Design parameters of the device for adjusting a trajectory of pneumatic puncher motion in soil

BB Danilov*, BN Smolyanitsky and DO Cheshchin

Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia

E-mail: *bbdanilov@mail.ru

Abstract. The calculation data are presented on forces required to deflect the rear end of the pneumatic puncher body at a wanted angle, given that a trajectory of its motion in soil should be controlled and adjusted. These data are taken as the basis to determine forces acting on elements of the device designed to change a trajectory of the controllable pneumatic puncher. The researchers determined the pressure value in the elastic chamber of the device for adjusting a puncher trajectory, under which it is feasible to deflect the tail section, responsible for control of a puncher motion track. Design dimensions of the load-bearing elements of the device under consideration are computed.

1. Introduction

The pneumatic puncher is considered the ease-in-operation and highly efficient punching facility for hole-making in a consolidated soil mass [1–5]. This process allows making holes of diameter up to 300 mm, including pioneer holes intended for further expansion [6]. However the scope of puncher application is restricted with hole-making length, as an increase in hole length is inevitably related to less probability for the puncher to reach precisely a final design point under ever-increasing influence of random deflecting factors [7]. Technological capabilities of these machines can be expanded by providing their motion along a preset trajectory, may be a curvilinear one, when a new-made hole reaches a design-prescribed underground area [8, 9].

Figure 1. Scheme of the device for control of a puncher trajectory (with deflection of the rear section): 1—screw of a pneumatic puncher; 2—screw; 3—sleeve pipe; 4—deflecting section; 5—air-intake hose (sleeve); 6—controller of the elastic chamber; 7—elastic chamber; 8—pneumatic puncher body.
2. Main characteristics of air puncher

The pilot design of a controllable air puncher with deflecting tail section is developed with the purpose to investigate experimentally the control of pneumatic puncher motion in a soil mass (Figure 1) [10, 11]. Pressure supply to elastic chamber 7 causes variations in geometric shape and creates the force capable to deflect a pneumatic puncher to a correct direction.

Computation of the specifications of the deflecting device to control a pneumatic puncher rests on relationships describing interaction of its components with a soil mass [12] and experimental study evidence [13]. Commercial pneumatic puncher IP 4605 is selected as the basic study object. Its geometric and energy parameters are reported below.

- Body radius \( r \), m: 0.0475
- Body length \( l_2 \), m: 1.51
- Gross mass of the machine \( m \), kg: 55
- Impactor mass \( m_y \), kg: 22
- Impact frequency \( v \), Hz: 5.4
- Energy of a single impact \( E_i \), J: 100
- Working compressed air pressure \( p_c \), Atm: 6
- External radius of air-supply line \( r_0 \), mm: 18

Sandy soil, widely available in the Novosibirsk Region, is selected as a soil mass model. Its specifications are:

- Density \( \rho \), kg/m\(^3\): 1700
- Porosity \( e \): 0.67
- Density in terms of impactor DorNII [14] \( C \), impact: 4–5
- Soil–metal friction factor \( \mu \): 0.7

With a view to design a deflecting mechanism it is necessary to determine a length of deflectable tail section of the body, deflection angle, pressure in the elastic chamber in order to generate a required deflecting force, as well as radial dimensions of basic load-bearing elements of the structure with account for restrictions dependent on a hole diameter.

The calculation scheme of interaction between a deflecting section of the air puncher and soil is shown in Figure 2.

The input data are a type and physical and mechanical properties of soil, a hole diameter, m; maximum radius of puncher motion trajectory in soil (displacement of the body \( \Delta y \) per 1 meter of hole length), m; deflection angle \( \gamma \) of the tail section; nominal compressed air pressure \( p_c \), Pa.

Figure 2. Operation diagram of the device for deflection of a controllable air puncher.
Of prime importance are the parameters, affecting $\Delta y$ and calculated; they are the length of deflecting rear section $l_r$, length of support bush $l_b$, and external radius of support bush $r_b$.

3. Determination of air puncher deflection

It is established based on the data on stabilization of pneumatic puncher motion that an average deflection of a puncher per 1 meter of hole length is equal to $\Delta y = 16$ mm/m [15]. According to the evidence reported in [14], such deviation can be reached at different combinations of length and deflection angles of the rear section of the air puncher; these combinations can be computed from the relationship plotted in Figure 3.

