Effect of a shock pulse shape on hollow pipe driving in soil: The field studies

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Abstract. This pilot research is aimed to advance vibropercussion driving of steel casings in soil in construction of underground utilities. The goal is to find mechanisms of fill of the casing tube with soil under different-shape shock pulses. The influence of the impact energy structure (shock pulse shape) is theoretically related with efficiency of hollow rod penetration in soil. The quantitative estimate of fill on the tube interior with soil uses a dimensionless fill factor. The influence of the tube diameter on increment in the soil plug length is demonstrated in terms of different percussive machines with different impact energies. The authors present a test bench and a procedure of the field research in various ground conditions, interpret the obtained data and compare them with the earlier results, both own and foreign.

1. Introduction

In open-ended pipe driving, soil enters the pipe interior. At an early stage of the process, the length of the soil plug is equal to the penetration depth of the pipe. As driving continues, the ratio of the soil plug length to the pipe penetration depth varies depending on different factors [1]. It can happen at a certain time that the soil plug is so packed that it prevents from entrance of a new portion of soil in the pipe [2–5]. In this case, the process can be assumed as the closed-ended pipe driving. In the open-ended pipe driving, the total soil resistance is composed of the external pipe–soil friction, internal friction of the plug, the plug front resistance and the face resistance of the annular section of the pipe [6–8]. Figure 1a shows the scheme of forces affecting the pipe before it is plugging with soil, and in Figure 1b, there is a clogged pipe with immovable plug.

Figure 1. Scheme of forces on pipe: (a) before plugging with soil; (b) after clogging with immovable plug.
2. Theory
The higher energy impact drives a pipe to a greater depth in soil [9]. Unfortunately, the impact energy is constrained. The limitations are imposed by the strength and longitudinal stiffness of a pipe to be driven, as well as by the higher cost of a percussion gear capable to produce impacts at higher energy. Percussive machine are designed so that to offer higher percussive capacity at lower size and weight. Structurally, the percussive capacity is a product of impact energy and impact frequency. It is improper to increase the percussive capacity of a pipe driving machine at the cost of the impact frequency exclusively. The necessary condition of pipe penetration in soil is the pipe end effort sufficient to break soil. As a pipe is penetrated deeper, the shock wave, while propagating along the pipe, decays owing to the higher resistance on the external surface of the pipe and the growing plug inside the pipe. For this reason, deep penetration of the pipe is not going to happen without sufficiently high impact energy. Figure 2 depicts two arbitrary shock pulses of the same energy, all other conditions being equal. This fact is confirmed by the formula of the stress wave energy [10]:

\[ A = \frac{c}{E \cdot S} \int_0^T F_i^2(t) dt, \]

where \( c \) is the sound velocity in metal; \( E \) is the metal elasticity; \( S \) is the cross-section area of the waveguide; \( T \) is the shock pulse duration.

![Arbitrary shock pulses.](image)

3. Experiment
For the pilot research into influence of the impact energy structure on the pipe penetration efficiency in soil, two pneumatic percussive machines were manufactured with equal impact energies (the difference was no more than 4%) but different weight pistons, which meant different impact velocities. The impact energy of the machines was 9.3 J at the pistons 0.5 and 1 kg in weight [15]. Unlike the impact machines for vertical pipe driving at adjustable impact energy within a wide range, in the case discussed, in horizontal ramming, it was only possible two test two designs of percussive machines.

Another objective of the research was to estimate influence of soil properties on formation of soil plug and on pipe penetration efficiency. According to tests [16], the ratio of clay particles and sand...
affects interaction of pipe penetration in sand. It was decided to undertake field tests since physical simulation of soil mass is nonpermissive for reproduction of natural bonding between soil particles and for making a soil mass with uniform physical and mechanical properties. The two experimental series on pipe driving in soil were implemented at Zelenaya Gorka test site of the Institute of Mining, and at a construction site nearby Koltsovo settlement, Novosibirsk area.

We analyzed sand and clay rocks having different properties. Soil at the test site has a sand/clay particle ratio of 20/80 and density of 1897 kg/m³ [17]. At the construction site, soil is sand to 85% having density of 1720 kg/m³ according to the lab analysis. The groundwater level is below the experimentation depth.

Figure 3 shows the experimental setup for pipe driving in soil. The metal framework of the experimental setup is placed on soil and fixated with bolt to eliminate any displacement during testing. The pipe to driven is arranged on the frame and connected with the pneumatic percussive machine using a conical adapter. For driving tests of different diameter pipes, the adapter has ring conical grooves for the pipe to become stuck under impacts. For measuring penetration depth of the pipe, there is a ranging mark set on the pipe end, and the ring cuts are made each 10 mm on the outer surface of the pipe. Inside the pipe, there is a dummy plug connected to a thin plastic rod. As the pipe is rammed in soil, the dummy plug is displaced by the soil plug entering the pipe. The length of the soil plug is registered using a measurement scale on the plastic rod.

Figure 3. Experimental setup for pipe driving in soil by impacts.

The air line to power the machine is equipped with a pressure regulator to adjust compressed air pressure if necessary (from 0.3 to 0.7 MPa). The driven pipe is pulled out from soil using a motor winch.

In the tests of the pipe diameter influence on formation of soil plug, three pipes with diameters of 32, 548 and 76 mm were driven in soil. Ramming was carried out by each machine separately (machine 1 with piston of 0.5 kg and machine 2 with piston of 1 kg). The length of the soil plug was measured each 10 cm of the pipe penetration.
4. Results
The quantitative estimate of the soil plug inside the pipe uses the specially introduced dimensionless fill factor \( \delta \) given by [18]:

\[
\delta = \frac{l_{plug}}{L_{pipe}} \cdot 100\% ,
\]

where \( l_{plug} \) is the length of the soil pipe, m; \( L_{pipe} \) is the depth of the pipe penetration in soil, m.

When soil stops entering the pipe (as in the closed-ended pipe driving), \( \delta = 0 \).

Figure shows the curves of the soil plug length versus the pipe diameter. The measurements are taken to a penetration depth of the pipe at 1 m in sand and loam.

![Figure 4. Influence of pipe diameter on length of soil plug.](image)

5. Discussion
The fill factor apparently decreases with the larger diameter of the pipes (Figure 4). Machine 1 produces a little higher fill factor, which can be connected with influence of penetration rate owing to higher inertia component of the driving force.

The fill factor in sand is on average 20% higher than in loam. The review of the foreign research [1, 18, 19] proves this conclusion. The difference in the fill factors in sand and loam is connected, first of all, with effect of tixotropic fluidization of soil under vibrational impact. For example, it was experimentally found [16] that soil with higher content of sand particles required lower force to be displaced but only in the mode of simultaneous impact action.

6. Conclusions
The increase in the pipe diameter results in faster growth of soil plug inside the pipe relative to the pipe penetration depth in all tests. The fill factor is higher in sand soil than in clay soil in all tests as well. The shape of the shock pulse has insignificant effect on the fill factor in the ground conditions analyzed.

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