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Foundation Engineering and Drilling by the Vibration Method

La Construction de Fondations et le Forage par la Méthode de Vibration

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Summary

The paper reports experimental data and theoretical studies carried out mainly by the Institute of Foundations concerning the influence vibration on the skin and internal friction of soil and the speed of driving piles into the ground. A brief review is given of the practical applications of vibration methods in the construction of foundations and in drilling in the Soviet Union.

Sommaire

On trouvera exposés dans le rapport les résultats de recherches expérimentales, effectuées dans la majorité des cas à l'Institut de Fondements et Fondations, sur l'influence de la vibration sur les frottements extérieurs et intérieurs du sol et sur la vitesse d'enfoncement par la méthode de vibrations verticales, fonction des paramètres d'oscillation avec les calculs correspondants.

En plus, un court aperçu est donné sur l'emploi de la méthode de vibrations élaborée en Union soviétique, dans différents ouvrages ayant trait à des traveaux de fondations ou de sondage (y compris sondages relatifs).

When piles, pipes and sheet piles are driven into the ground, the soil resists penetration along the sides of the driven element (frictional resistance) as well as against its bottom point (point resistance).

The frictional resistance consists of the skin friction forces (Coulomb and viscous) acting between the soil and the driven element. When the latter remains in the soil for a long time, the forces of adhesion of the soil to the surface of the driven element have to be overcome before extraction can take place; these forces act only at the beginning of extraction.

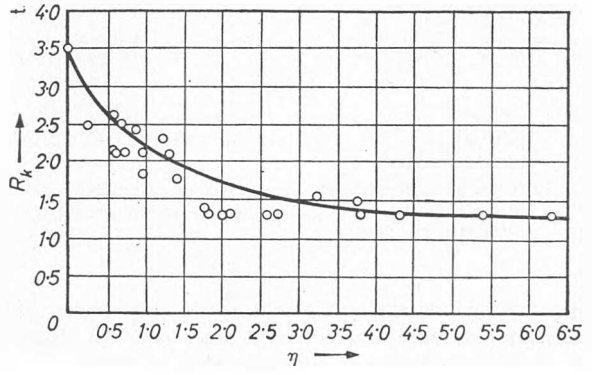

Fig. 1 Dependency of wooden pile extraction resistance R_k (ton) on the ratio η of oscillation acceleration to gravity acceleration (experiments of N. A. Preobrajhenskaja). The pile was extracted from a depth of 4 m immediately after having been driven

La résistance de pieux en bois à l'arrachement, R_k, en fonction du rapport entre l'accélération due aux oscillations et celle due à la pesanteur (expériences de N. A. Preobrajhenskaja). Le pieu fut arraché d'une profondeur de 4 m immédiatement après le battage.

Point resistance is the resistance of the soil to being pressed out sideways. The nature of the point resistance differs from the skin resistance and is determined mainly by the soil strength, which depends on the internal soil friction and adhesion forces and on the depth of penetration and the cross-section of the driven element.

Experimental research by the author (1935), carried out as long ago as 1934–37, showed that vertical vibration of the driven element leads to marked decrease in the skin resistance of the soil. Thus, during one of these vertical vibration experiments, with an amplitude of 4 mm and an angular frequency of 70 sec^{-1} on a double T beam No. 55 driven into the soil to a depth of 17 m, the resistance of the soil to extraction was equal to only 3 ton, instead of over 80 ton without vibration.

The experiments have also shown the important influence of vibration on the internal friction of sandy soil (Barkan, 1949).

