*, at acceleration stroke S of the ram in *m*, with a mass of ram *G* and a thrust *R* of the rocket engine in *kg*, and the earth acceleration $g = 9{,}81$ m/s^2. The formulas are derived by using the motion of material particle theorem from the Classical Theoretical Mechanics. It is assumed that the thrust *R* is constant during the whole acceleration stroke *S*, the mass *G* of the *Ram & IRE* set does not change and the friction in he hammer guide as well as the air resistance are neglected. These assumptions do not change the impact speed *V* by more than 1%, because structurally the stroke *S* is not greater than several meters, a small quantity of fuel is used and the friction is insignificant when lubrication is assured. The speed *V* is less than 20 m/s and so it is not substantially influenced by the air resistance. That is why the formulas given are fully reliable and convenient for application.

Table 5 : Formulas for determination the driving speed V

No.	Driving direction	Formulas for the impact speed
1.		$V=\sqrt{2gS(\frac{R}{G}+1)}$
2.		$V=\sqrt{2gS.\frac{R}{G}}$
3.		$V=\sqrt{2gS(\frac{R}{G}-1)}$
4.		$V=\sqrt{2gS(\frac{R}{G}+\sin\alpha)}$
5.		$V=\sqrt{2gS(\frac{R}{G}-\sin\alpha)}$

The evaluated speed *V* and the impact energy *E* of an IRE-2- modernized tube diesel hammer with a ram mass of 1 250 kg are given in Table 6, compared with the possibilities of non-modernized PDH. The total superiority of the modernized PDH is obvious.

Angle	[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
Parameters	V	E	V	E	V	E	V	E	V	E	V	E	V	E
	m/s	kgm	m/s	kgm	m/s	kgm	m/s	kgm	m/s	kgm	m/s	kgm	m/s	kgm
PDH	7,00	3120	6,50	2690	IMPRACTICABLE									
PDH+IRE	9,90	6360	9,61	6000	9,04	5310	8,60	4800	7,07	3240	5,76	2156	5,30	1825

Table 6 : Comparison between PDH (tube diesel pile hammer, ram of 1 250 kg or 2 756 lbs) and PDH+IRE

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In 2001-2002, we proposed the project "Modernization of PDH" to a team of post-graduate students of the Wharton Business Faculty, University of Pennsylvania (USA). The students participated with this project under the name "Jet Technologies" in the Wharton Business Plan Competition and were ranked amongst the seven big finalists(Wharton, 2002). However, the comments of some PDH manufacturers in the press were that the IRE fixation to a ram is impossible (E. Schurenberg, 2002). The experiments and structures realized by us later disprove these statements. One of the arguments was that the ram speed is too big. For designers of the blacksmith and forging hammers such statements sound not seriously because the falling part of the PDH does not develop an impact speed greater than 7 m/s, and the hammers used in metal working usually work at speeds of 6-9 m/s. High-speed hammers which deform special alloys and sophisticated articles work at speeds of the impact body of about 16-22 m/s and even a hammer working at an impact speed of 40 m/s is constructed. All problems of fixing of the tools to their impact parts are solved and there is no problem connected with fixing the IRE to the ram of PDH which we have proved in practice. By our opinion, a pile driving at a speed of 6-7 m/s is wrong. An elementary increase of the driving speed with only 2 m/s, e.g. to increase it from 7 m/s to 9 m/s, will lead to reduction of the ram mass with about 40%. The use of metal piles makes it totally pointless to object to driving at higher velocities. We propose to go to driving at velocities of the order of 9-11 m/s, and even 12 m/s. In this way you can put an end to this unjustified and expensive gigantism in the production of impact parts. Of course, for higher impact velocities, single-piece forged impact parts are more suitable than castings. For reinforced concrete piles probably an additional strengthening and reinforcement of the steel fixture will be needed, but this is not an obstacle for the technology of their elaboration.

It is worth mentioning one more advantage of the IRE and this is the possibility to work even at the lowest temperature. This advantage is particularly important for fortifications in northern and polar regions where the whole construction lies exceptionally on piles and it can only be practiced during a small part of the year.

The third scheme (C)is the most complicated one but has the unique applicability. It is well known that the rocket engine is the only engine that is able to work independently from the environment. So the rocket engines today work without problems in airless space, air atmosphere and water. Due to this ability, the rocket engine nowadays is considered an ideal engine for powering of the ram in underground pile driving hammers at all existing depths. The fact that it will work in water environment is a possibility to use an electrical rocket engine whose working medium is the surrounding water (Bodurov P. &Genchev V., 2011). By heating and evaporating water in the rocket chambers, a jet thrust is generated which will move the ram up and down or forward-backward. The evaporation of water can happen in three ways:

- By using a high-frequency induction current – similar facilities are used in metallurgy. In this way a temperature of the order of 3 000 ℃ can be reached;
- By using a voltaic arc, similar to one used in electric welding – in this way a temperature of the order of 5 000˚C can be reached;
- By using a laser which will allow to reach a heating temperature of the order 4 000 - 10 000˚C.

We think that using a laser is the most suitable because it allows to obtain an instant evaporation of water in the rocket chambers by short pulses from nanoseconds to microseconds. The temperature of water evaporation increases with the increase in the depth. For example, at a depth of 7 000 m the temperature of evaporation is 730˚C and this is not a problem for the laser. We expect that in the forthcoming years it will be necessary to extract oil from ocean depths of 7 000 m and then the ram powered by electric rocket engine will have no alternative (Bodurov P. & Genchev V., 2012). The electric rocket engine can also be used for working on dry land.

V. Conclusion

The experimental results and information reported in the present article lead to the general conclusion that the time has come to accept the industrial rocket engine (IRE) as powering force for the PDH. Its introduction is logical in the context of the 40-years renovation cycle of the PDH and the new problems arising for its applications discussed by the authors. Implementation of the schemes for realization of the IRE-powered PDH will enable to create new possibilities and to solve important production problems such as:

- Pile driving at any angle in the space;
- Pile driving at higher speeds;
- Reduction of ram masses;
- Pile driving at lowest earth temperatures;
- Pile driving at any depths under water;
- Pile driving with combined ("controllable") impact.

Introducing the new ways of powering with unique qualities will lead to optimization and enhancement of the thousand-year technology for pile driving. With its help, we can better cope with the rapid increase of climate-related disasters worldwide, reclamation of the ocean floor and unique building projects on land.

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