

DRIVING PRECAST CONCRETE PILES BY VIBRATION*

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1. Vibrating equipment

1.1. Present situation of mechanization in the construction of pile foundations

Alongside with the overall technical development, among building industrial methods, those susceptible to be maximally mechanized are ever more extended. Increasing use of precast concrete piles was prevented for quite a long time by the lack of suitable, up-to-date equipment for driving the piles. Research work in the recent decade resulted in modern equipment for the complex mechanization of piling, largely widening the field of uses of precast piles. About twenty years ago the maximum depth to which precast piles could be used was considered still as 12 to 15 m, whereas today precast piles are driven to a depth of 50 m and more in practice, being manufactured in lengths of 5 to 8 m according to the production and driving technology.

In the recent decade pile foundations have become rather popular, their field of uses increasing both in civil engineering and in construction. Recently, the technical-economical conditions necessary for a break-through of pile foundations are likely to exist. Multiple practical data obtained in the Soviet Union prove that piles are economical to replace strip foundations deeper than 1.5 m. During 1966 in the Soviet Union nearly 3 million precast concrete piles have been driven for housing and industrial buildings, against about 200,000 in 1962.

Recently, pile foundations began to spread also in Hungary, though no appreciable development can be spoken of. This slow trend seems to be due chiefly to the lack of appropriate, up-to-date pile driving equipment. The situation is also unfavourable as to piling rigs which are primitive and unfit for mass production, especially when place and direction of piles have to be observed accurately.

This paper deals with the vibration effect on the soil structure and mechanical properties, with problems of a group of modern equipment for

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driving precast piles, namely vibrators and vibrating hammers, as well as with their proper use. Though correlations between technological and structural problems of pile foundations are outside the scope of this study, nevertheless it has to be stressed that a right solution for pile problems involves complex consideration of both structural and technological problems.

1.2. Different kinds of pile driving equipment

The latest development trend is to use vibrators and vibrating hammers for pile driving. Vibrated-in sheet piles have been used for quite a while, whereas for pile foundations, vibration is used only since recently.

According to the kind of dynamic effect, vibrators belong to two groups:

- vibrators of a pure vibration effect;
- vibrating hammers combining vibration and blow by transmitting, besides of periodical vibrations, also periodical impacts on the loaded body.

The following can be said in favour to use vibrators and vibrating hammers for pile driving:

- they are safe in operation and permanently ready for use, pile driving requires no preparatory work;
- they can be used not only for piles but also for large diameter pile wells, even over 2 meters (wells of this size cannot be driven by simple ramming);
- pile driving can be completely automatized with constant control of the stress arising in the pile;
- either vibrators or vibrating hammers can be used in groups for driving pile wells, in this case individual vibrators and vibrating hammers may be of low efficiency and machines of different efficiencies can be grouped.

1.21. Vibrators. The method of pile driving by vibrator is known for about 30 years, without exactly defining its field of uses.

It seems expedient to classify vibrators in 3 groups according to their practical use:

- lightweight vibrators up to 15 kW
- medium weight vibrators of 15 to 44 kW
- heavy weight vibrators over 44 kW

According to laboratory and field tests, specific uses of vibrators in each category are the following:

Lightweight vibrators (2.2 to 10 kW) suit for driving elements of small cross-section and of about 100 to 300 sq.cm surface in granular, water saturated soils.

Medium weight vibrators (11 to 25 kW) suit to drive or extract 15 to 25 cm diameter steel tubes or to drive 10 m long, 35 cm diameter timber piles.

•26 to 44 kW vibrators can drive 25×25 cm reinforced concrete piles to a depth of 7 to 10 m, and heavy-duty sheet piles to about 15 m depth.

Medium weight vibrators lend themselves for most foundation work in residential and industrial building.

The group of heavy weight vibrators includes vibrators of 80 to 200 kW. With 80 kW vibrators, piles of 2 m \varnothing can be driven to 8 to 12 m in granular, saturated soil. Vibrators of 160 to 200 kW are used for driving large size well piles 2 to 6 m \varnothing to depths of 15 to 20 m.