In later years, the influence of vibration on the internal and skin friction of soil had been studied by the author's collaborators, Savchenko and Preobrajhenskaja. Results of research have shown (see Figs. 1 and 2) that the main vibration parameter influencing the skin and internal friction of a soil

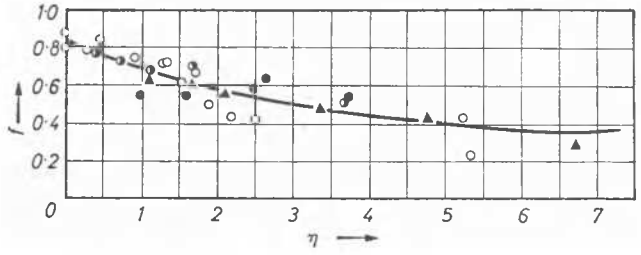

Fig. 2 Variation of coefficient of internal friction of sand (f) with the ratio (η) of oscillation acceleration to gravity acceleration (experiments of I. A. Savchenko)

Variation du coefficient de friction interne du sable avec le rapport entre l'accélération due aux oscillations et celle due à la pesanteur (expériences de I. H. Savchenko)

is the acceleration. If the skin resistance against penetration and extraction also contains adhesive forces, the effect of vibration (at constant acceleration) depends markedly on the amplitude.

The skin resistance, which depends on the penetration velocity of the piles, pipes and sheet piles, is mainly influenced by the vibration acceleration.

If the vibration is constant, its effect on the internal friction of sand depends on the moisture content and on the granulometric composition. The minimum effect of vibration was found for a moisture content of 13 per cent (by weight). For a fixed vibration the coefficient of internal friction decreases in direct proportion to the increase of the sand grain diameter.

The effect of vibration on resistance to penetration has not been sufficiently investigated at present. Experiments carried out by the author, as well as by SHEKHTER (1955) and PREOBRAJHENSKAJA (1956) have shown that the principal vibration parameter influencing pile driving speed (when penetrating to a small depth, the soil resistance is mainly at the point) is the amplitude corresponding to a recoverable penetration of the pile point into the soil at each oscillation (BARKAN, 1953). Beginning at some value of the amplitude (Fig. 3), penetration speed increases in direct proportion to the amplitude. At amplitudes below the critical value (threshold of vibrational penetration), practically no penetration is obtained.

Frequency has practically no influence on pile driving speed. Therefore, it may be said that the point resistance of the soil increases in direct proportion to vibrator frequency and thus pile driving by the use of high frequency vibrators is not expedient.

The results of experiments carried out by Preobrajhenskaja have also shown that at constant amplitude and frequency penetration speed decreases exponentially with the pile cross-

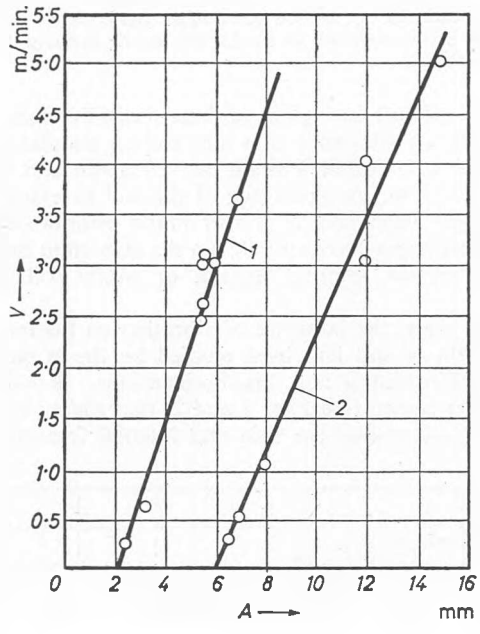

Fig. 3 Dependency of pile driving speed (V) (m/min) on oscillation amplitude (A) at constant depth (author's experiments); 1 = wooden pile; 2 = pipe, diameter 325 mm, with mandrel

Dépendance de la vitesse de battage (V m/min) de l'amplitude de l'oscillation (A) à profondeur constante (expériences faites par l'auteur; 1 = pieu en bois, 2 = tuyeau)

section. It may be assumed also that the point resistance of the pile increases exponentially with the cross-sectional area of the pile section. This result fixes the limit of practical application of the vibration method of driving piles.