Values of coefficients $A$ and $B$ for the most popular air puncher models are cited in the table. They correspond to sandy soil of density $\rho = 1700$ kg/m$^3$ and $\rho = 1800$ kg/m$^3$, specific for Novosibirsk specimens [16].

| Pneumatic puncher model | $D$, mm | $E$, J | $L$, m | $\rho = 1700$ kg/m$^3$ | $\rho = 1800$ kg/m$^3$ |
|------------------------|---------|--------|--------|----------------------|----------------------|
|                        |         |        |        | $A$                  | $B$                  |
| IP4610                 | 55      | 15     | 1.2    | 0.505                | 0.509                |
| MP-55                  | 55      | 20     | 1.15   | 0.552                | 0.559                |
| PP66K                  | 67      | 65     | 1.24   | 0.954                | 0.954                |
| PP66D                  | 67      | 80     | 1.46   | 1.218                | 1.217                |
| SO144                  | 71      | 65     | 1.35   | 1.030                | 1.015                |
| MP-80                  | 80      | 70     | 1.21   | 0.803                | 0.805                |
| IP4605                 | 96      | 100    | 1.5    | 0.996                | 0.980                |
| IP4603                 | 130     | 220    | 1.4    | 1.110                | 1.095                |
| MP-145                 | 145     | 400    | 1.83   | 1.743                | 1.713                |
| SO134                  | 155     | 500    | 1.7    | 1.570                | 1.534                |

As per the table, the relationship in Figure 3 for pneumatic puncher IP 4605 is described by empirical formula:

$$l_r = 0.996\gamma^{-0.835}.$$  (1)

The length of the internal support bush is selected considering a length of deflectable rear section with account for necessity to insert a device for the elastic chamber control inside of it (Figure 1). It is found in sketch design that an average length of this device is $l_y = 0.07$ m. Then a length of the internal bush is assumed equal to:

$$l_b = l_r - l_y.$$  (2)

The maximum external radius of the support bush is determined in terms of provision of the required cross-section area of the exhaust channel according to formula:
\[
\max \ r_b = \sqrt{(r - t)^2 - 4.5(r_0 - t_0)^2}, \tag{3}
\]

where \( r \) is external radius of the deflected section, m; \( t \) is thickness of a wall of the deflected section, m; \( r_0 \) is external radius of inlet pot, m; \( t_0 \) is thickness of inlet pot wall, m. Then at \( t = 0.004 \) m, \( t_0 = 0.003 \) m; the maximum radius \( r_b = 0.03 \) m.

Pressure in the elastic chamber, required for punching the deflectable rear section of the air puncher body into a soil mass, is determined depending on deflection angle from expression:

\[
p_c = \frac{0.776(l_c)^{2.34} \rho_{str}^{0.33}}{(l_b - l_{cd})^2 r_b} (E r \ tg(\gamma))^{0.67}, \tag{4}
\]

where \( E \) is general modulus of soil mass strain, Pa; \( \rho_{str} \) is structural strength of the soil mass, Pa; \cite{17, 18}; \( l_{cd} \) is length of control device, m; \( \gamma \) is deflection angle of the rear section, deg.

Substituting length of the deflectable rear section (1) into (4) it is possible to calculate the pressure in the elastic chamber which is high enough to provide deflection of the rear section by angle \( \gamma \). This relationship is plotted in Figure 4.

**Figure 4.** Pressure \( p_c \) required to turn the rear section of the body by angle \( \gamma \).

Evaluation of pressure in the elastic chamber reveals that working pressure of the air used as an energy carrier in an impact device operation is not sufficient to generate the force, necessary for deformation of hole wall, subjected to deflection by the rear section of the body; a higher pressure is demanded. Considering insufficient volume of the elastic chamber, high-pressure compressors of small capacity, such as Kraftmann ARCTURUS with maximum pressure of 3.5 MPa can be employed as accessory facilities \cite{19}.

Pressure of 3.3 MPa in the elastic chamber can induce the maximum deflection of the rear section by 4.6°. Then the length of deflectable rear section, identified from the curve in Figure 3 or from formula (1), is equal to \( l_b = 0.9964.6^{-0.835} = 0.279 \) m.

To lower specific amount of metal per a structure, it is feasible to manufacture the support bush of less radius, provided that the bearing surface for the elastic chamber is sufficient (Figure 5).

**Figure 5.** Geometric parameters of the cross-section of the device for deflection of the air puncher: 1—deflectable rear section; 2—elastic chamber; 3—air intake hose; 4—support bush; 5—bearing surface
Considering formula (2) and values $I_b$, strength condition of the support bush is used to determine its minimum external radius for pressure $p_c$:

$$\min r_b = \sqrt[3]{0.636} \frac{\sqrt{2.468 \sigma_{ys} r_0^2 + l_b^4 p_c^2}}{\sigma_{ys}}$$

where $\sigma_{ys}$ is yield stress of bush material, Pa.

For steel 35X at $\sigma_y = 750$ MPa [20] the minimum radius of the support bush is $\min r_b = 0.022$ m. The rational length of the deflectable rear section of the device body, which provides the structure strength and a satisfactory value of rotary motion of the rear section to compensate random deviations of the air puncher within a soil mass is $l_b = 0.279$ m under 3.3 MPa pressure in the rear chamber. Then from formula (2) the support bush length $l_b = 0.209$ m in the range of its external radius $r_b = 0.022$–$0.030$ m.