1.22. *Vibrating hammers.* Some 10 years ago, vibration effect and blow had been combined by a new system pile driving equipment; the vibrating hammers. Though there exist vibrating hammer types proved by tests in the Soviet Union, in Poland and in Germany, their improvement in design and performance goes on. In the Soviet Union 4 or 5 fundamental types are being developed. Field tests on these new type vibrating hammers have been accomplished and serial production started.

Test results with vibrating hammers showed the pile driving technology to be essentially simplified.

Vibrating hammers operate at frequencies lower than vibrators do, these being in general from 400 to 3600, and from 400 to 1400, respectively. The main objection to vibrating hammers is that pile driving occurs under the own weight of the equipment. The dynamic effect imposes extra loads on the motor of the vibrating hammer the axle of which gets soon deformed. Long-term field tests in the Soviet Union and experiences with vibrating hammers — handed out to different construction enterprises for observation — established that the motor of the vibrating hammers might be considered as safely operating up to 200 hours working time. Experimental data show that a machine with properly chosen rating is able to drive a pile to the desired depth in about 10 to 25 minutes, what means that one motor can drive 600 to 700 piles. Obviously, not the entire vibrating hammer but only the motor has to be replaced after 200 hours which may be mass-produced cheaply.

The prospective extension of vibrating hammers is helped by the fact that some kinds are directly suitable for earthwork compaction as well.

Also the vibrating hammers can be divided into 3 groups:

Lightweight vibrating hammers of max. 2.2 to 6 kW power are suitable to drive elements up to a surface of 300 sq.cm in cohesive soils, including clays. Vibrating hammers of 11 to 15 kW can drive reinforced concrete piles 5 m long and 25 \times 25 cm \varnothing .

Medium weight vibrating hammers (22 to 44 kW) are used to drive reinforced concrete piles of 35 \times 35 cm cross-section to 10 to 12 m depth, whereas heavy sheet piles can be driven to 16 to 18 m depth.

Heavy weight vibrating hammers are of 45 to 80 kW efficiency. They are able to drive reinforced concrete piles of 40 \times 40 cm cross-section, to depths of 12 to 14 m or to drive 1 m \varnothing tubular piles in medium cohesive soils to 10 to 12 m.

Vibrating hammers over 80 kW are not designed, because of the undue difficulties in constructing such a formidable equipment, i.e. choice and manufacture of the hammer springs and the important stress increase in the mechanism. Besides, there is no need for an even more powerful apparatus for example in driving heavy piles; if necessary, several vibrating hammers can be electrically connected and operated in synchron.

Efficient site use of vibrators and vibrating hammers depends on the correct selection of the different types with regard to pile dimensions and soil conditions. Vibrators and vibrating hammers are very useful to drive piles, tubes and other elements, but their wide-spread use is only to be expected after theoretically clearing structural problems of the driven elements and improving the lifetime of vibrator and vibrating hammer mechanisms. Shockproof motors for vibrating hammers are of major importance.

2. The optimum conditions of pile driving by vibration

2.1. Physical aspects

In vibrating piles, axial oscillation of the pile has to be aimed at. Using a vibrator of an adequate type and gradually increasing the number of excenter revolutions from zero to a determined limit, a displacement between pile and soil causing rupture occurs within a rather narrow frequency range. The frequency corresponding to this instant is the rupture frequency denoted by ω_{mean} .

After rupture, the pile movement in the soil mass has been observed to become similar to that of a piston in a cylinder and the soil resistance to sharply decrease. In consequence, for driving or extracting the pile a relatively small external force suffices, a tenth or hundredth part of the force necessary to produce the same effect without vibration.

By further increasing the vibration frequency, the amplitude becomes constant, approaching the amplitude A_0 of the pile's natural frequency.

This phenomenon can be well followed on diagram 2.1. The continuous line represents the actually measured variation of vibration amplitude of the pile, while by dotted line is shown — as reference — the vibration curve which would arise if adhesion between pile skin and soil were strong enough to prevent rupture during vibration.

Diagrams 2.1 *a* and *b* are for the cases where rupture between pile and soil occurs in the ranges below and above resonance, respectively.

The former effect occurs upon driving the pile with a low-frequency, heavy vibrator, while the second curve applies to the case where a high-frequency vibrator can excite a stimulus too small to induce rupture between

pile and soil in the range of resonance. This accounts also for the resonance occurring when piles are driven by high-frequency vibrators.