The inertial and non-inertial loads acting on the driven element influence the speed and maximum driving depth, in addition to the oscillation parameters, cross-section of the driven element, penetration depth and soil properties.

When other conditions are equal there is an optimum value of the inertial load (i.e. the weight taking part in the oscillations to which the driven element is subjected) at which the speed and penetration depth reach a maximum value. This optimum value of inertial load depends on the oscillation parameters, the cross-sectional area of the driven element, the soil properties, and, in particular, on those parameters determining the influence of vibration on internal and skin friction.

The use of non-inertial loads (those not taking part in the vibrations) when the element is driven by vibration was proposed by SAVINOV *et al.*, (1954) as an expedient to increase the speed and depth of penetration. In practice this additional load is determined in each case by taking into account the vibrator design and the increase in capacity of the crane which is required to lift the sprung load.

Experimental data available at present enable the relationship between penetration speed, amplitude and frequency to be determined.

In this connection the practical value of the theory of vibratory driving and the theory of the vibration of the driven element is evident (NEUMARK, 1953).

The vibratory driving theory has been developed by V. I. Neumark, M. N. Kushul, A. V. Shliakhtin, I. I. Blekhman, the author and others.

Experimental research by the author and his collaborators O. J. Shekhter, N. A. Preobrajhenskaja and V. N. Tupikov, has shown that the linear oscillation theory may be used for the calculation of the necessary vibrator parameters, when the amplitudes are not very large (less than 10 mm), by taking into account the recoverable and non-recoverable soil reactions.

The graphs in Fig. 4 show the coincidence of calculated resonance curves (solid lines) and experimental values of amplitude (shown by circles).

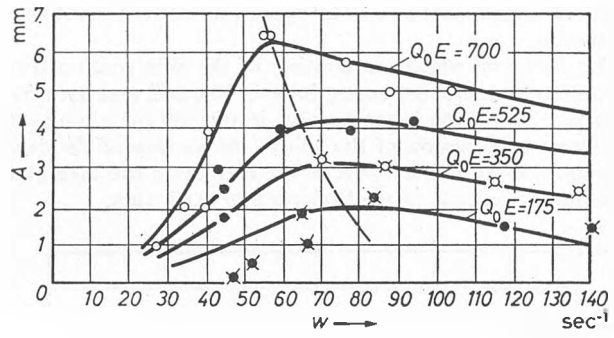

Fig. 4 Calculated and experimental resonance curves of vertical oscillations of piles (Q_0E eccentric moment of vibrator in kg/cm)

Courbes des résonances (théoriques et calculées) des oscillations verticales des pieux (Q_0E moment excentrique du vibrateur en kg/cm)

When driving is carried out by vibrators with a large eccentric moment and the amplitude is very large (over 10 mm), the linear oscillation theory is inadmissible; in these cases, in particular, the frequency of the driven element depends on the amplitude.

The values of the recoverable soil reaction do not depend on the penetration depth, while the non-recoverable reactions increase approximately in direct proportion to the depth. Because of this, the natural frequency of vertical vibration does not change with penetration depth, but the vibrator motor output increases in direct proportion to the depth; its value depends on the penetration speed.

Penetration into soil is carried out by vibrators with limiters (impact vibrators) or without limiters (TSAPLIN, 1953) the parameters of which are chosen to suit the soil conditions, penetration depth and the dimensions of driven element.

At the present time four types of vibrators, differing in parameters and in design, are used in the Soviet Union for driving sheet piles, pipes, reinforced concrete piles, cylinders, and for the construction of sand piles. The specifications of these vibrators are given in the following table.

