Evaluation of Tip Resistance to Auger Drilling

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ABSTRACT: Analytical solution for auger tip resistance in soils is presented. It involves several drilling parameters: torque, axial force, rotation speed, linear velocity. Tip resistance to auger drilling can be used to soil strata identification and to interpretation mechanical properties of soils in the same way as is done for cone penetration test.

1 INTRODUCTION

Cone penetration test (CPT) method is broadly applied to both soil strata identification and to evaluation of soil strength and deformation parameters. In the latter case correlation equations are applied between CPT data and laboratory test data (Robertson, 1983).

Drilling penetration method is, in our view, a more attractive method. Firstly, this method differs from CPT in that it is applicable both in clays and in sands as well as in coarse-grain and in frozen soils. Secondly, the method enables determination of soil Young modulus and shear force with no correlations applied. Also other soil parameters can be found by application of correlation equations.

1 EVALUATE THE TIP RESISTENCE

In order to evaluate the down-hole tip resistance to penetration *F* we applied solutions from published papers on auger soil cutting of soil or displacement of loose materials with auger conveyors (Zacny, 2007).

Figure 1 shows main parameters, measured during drilling tests. As is evident from Figure 1, unlike CPT drilling enables measuring penetration force (vertical load) Q (N), torque M_{rot} (Nm), drilling column weight G_1 (H) and soil weight on flanges G_2 (N), flanges tilt angle α (degrees), vertical displacement V (m) and angular frequency of revolution ω (rad/s).

Auger drilling efficiency depends on M_{rot}, Q and ω. Drilling practical experience prompts that rotation speed shall be roughly 100-300 rpm or 1.67-5 rad/s for different soils. The lower limit of rotation frequency is limited by soil lower displacement rate.

Low frequencies allow drilling while viscous dense clays may require frequencies up to 300 rpm and higher. Sand can be drilled through at relatively low frequencies while viscous dense clays may need up to 300 rpm and more.

In order to displace soil from the bits with smooth interface between cutting blades and auger spiral it is necessary to reciprocate the drill bit and to pour water in the hole. Maximum rpm is limited by the drill bit vibrations i.e., by purely technical drilling rig parameters in general.

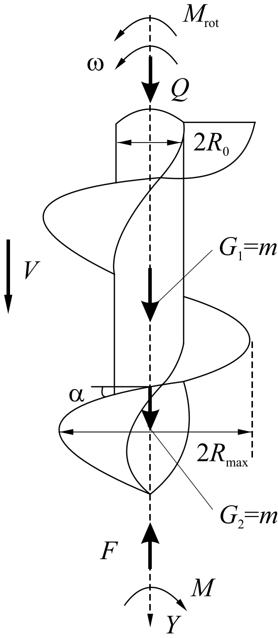

Figure 1. Parameters, measured during drilling penetration

Depending on geometrical parameters of the bit and its friction ratio over soil there exists a minimum drill bit rotation rate that ensures non-stop soil movement up to the surface. This critical rotation speed can be found as follows.

As is known soil moves against the auger. The drilled soil moves to the auger flanges and due to centrifugal forces presses against the borehole cylindrical wall. The friction and gravity forces somewhat slow down a soil particle movement against the auger surface i.e. it rotates with lower angular speed than that of the auger.

The final equation for minimum auger rotation frequency, required to lift soil is as follows (Zacny, 2007):

$$\omega_{\text{rot}} \geq \sqrt{\frac{g\left(\sin\alpha + \tan\varphi_{ag}\cos\alpha\right)}{K_1 R_{\max}\tan\varphi_s\left(\cos\alpha - \tan\varphi_{ag}\sin\alpha\right)}} \tag{1}$$

or in rotations per second (Hz):

$$N_{\text{rot}} \geq \sqrt{\frac{g\left(\sin\alpha + \tan\varphi_{ag}\cos\alpha\right)}{4\pi^2 K_1 R_{\max}\tan\varphi_s\left(\cos\alpha - \tan\varphi_{ag}\sin\alpha\right)}} \qquad (2)$$

where $\tan\varphi_s$ = friction coefficient soil-against-soil; $\tan\varphi_{ag}$ = friction coefficient soil-against-steel; and K_1 = soil-against-soil friction ratios.