As to the examination of soil-borne phenomena, these are extremely complicated and only their general bearings are known so far.

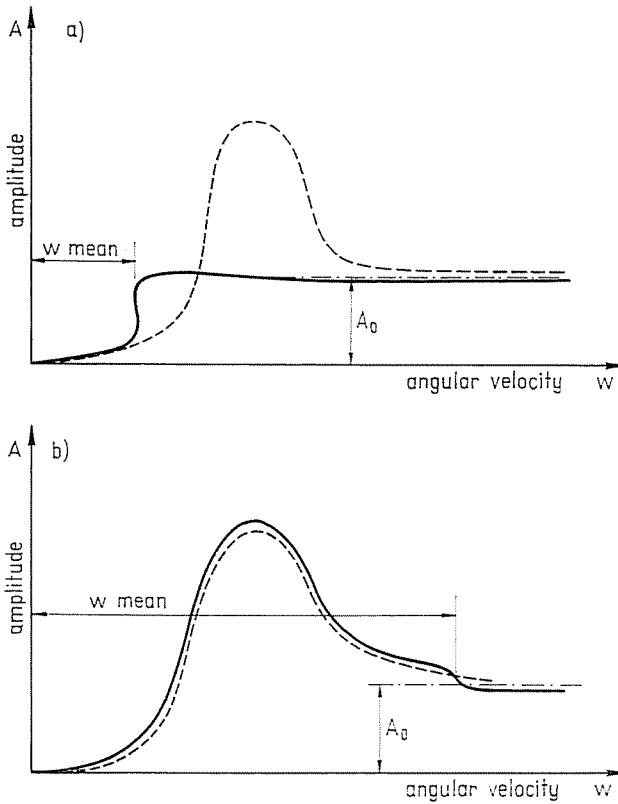


Fig. 2.1. Relationship between vibration amplitude and frequency

Results of special experiments and of field observations on the behaviour of soil grains in the area directly adjacent to the *pile surface* show that the standard process occurring in this zone, i.e. soil compaction, is due to quite a number of factors, such as wedge effect of the pile, vibration, flow of ground water pressed out of the pores during soil compaction. This process is additive to the temporary weakening of adhesion between soil grains and the pile shaft.

Field tests had proved that not only in sands, but also in weak cohesive soils, compaction occurs in a zone around the pile corresponding in size to twice or three times its diameter. This is also indicated by the settling on the surface.

In saturated loose soils, partial or complete loosening of the soil in the domain around the pile during driving is a rather common phenomenon. No doubt, interior and exterior connections of the soil grains are weakened, favouring more or less the decrease of the friction resistance on the pile skin arising during driving.

Assume a heavy body with a plane bottom supported on a horizontal surface. If this body is to be displaced, a horizontal force — exceeding the friction force — is to be applied. Vibration i.e. application of a periodical force of suitable frequency and amplitude enables any small exterior horizontal force to induce a displacement, in spite of the fact that no change occurred in the physical condition neither of the moving material, nor of the material remaining in place. Here these periodical forces counteract by themselves the friction, changing completely the behaviour of the moving body which is subject to an exterior force.

The course of the same phenomenon is much more complicated in soil, where it is related to the soil grain displacement, the phenomenon itself, however, remains the same.

The phenomenon occurring in the *soil area under the pile tip* is not less complicated. Here also the grains get compacted, but in addition the laterally and upwards directed expulsion of the soil is of importance. In saturated soft soils this process goes ahead rather easily, because of the loosening produced by vibration, in cohesive soils and under other difficult conditions, however, the impact effect of the pile tip is of decisive importance.

2.2. Factors influencing depth and rate of pile driving

2.21 *Theoretical considerations.* Many research workers studied the problem of driving piles by vibration. Several of them tried to establish a relationship between driving rate and the characteristics of the vibrating machine, supposing that skin friction and tip resistance values are constant during driving and are independent both of the frequency and of the amplitude. Experiments prove without doubt that skin friction and tip resistance values change during driving. This follows from the fact that vibration alters both the angle of internal friction and the soil cohesion. Especially in sand soils, vibration has a substantial effect on pile tip resistance. A large group of theories, (by NEUMARK, KUSUL, BLACKMANN) neglect the relationship between soil features and the change in pile tip resistance, supposing the displacement of the pile to be linear between given limits. With such reservations these theories can be used to determine the factors influencing the driving rate.