Type of vibrator	*Speed,* r.p.m	*Eccentric moment,* kg/cm	*Unbalanced force* ton	*Vibrator weight* ton	*Motor output* kW	*Amplitude* mm	*Acceleration* g
BT–5	2,500	350	21·8	1·3	28	1–2	6 to 12
VPP–2	1,500	1,000	22·5	2·2	40	4–6	9 to 14
100	800	3,000	20	1·8	28	8–10	6 to 10
VP	400	10,000	16	5	60	10–20	3·2 to 6

In Figs. 5 and 6 are given views of vibrators VPP–2 and 100; vibrators BT–5 and VP do not differ in design from vibrator 100. Vibrator VPP–2 differs from all other types in that it has a non-inertia load of approximately 1·5 ton, including the weight of the electric motor.

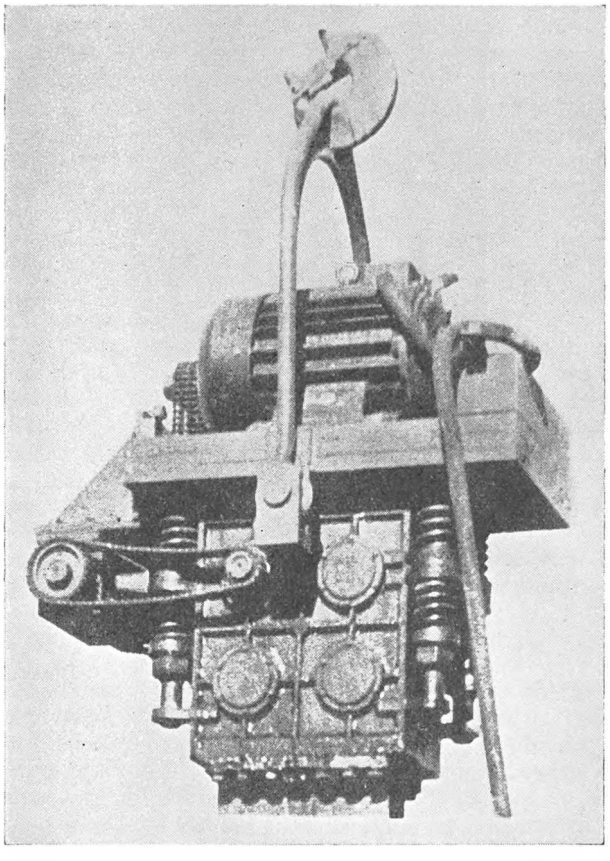

Fig. 5 General view of VPP–2 vibrator with sprung load (designed by Q. A. Savinov and A. J. Luskin)
Vue du vibrateur VPP–2 avec charge à ressort (projet de O. A. Savinov et A. J. Luskin)

The data given in the table show that as the eccentric moment increases the vibrator speed drops. Decrease of eccentric moment and increase of frequency are needed to avoid excessive increase in the disturbing force and power consumed for maintaining the oscillation.

The accelerations of the first three vibrators do not differ. Therefore, they affect the skin resistance by about the same amount.

The amplitude of these vibrators differs greatly, and thus determines their field of application. Vibrator BT–5, causing oscillations with an amplitude of only 1 to 2 mm, is used only for driving steel sheet piles into water-saturated soil to a depth up to 8 to 10 m. The penetration depth of sheet piles, when using VPP–2 vibrators (designed by Savinov and Luskin) into the same soil, is up to 12 to 14 m. Moreover, the same vibrator may be used for driving sheet piles into sand with a natural moisture content and for cutting through thin layers of clay. Vibrator 100, causing vibrations with an amplitude up to 1 cm, possesses higher driving capacity and allows sheet piles of any section to be driven into water-saturated sand to a depth of 14 to 16 m, and it cuts through clay strata of medium strength up to 4 m thick. This type of vibrator is also widely used for the construction of sand piles.

The VP vibrators, designed by TATARNIKOV (1955), are used for driving reinforced concrete piles, mainly through sandy soils, to a depth of up to 10 m, while greater depths may be reached when water jets are used. More powerful vibrators of this type were used simultaneously with water jets for driving reinforced concrete cylinders when building bridge piers.