In order to analyze the above equations there were staged field tests. The hole was drilled by a continuous 135 mm external diameter auger, equipped with a 151 mm diameter three-piece bit. The drilling parameters were measured with a automatic measuring system. The analyses borrow parameters: K_1, $\tan\varphi_s$ and $\tan\varphi_{ag}$ were assumed constant, the latter were determined from tests in flat shear conditions. Unit weight of soil γ_s is accepted as average value for the borehole from results of laboratory tests. Auger geometrical parameters $R_{\max}$ and R_0, α and mass auger m_0 and the soil m_s were directly measured.

Figure 2 shows two graphs: bit rotation frequency versus depth dependence and the dependence, calculated as per equation (2), of minimum necessary rotation frequency for successful delivery of soil to the surface.

In order to determine tip resistance *F* to descent into the borehole use the schematic on Figure 1.

The sum of all forces projections on vertical axis $\sum Y = 0$:

$$Q + m_s g + m_0 g +$$
$$+\left(\tan\varphi_{ag} m_s g\cos\alpha + \tan\varphi_{ag}\tan\varphi_s m_s R\omega^2\sin\alpha\right)\times$$
$$\times\sin\alpha K_1 - F = 0\,. \qquad (3)$$

Only for *F*:

$$F = Q + g\left(m_s + m_0\right) + \tan\varphi_{ag} m_s \times$$
$$\times\left(g\cos\alpha + \tan\varphi_s R\omega^2\sin\alpha\right)K_1\sin\alpha\,. \qquad (4)$$

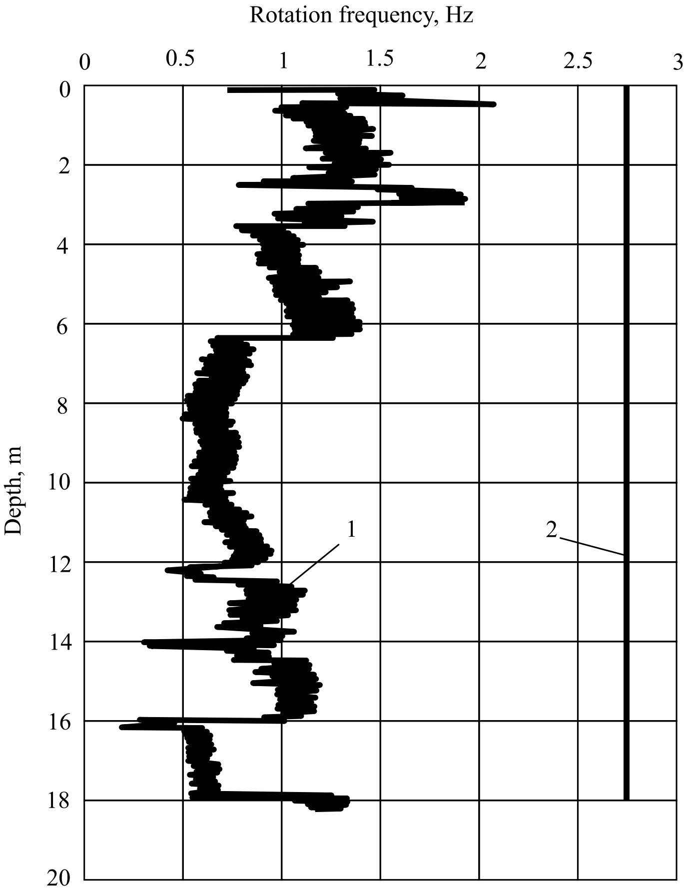

Figure 2. Bit rotation frequency profile: 1 – measured rotation frequency; 2 – minimal analytic rotation frequency

Substitution of test data in equation (3) yielded the graph of dependence (Figure 3) of the third term share in equation (3) in the overall sum for *F*.

