Formation of impulse load on operating tool driven in soil

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Abstract. The author describes the experimental estimation procedure of impulse load generated in a rock-breaking rod overcoming resistance of soil. Oscillograms of power impulses in a pipe column are obtained in operation of generators with different energy efficiency and frequency. Penetration rate of a rod with selected geometry under vibration–percussion action is calculated. For comparison, the static force required for hammerless driving of rod in soil is found.

1. Introduction
At all stages of construction and underground mining connected with earthwork, a set of special technologies is used. It includes reinforcement of foundations under old and new structures, construction of cementation piles, bridge pillars trestle bridges and power lines, reinforcement of excavation and embankment slopes, construction of shields and screens, making channels for placement of closed design utility lines [1]. Percussion driving of various rod element in structures in elastoplastic subsurface layers of rock mass and soil have found wide application in actual practice [2–4].

Among diverse technological tools, a certain place belongs to impulse-generating machines with convert energy of compressed air to cyclic to-and-fro motion of piston. The latter, via some intermediate assemblies, interacts with the driven body by transmitting kinetic energy to it and performing useful mechanical work [5, 6].

The Institute of Mining, SB RAS, has been for a long time carrying out investigations aimed at improvement of this class percussive tools to meet incremental needs of construction industry [7–9]. It is impossible to improve efficiency of vibro-percussion technologies without comprehensive study into interaction of elements in the oscillating system of impulse generator–driven element–soil.

The next research cycle was focused on finding mechanisms of change in the characteristics of power pulse transmitted to a pipe column and in the displacement rate of the latter in elastoplastic soil under the action of different sources of cyclic impact in combination with addition static load.

2. Experimental setup and results
The body penetrated in soil was a steel pipe column 1 (Figure 1) composed of two sections with a threaded coupling. The outer diameters of these components were 33 and 40 mm, respectively. The pipe head 1.9 m long, interacting with soil, was equipped with a cone with a nose angle of 60°. At the opposite end of the second element, different model percussion units 2 were arranged. The coupling was universal reducing nozzle 3 with internal conical cavity with a nose angle of 4°to the pipe axis, which allowed reliable fixing of the impact source without auxiliary tension pullers. Additional static load was created by a set of loads 4 with an overall weight of 50 kg. The force transmission was
implemented via an intermediate damping element 5 and a bolt 6 placed in the crosshole of the driven pipe.

![Figure 1. Experimental design: 1—pipe column; 2—percussion unit; 3—reducing nozzle; 4—additional load; 5—damper; 6—bolt; SM—strain meter; SA—signal amplifiers; ADC—AD converter; PC—portable computer.]

Soil was represented by sandy clay in natural occurrence, with decreased moisture content.
Experimentation involved some preparations:
—making of pilot holes 0.5 m deep from the soil surface to direct the pipe column vertically;
—preliminary penetration of the pipe head 1.9 m long;
—connection of the second pipe, assembly of the force sensor and vertical ruler 2 m long, with a scale interval of 1 mm, for the continuous monitoring of penetration process.

The pipe column driving was video recorded by camera ONY HDR-SR10E for step-frame processing of the resultant video using computer program Picture Motion Browser and for calculating average penetration rate per 0.1 m. Recording started at the mark of 2.3 m and ended at the depth of 3.5 m. The impact generators were replaced every 0.3 m of penetration. For reliability, each variant was repeated not less than 3 times, which made in total 15 tests and subsequent driving of 3 pipe columns.

Figure 2 shows the plots of power impulses generated in the drive pipe column by different sources of external cyclic percussion action in combination with constantly applied static force of gravity load. It is seen that the maximum amplitude of impact transferred to the driven pipe by the majority of the air hammers ranges as $F_{\text{max}} = 20–25$ kN (Figures 2b–2e). This parameter is independent of the dimension of the impact tools having considerable difference in the initial energy efficiency (table). An exception is the impact impulse generator represented by Typhoon-0.5 with the lowest weight of the piston, $m_p = 0.5$ kg, and the lowest blow energy $E = 4.5$ J. In the meanwhile, the amplitude of the force recorded in the pipe is never higher than $F_{\text{max}} = 15$ kN (Figure 2a). In the period between the neighbor blows, the soil–pipe–additional load–impact tool system is at rest. At the same
time, it is seen in Figures 2c–2e that the resulting force acquires negative values at some stages. This is reflective of insufficient weight of the added load \( G = 0.5 \) kN required to completely balance the reactive recoil \( F_r = 0.92 \) and \( 1.20 \) kN (table) in operation of Typhoon-1-2.4 and Typhoon-4, respectively, which acts in opposite direction to the pipe penetration. In the driven element, tensile stresses arise, which, together with elastic response of soil and under insufficient adhesion between the pipe surface and hole walls, can cause separation of the head nozzle from the hole bottom.