For the first time in constructional practice vibrators were used for driving steel sheet piles during the construction of the first cellular cofferdam in the Soviet Union at the Gorky hydro-

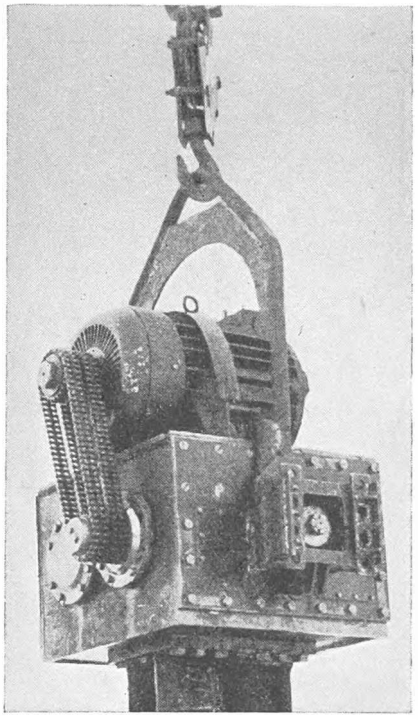

Fig. 6 General view of 100 vibrator (designed by V. N. Tupikov)
Vue du vibrateur 100 (projet V. N. Tupikov)

electric development in 1949 (Fig. 7). The technique of sheet pile driving by vibrators was established at this site. Sheet pile driving by the BT–5 vibrator into water-saturated sand to a depth of 9 to 12 m was carried out in the course of 2 to 3 minutes.

Even though the method was new, the results at this site showed that the vibratory method greatly increased the efficiency and lowered costs of sheet pile driving. It was found, in particular, that while vibrator efficiency for an 8 hour shift reached 31 sheet piles, the efficiency of a pneumatic pile-driver did not exceed 18 sheet piles. Power consumption by the vibrators was 4 times smaller than by the pneumatic pile drivers, while savings in labour cost were equal to 46 per cent. Vibrators did not require the use of compressors and air lines or steam boilers, steam lines, transportation and storage of fuel. Instead of pile-drivers it was possible to use the 3-ton tower cranes that are commonly used on building sites for lifting the sheet piles.

While the use of ordinary pile-drivers in winter conditions

(due to freezing of condensate and other causes) was hampered, low temperature in no way affected operation of the vibrator.

It was also found that the lateral displacement of piles when using vibrators was considerably smaller than when using pneumatic pile drivers.

Finally, the fact that vibrators did not deform the sheet piles and permitted easy extraction without using heavy pile lifting equipment enabled the same piles to be used repeatedly. When the cellular cofferdam became unnecessary in 1955 all the sheet piles were extracted by vibration and were used at other sites. A total of 3700 sheet piles were driven by vibration at the Gorky hydroelectric development.