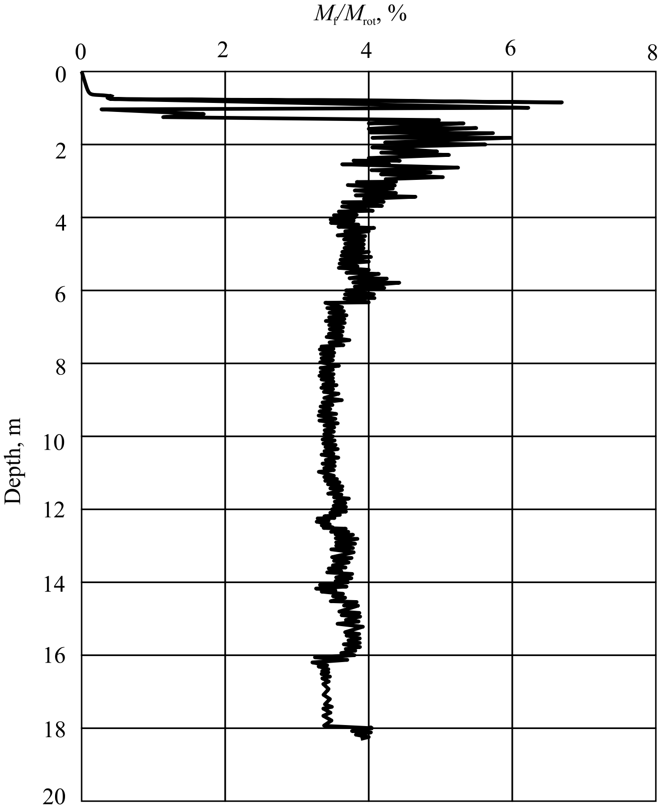

Figure 3. Share of the third term in equation (4) in the total sum at rotation frequency 0.5÷1.5 rps

Diagram on Figure 3 shows that the share of the third term at rotation frequency up to 1.5 rps is not essential and does not exceed 4% at most for coarse sand while frequency 3 rps this share would have been greater than 50 %. However, because of small share of the vertical load work in the total work of drilling the soil (see Figure 4), the contribution of coefficients selection is negligible with plotting full power, spent on drilling.

In view of this it is not correct to compare the value of tip specific soil resistance under CPT probe with the specific downhole soil resistance under the cone, because we have a different soil destruction type here. In the first case the probe is sunk without rotation while in the second case it mainly sunk due to auger rotation with practically no axial force. It is illustrated by Figure 4, showing that drilling of soil is mostly effected by torque. During drilling operation soil is "cut'' by the bit teeth at a certain value of the vertical bit pressure on soil. The bit sinks downhole per one rotation while the value of the applied torque depends on the soil properties and the bit geometry.

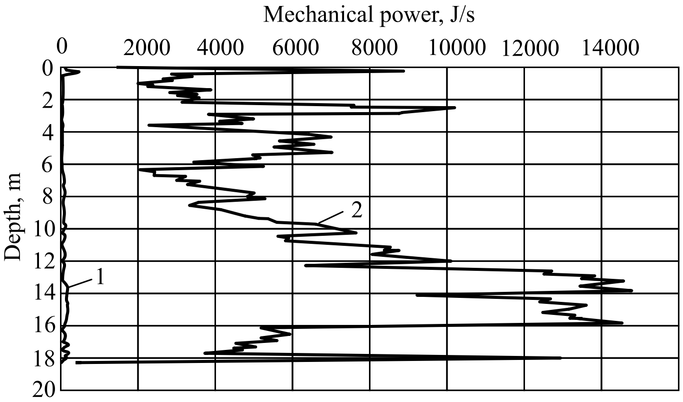

Figure 4. Vertical load power for drilling soil by the vertical load (1) and torque (2)

The dependence of the tip resistance (pressure) is more universal for augers of all dimensions:

$$P = \frac{F}{\pi R_{\max}^2} = \frac{Q + g\left(m_s + m_0\right)}{\pi R_{\max}^2} + \frac{\tan \varphi_{ag} m_s \left(g \cos \alpha + 4\pi^2 N^2 \tan \varphi_s R_{\max} \sin \alpha\right) K_1 \sin \alpha}{\pi R_{\max}^2} \tag{5}$$

Figure 5 shows two relationships: the first (1) one was obtained by direct measurements while the second (2) one was calculated as per equation (5). With the exception of the initial stage, the borehole was drilled with no applied axial load from the drilling rig but just under the weight of the bit and soil on it and also due to reaction force from soil displacement upward.