4. Conclusions
The established relationships and reported calculation formulas enable to determine basic design parameters and dimensions of the device for deflection of the controllable air puncher, manufacture of the basis of serial production machines: pressure in the elastic chamber, length of the deflectable section, length of the support bush, minimum and maximum radius of the support bush.

Acknowledgements
The work is fulfilled within research project VIII.74.3.1, State Registration No 01201353208.

References
[1] Gurkov KS, Klimashko VV, Kostylev AD et al 1990 Pneumatic hammers Institute of Mining Siberian Branch Russian Academy of Sciences Novosibirsk (in Russian)
[2] Rybakov AP 2005 Basics of trenchless technologies Moscow Press Bjuro No 1 (in Russian)
[3] Yao Ningpinga, Zhang Jie, Jin Xinga, Huang Hanjinga 2014 Status and development of directional drilling technology in coal mine Procedia Engineering Vol 73 pp. 289–298
[4] Shadrina A, Saruev L, Vasenin S 2016 The technology improvement and development of the new design-engineering principles of pilot bore directional drilling IOP Conf. Series: Earth and Environmental Science 43 (2016) 012068. doi:10.1088/1755-1315/43/1/012068
[5] Ratskevich GI, Kozlov VA, Kostylev AD 1978 Application of pneumatic machines percussion device for underground structures Building equipment No 5 pp 8–10 (in Russian)
[6] Sudnishnikov BV, Kostylev AD, Tupitsin KK 1970 Pneumatic punchers in construction and mining Journal of Mining Science No 2 pp 44–49
[7] Kostylev AD, Chepurnoy NP 1969 Investigation of the accuracy of drilling wells with pneumatic punchers with a different cylindrical body part, Pneumohydraulic power pulse systems Novosibirsk Issue 2 pp 62–70 (in Russian)
[8] Kostylev AD 1996 The experience of creating controlled pneumatic punchers Journal of Mining Science Vol 32 No 6 pp 77–82
[9] Kostylev AD, Tupitsyn KK, Cherdenikov EN, Karavaev AT 1985 Controlled pneumatic hammer Journal of Mining Science Vol 4 pp 59–63
[10] Danilov BB, Smolyanitsky BN, Cheshchin DO 2015 Justification of basic diagrams of horizontal drilling deflectors Journal of Mining Science Vol 51 No 3 pp 553–561
[11] Pat. 156648 RF 2015 The Device for direction changing of motion of pneumo-punch machine BN Smolyanitskiy BB Danilov ND Siryamin DO Cheshchin the applicant and the patent holder Institute of Mining Siberian Branch Russian Academy of Sciences No 2015115184/03; publ 22.04.2015, Issued 2015, Bu.No 31. (in Russian)
[12] Danilov BB, Smolyanitskiy BN, Chanyshchev AI, Cheshchin DO 2017 Determination of forces to change the trajectory of the pneumatic punch in the ground Journal of Mining Science Vol
[13] Danilov BB, Cheshchin DO 2016 Determination of the location of the center of rotation of the body of the pneumatic punch in the ground under the influence of a deflecting force Interexpo GEO-Siberia 2016 XII International Scientific Conference Subsoil Use. Mining. Directions and technologies of prospecting, exploration and development of mineral deposits. Geoeconomy Novosibirsk SSUGT Issue 3 pp 45–48 (in Russian)

[14] GOST 5180-84 1993 Soils Methods for laboratory determination of physical characteristics Moscow Izd-vo standartov (in Russian)

[15] Kostylev AD Chepurnoy NP 1969 Some results of the study straightness punching holes in the ground hammers Journal of Mining Science No 5 pp 41–44 (in Russian)

[16] SNiP 2.05.02-85 2013 Car roads Moscow Izd-vo standartov (in Russian)

[17] Osipova MA, Sviridov VL 2013 Structural strength as a criterion for assessing the deformability of loess soils Polzunovskiy vestnik Vol 4–1 pp 26–28 (in Russian)

[18] Osipova ON, Dyba VP, Galashev YuV 2016 Depth study of compressible thickness of the base in full-scale experiment Procedia Engineering Vol 150 pp 2245–2249

[19] Model range of compressors Kraftmann Arcturus, URL: http://www.kraftmann-compressor.ru/compressor-kraftmann-arcturus.html [Model line of compressors Kraftmann Arcturus, URL: http://www.kraftmann-compressor.ru/compressor-kraftmann-arcturus.html (reference data 05.04.2018)]

[20] Anuriev VI 2006 Directory of the Constructor-Machine Builder Moscow (in Russian)