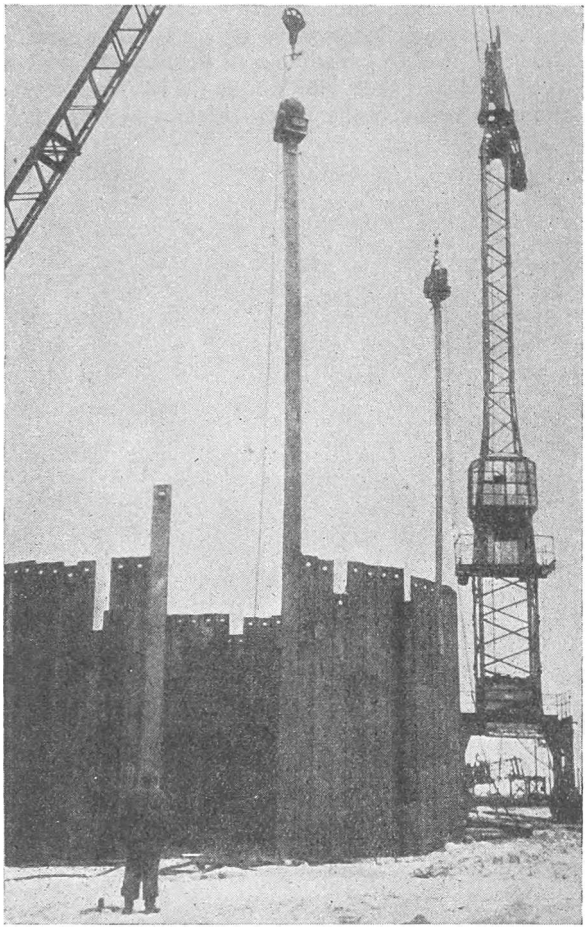

Fig. 7 Driving of steel sheet pile by vibrator during the construction of the cellular cofferdam at the Gorky hydroelectric development (driving time, to depth of 9 to 12 m, is from 2 to 3 minutes)

Battage par vibration de palplanches d'acier pour le barrage hydro-électrique Gorky (enfoncement de 9 à 12 m, en 2 ou 3 minutes)

The successful application of the vibratory method at the Gorky hydroelectric development served as an important impulse for further application of this method.

In subsequent years, pile driving by vibration was carried out at several large hydraulic projects in the Soviet Union (in particular, at the construction of the Stalingrad, Kama, Kuibishev, Kakhovka, Dubassovski hydroelectric stations), as well as at several industrial projects, and on the underground railway, etc.

At the construction of the Kama hydroelectric station, in complex geological conditions, heavy sheet pile sections (type PZ–38, Larsen IV and V) were driven. At the construction of the Stalingrad and Kakhovka hydroelectric stations the modern types of vibrators (VPP–2 and 100) were used for the first time, and in consequence the penetration depth of sheet piles driven by vibration was increased up to 14 to 16 m, and the efficiency of the vibrator was increased considerably. In particular, during the construction of the Stalingrad hydroelectric station (Medvedev and Shestopalov, 1953; Kalmikov and Belash, 1954) the efficiency reached 53 sheet piles per shift.

The total weight of steel sheet piling driven by different vibrators at various sites is about 70,000 ton, a considerable part of which was driven to a depth of 9 to 14 m.

Sheet piles have been driven through various soils: water-saturated sand, dense silt, sand with layers of sandy loam, clay

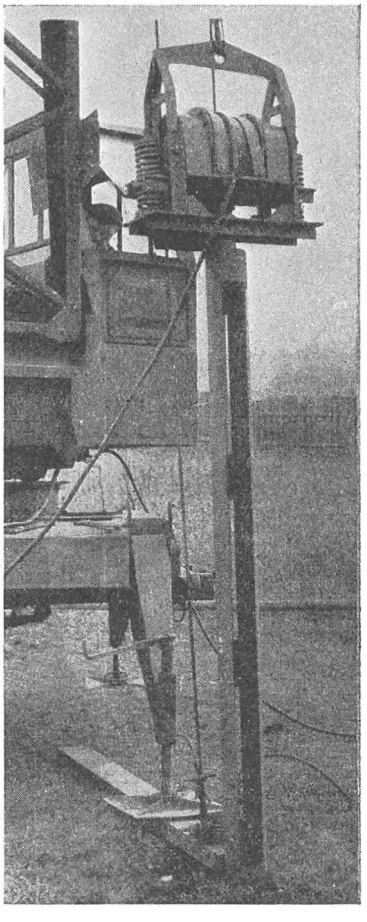

Fig. 8 'Vibrosonde' with a vibrating hammer fastened to it, used for drilling small holes

'Vibrosonde' avec marteau vibratoire pour le forage de trous de petites dimensions

and gravel. Pile-driving by vibrators was especially effective in water-saturated soil, and penetration speeds reached 10 m/min.