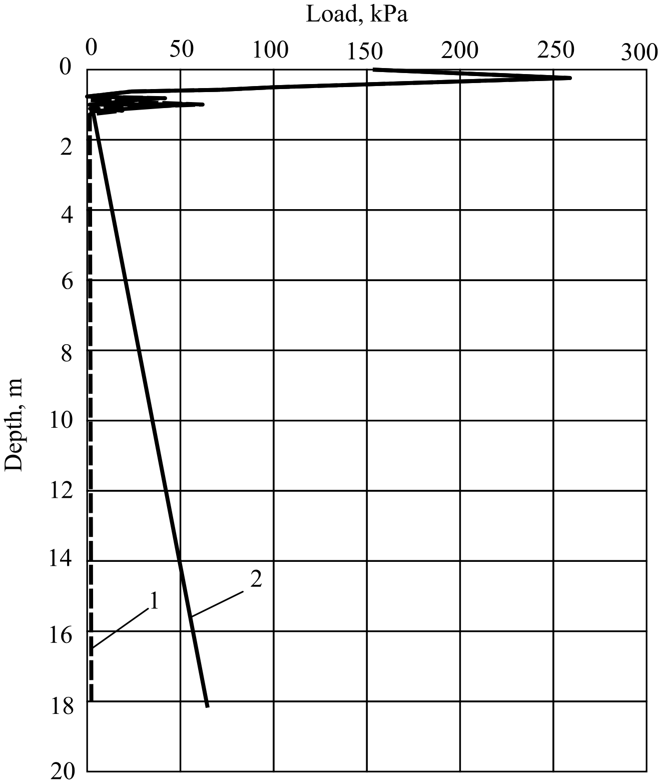

Figure 5. Vertical load *Q* (1) and tip resistance *P* (2) profile

The value of the downhole torque *M* can be found from the moments equilibrium condition:

$$\sum M = M_{\text{rot}} - M_f - M = 0, \tag{6}$$

where M_{rot} = measured torque, created by the drilling rig; M = torque share for soil destruction downhole; M_f = drilling bit friction force moment against borehole wall, which is found from the following expression:

$$M_f = \tan \varphi_{ag} m_s \left(g \cos \alpha + \tan \varphi_s R_{\max} \omega^2 \sin \alpha\right) \times \times K_1 \cos \alpha R_{\max} \,. \tag{7}$$

Thereby the torque *M* can be calculated from equation:

$$M = M_{\text{rot}} - \tan \varphi_{ag} m_s \times \times \left(g \cos \alpha + \tan \varphi_s R \omega^2 \sin \alpha\right) K_1 \cos \alpha R_{\max} \tag{8}$$

By inserting data in equation (7) there was found the dependence of the soil friction torque against the borehole wall M_f over the torque, generated by the drilling rig M_{rot}. The main conclusion from this equation consists in that if soil is lifted to the surface along the auger then drilling parameters measurement on the surface yield results close (2-3% at Figure 1.5 rps and 8-10% at 3 rps) to the values, measured downhole (Figure 6). Hence, drilling parameters measured on the surface are identical with just a minor error.

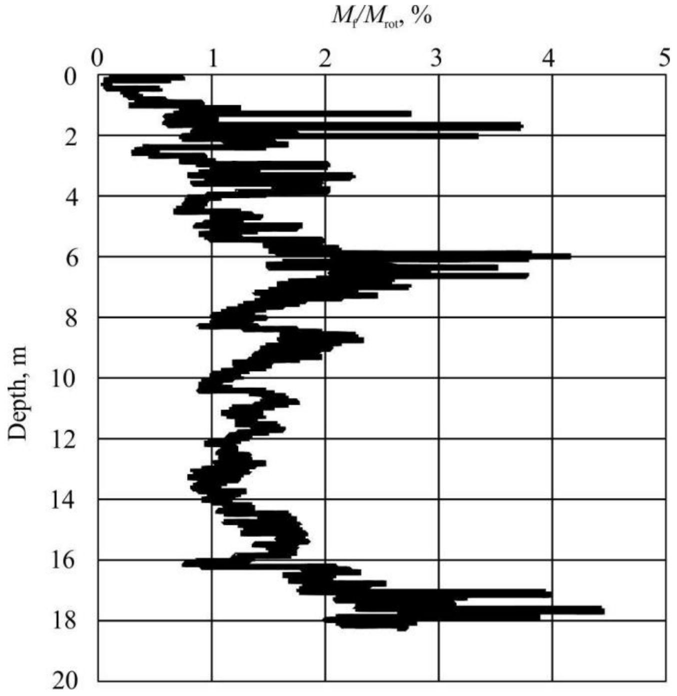

Figure 6. Ratio of soil borehole friction torque M_f against borehole wall to drilling machine torque M_{rot}