After the accomplishment of all tests, the video records were processed, the process of pipe displacement in soil was analyzed and the average penetration rates were calculated for each mode of pneumatic hammers. The results are presented in Figure 3.

\[
V \times 10^{-3}, \text{ m/s}
\]

![Figure 3. Average penetration rates of pipe under action of different impact sources.](image)

According to these results, in the given conditions of the experiments, the start of the stable penetration of the pipe column at the rate \( V = 1.17 \times 10^{-3} \) m/s is observed under action of Typhoon-1 hammer with the characteristics \( m_p = 1 \) kg and \( E = 9 \) J. Then, with more powerful hammers, the process of penetration accelerated considerably. It should be mentioned that the air hammers Typhoon-1-2.4 (\( m_p = 1 \) kg, \( E = 10 \) J, \( p = 2.4 \) MPa) and Typhoon-4 (\( m_p = 4 \) kg, \( E = 35 \) J, \( p = 0.6 \) MPa) have close results. For instance, despite considerably different dimension, weight of piston and blow energy, the penetration rates of the machines are \( V = 4.26 \times 10^{-3} \) m/s and \( V = 4.93 \times 10^{-3} \) m/s, respectively, which is the difference of not more than 15%. Evidently, for Typhoon-1-2.4, the lower energy component of the impact capacity is compensated by the higher blow frequency \( f = 41 \) Hz, which is achieved thanks to transition from the standard compressed air pressure \( p = 0.6 \) MPa to the higher value \( p = 2.4 \) MPa at the same pre-blow velocity of the piston.

Finally, the static force pipe driving in the same soil was determined in an additional experiment. The force generator was the hosting device, and the force was transferred to the pipe via a rope-and-block system. The force measurement system was the same set of elements as in the vibration-percussion tests (Figure 1). We determined resistance of soil to penetration of a compound rod composed of elements with diameters of 33 and 40 mm, with a conical nose. The results are depicted in Figure 4 as the plot of change in the driving force with the increasing depth of the pipe penetration. It is seen that in the main section of the path, from the mark of 2.4 m to the mark of 3.4 m, the resultant force of resistance ranges as: \( R = 16–20 \) kN. In the starting and ending sections, \( R = 14–15 \) kN.
These data correlate well with the plots of the impact impulses (Figure 2) and the average penetration rates of the pipe (Figure 3) in the framework of the static calculation model, according to which translational motion of the pipe–added load–percussion tool system is only implemented if the total frontal and lateral drags due to soil resistance is overcome. For instance, the amplitude of the impulse load transferred to the driven element by Typhoon-0.5 \( (F_{\text{max}} = 15 \text{ kN}) \) is insufficient for plastic deformation of soil at the hole bottom; as a result, the system is not drive by each blow and the average penetration rate is zero \( (V = 0) \).

For the assured penetration of a body with the given linear sizes in soil with the total resistance \( R = 16–20 \text{ kN} \), the force amplitude generated by the coupled action exerted on the pipe by various impact generators and added load \( G = 0.5 \text{ kN} \) is set at the level of \( F_{\text{max}} = 20–25 \text{ kN} \). In this case, the translational motion velocity of the pipe ranges as \( V = (1.17–4.93) \cdot 10^{-3} \text{ m/s} \) and depends on the energy \( E \) and frequency \( f \) of blows of different pneumatic hammers, and on the value of the additional static force \( G \). With regard to physical and mechanical properties of soil, as well as to backward displacement of the pipe column under elastic response of soil and recoil of the percussion tool, the mentioned relation in the first approximation is given by \[12\]:
\[
V = \left[ \frac{E \eta}{R - G} \left( \frac{Q + F_0}{q S k + G} \right) \right] f,
\]
where \( \eta \) is the coefficient of the impact impulse transfer; \( Q \) is the elastic response of soil, \( \text{N} \); \( F_0 \) is the recoil force, \( \text{N} \); \( \lambda \) is the backward displacement of the pipe column, \( \text{m} \); \( q \) is the normal lateral pressure of the hole walls, \( \text{Pa} \); \( S \) is the total area of lateral contact between the driven element and soil, \( \text{m}^2 \); \( k \) is the metal–soil friction factor.

3. Conclusions
1. In the technologies of vertical driving of metal structures by percussion with application of additional static load exceeding recoil of pneumatic hammer and approximately making not more than 5–10% of the stable amplitude of the impact force: \( G \geq F_0 \approx (0.05–0.1)F_{\text{max}} \) makes it possible to reduce backward displacement of the driven system under elastic response of soil and, as a consequence, to improve efficiency of the driving process. It is advisable to use gravity loads of required weight and place them in the driven pipe with an intermediate damping flexible suspension.
2. Comparison of the results obtained with Typhoon-1-2.4 and Typhoon-4 pneumatic hammers having the same pre-impact velocity of the piston \( (4.2–4.5 \text{ m/s}) \) proves that, under condition that these machines ensure the ultimate energy of unit blow \( (E \geq 9 \text{ J}) \), required to overcome resistance of soil, the solution to the problem of improvement of driving efficiency can be connected with the considerable expansion of the impact frequency range \( (41 \text{ Hz as against } 9 \text{ Hz}) \). Such approach allows reaching similar velocity characteristics \( (V = 4.26 \cdot 10^{-3} \text{ m/s} \text{ and } V = 4.93 \cdot 10^{-3} \text{ m/s}, \text{respectively}) \) at the smaller weight and size of high-frequency percussion facilities with the piston weight \( m_p = 1 \text{ kg} \) and \( E = 10 \text{ J} \) as compared with \( m_p = 4 \text{ kg} \) of the hammer with \( E = 35 \text{ J} \).
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