While vibrators were being used for driving sheet piles they were also used for other building operations at the same time. For example, the vibratory method has been used in the construction of sand piles. This work was carried out under the guidance of the author (1953), by U. M. Abelev and E. V. Svetinsky. All the principal operations for the construction of these piles (i.e. sinking of the steel pipe, compaction of the sand-gravel mixture into the pipe to form the pile, and extraction of the pipe from the soil) were carried out by the same vibrator 100 rigidly fastened to the pipe. Since the vibrator caused oscillations of large amplitude (approximately 10 to 12 mm) and low frequency, it was equipped with special shock-absorbers to prevent transmission of the vibrations to the crane.

In weak, very silty, water-saturated sands, the penetration of the 325 mm diameter pipe was carried out with the aid of a vibrator to a depth of 7 m in 0·5 to 1 min. Pipe extraction by vibration greatly lowered the skin resistance to extraction and only a 4 to 5 ton crane was used. Consolidation of the ground by sand piles formed with the use of vibrators has permitted the admissible pressure on the soil to be increased from 3 to 5 times. In the Soviet Union, over 35,000 sand piles have been made with the aid of vibrators at various sites.

The use of vibrators for driving piles is of limited application, as vibrators can only overcome the high point resistance of the pile with difficulty. However, the combined method of vibration and water jets will certainly be widely used in the future.

The vibratory method, proposed by V. N. Tupikov and the author, for drilling exploratory bore holes up to 25 m deep has been found to be very efficient. The principal requirements of the equipment and drilling methods for the use of vibration in exploratory drilling have been determined by collaborators of the author (Yéfremov and Levshinsky), as well as by Gumensky, Yatsenko and others at many sites on various soils.

The vibratory method of drilling holes consists of sinking into soil, by means of a vibrator or vibrating hammer, the so-called 'Vibrosonde' comprising a short pipe with a vertical slit (Fig. 8). The 'Vibrosonde' is sunk 2 m into the soil, and is then extracted with its core.

Research has shown that soil specimens obtained in this way do not differ in their physical and mechanical properties from specimens taken directly from pits and give quite a precise knowledge of the lithological properties of the soil.

This method of drilling holes may be used for depths up to 25 to 30 m in various soils and has very good technical and economic qualities.

For drilling the holes it is best to use light-weight vibratory hammers (instead of vibrators), their output being 1·5 to 2 kW, and their weight from 100 to 120 kg. This ensures easy transportation, which is very important for geological prospecting.

For drilling hard rock (granite, dolomite, marble, etc.), and especially for drilling at great depths, the foregoing method is no good and the tool must be rotated.

Experimental research, carried out under the guidance of E. L. Tachiev and the author, by V. M. Slavsky, F. F. Voskresensky and G. D. Viskrebtsov has shown that the use of vibration on a rotary bit not only greatly increases the drilling speed but also markedly increases the depth drilled by one bit.

Experiments have shown that the effect of vibration (accounted for by increase in the drilling speed) rises in direct proportion to the live and dead loads on the drill and reaches a maximum value at an optimum bit speed, which is in the range of 100 to 150 r.p.m. for hard rock.

The use of vibrations at the top of drill rods during rotary drilling is only satisfactory for small drilling depths (not more than 25 to 30 m); for greater depths special shaft vibrators fixed directly over the bit must be used.

The vibratory method also promises to give interesting results, from the practical point of view, in other constructional operations, particularly in mechanical earth excavation (Shkurenko, 1956). Experimental research on this subject carried out, under the guidance of the author, by Shkurenko has shown that it is possible to decrease considerably the shearing resistance of the soil if vibrating tools are used. Tests have shown that the effect of vibration is directly proportional to the vibration speed, and the best effect is achieved when the vibration takes place in the direction of shear; for greatly decreasing soil shear resistance (by 50 to 60 per cent, in comparison with shear resistance without vibration), the cutting tool must vibrate in the range of 150 to 180 cycles/sec.

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