One of the parameters, measured in drilling probing, is a mechanical power of the rotating load at the current drilling depth, kJ/s:

$$A = 2\pi M\omega, \tag{9}$$

where M= current torque; ω= drill bit rotation frequency.

This parameter relates to work per second (power), and is called specific work. Analysis of test results showed formation of "gaskets" i.e., uncontrollable deviations of profiles of work, spent on soil drill-outs. As is seen on the torque work profile (Figure 7, curve 1), the torque increases during submersion of the current auger (intervals AB and CD, and after its cleaning it drops down (intervals BC and DE). Evidently, it is not just a coincidence, and these "false" spikes of readings are caused by formations of "gaskets" and soil transportation stops. Torque work profiles calibration enables accounting for these deviations. The true value of work are the values, obtained at the beginning of the auger submersion after cleaning (Figure 7, curve 2).

Deep drilling parameters are listed at the beginning of this paper. They are used to determine specific energy, which is the amount of work, necessary for drilling unit volume of soil (Teale, 1965):

$$E = \frac{Q}{A} + \frac{M\omega}{Av} \tag{10}$$

where Q = axial force, applied to the tool in the downhole, including weight of the drilling string, weight of tool and rotating head together, axial force, applied to the drill string; v = drill tool translation movement velocity.

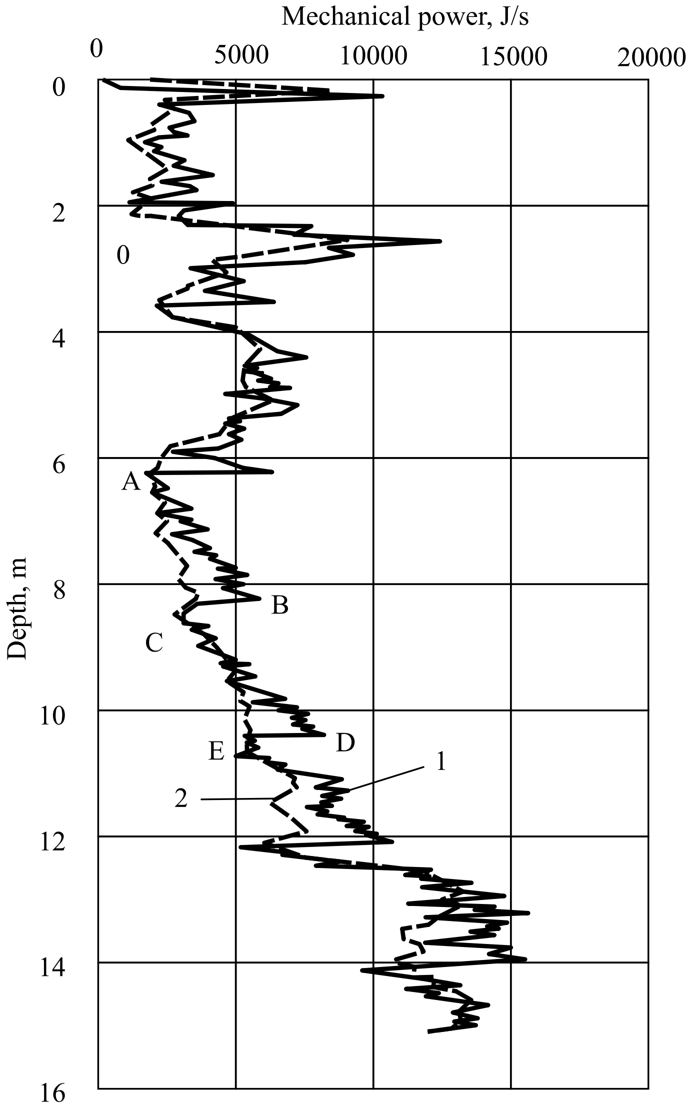

Figure 7. Mechanical power

Specific energy index is used to optimize drilling of deep vertical, slated and horizontal holes. Penetration rate depends on several factors, including the load on the tool, rotation rate, pressure gradient in the bottom hole, drilling mud, rock strength, etc. However, specific energy index is not used in engineering geology in spite of the fact that the similar holes are drilled, but not so deep. Figures 4,5 show that the role of the first addend in equation (10) on auger hole drilling is negligible as compared with the work, produced by torque. In this case equations (9) and (10) coincide. On the Figure 8 there are shown two curves, characterizing dependence of the specific work dependence on specific energy versus depth. Both graphs are almost identical and could be applied to determine the thicknesses of strata of different strengths.

Drilling parameters variation are due to soil properties. For the given type of soil or rock variations of just one of the recorded parameters are decisive. However, although it helps interpretation it is possible that two different types of soils would have a similar domineering parameters. Therefore, it is very important to do initial calibration after completion at least one hole near sampling holes, and then to compare the values of parameters with lithology, obtained from holes for sampling monoliths. In the absence of holes for sampling it is more difficult to identify the formation nature. This problem is solved easily for hole drilling with hollow full-bore augers with sampling monoliths with a thin-wall sampler.

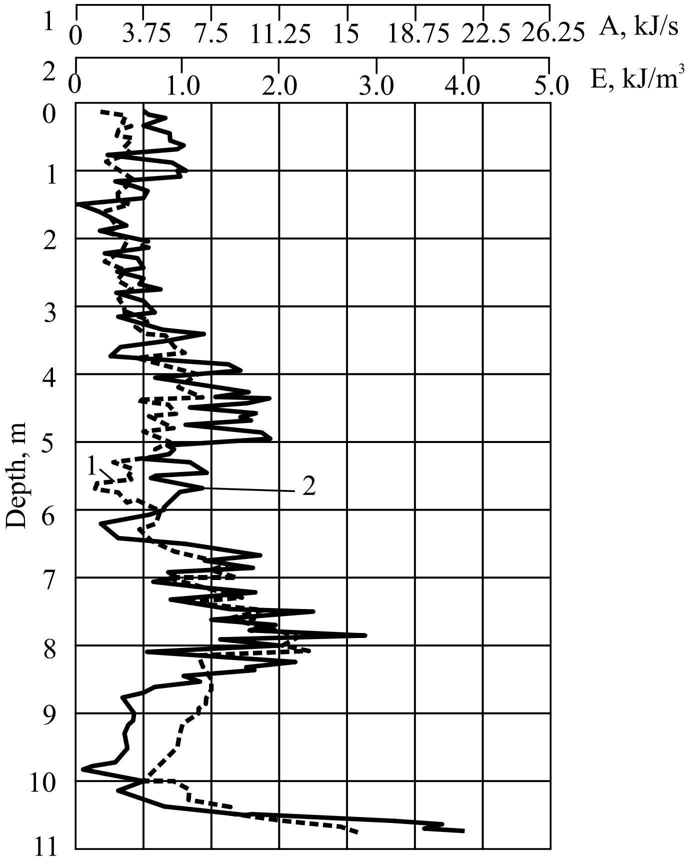

Figure 8. Specific work (1) and specific energy (2) in the course of hole drilling

2 CONCLUSION

Down-hole tip resistance is the sum (1) of the vertical load on the bit from the machine, weight of auger with the captured soil (2) and the reactive force due to soil transportation that depends on soil-soil and soil-auger materials interaction, flanges inclination angle (3). The third term can be from 1 to 30 % and more, depending on friction ratio, rotation frequency and inter-flange space filling ratio.

If soil is successfully displaced along the auger with no “gaskets” formed, then it can be assumed with less than 10% error that drilling parameters surface measurement produce realistic data on work, spent on soil drilling in the down-hole.

The portion of work for soil drilling per unit time, performed by the vertical load is much less than that by the torque (less than 5 % of the total sum).

Specific work or specific energy indices can be applied to determine soil layers thicknesses, having different strengths.

Tip resistance to auger drilling can be used to interpret mechanical properties of soils in the same way as is done for CPT. In order to do it available correlation relationships between tip resistance and soil stiffness/strength parameters can be applied.

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