According to these theories, the tip resistance of the driven pile increases up to the point where the pressure at its tip reaches a maximum. A further displacement would leave the tip resistance unchanged. At this stage, the

relationship between the tip resistance arising in the soil and the depth of the driven element is plotted in diagram 2.2. Point *A* in the curve corresponds to the instant of the impact between the pile tip and the soil. Upon further driving, the soil reaction sets in and increases up to a pile displacement x_1 . In this case the tip resistance value increases linearly with the displacement. At a pile displacement $x = x_1$ also the tip resistance reaches a maximum P_{max} . This remains unchanged until the pile begins to rise due to an exterior force. From this moment on, the elastic tip resistance gradually decreases and

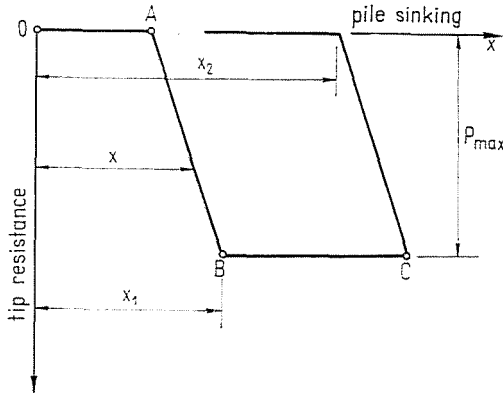


Fig. 2.2. Change in pile tip resistance during one vibration period

when the contact between soil and pile tip ceases, the tip resistance is zeroed. Upon further lifting, the tip resistance x_2 remains 0. After reaching its maximum lift the pile begins to sink again, after a time, the pile tip collides against the soil, and the whole process is repeated.

A vibration amplitude drives in the element by a length \overline{BC} , depending on the soil properties, on the load applied on the driven element and on the vibrator rating.

Study of the process of vibrational driving shows the essential factors to be:

- intensity of vibration, to decrease internal resistance of the soil;
- magnitude of driving force (weight of pile, of vibrator and of other equipment) as direct cause of sinking.

Experimental results show that a pile can only be driven by vibration at an amplitude over a value A_0 as seen in Fig. 2.3. The critical amplitude corresponds to the limit value of elastic soil resistance. The critical value A_0 depends mainly on the vibration frequency, on the soil properties and on the pile size and shape. *The larger the pile cross-section and the lower the frequency, the higher is the critical value A_0 .*

Fig. 2.3b clearly shows the vibration amplitude to be approximately proportional to the moment of the vibrator excenter, and a relationship to exist between the sinking rate and the amplitude. The curve shows the *pile driving rate to increase together with the amplitude up to an efficiency limit A_n* , beyond which the rate cannot be increased any more.

Soil friction on the pile skin surface is overcome by a vibration frequency sufficient to develop a coercive force able to counteract this soil resistance.

Let us mention that the *favourable effect of frequency on the driving rate* — all other conditions being constant — *can only be felt in a limited*

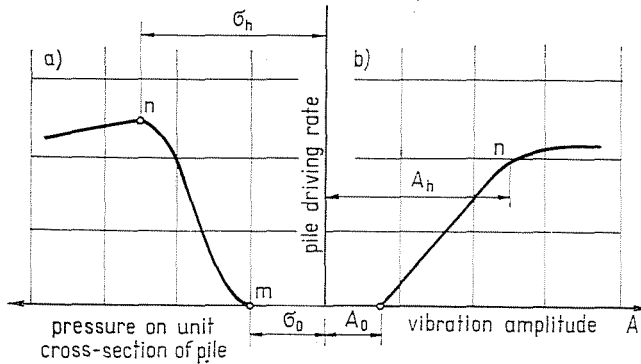


Fig. 2.3. Pile driving rate vs. a) sole stress transmitted to the pile; b) vibration amplitude

zone. Both theoretical and experimental results evidence restrictions of the frequency effect on the driving rate. Actually, empirical data are available, helping to determine specific critical resistance values of a pile or a sheet pile as a function of the soil properties and of the structure to be driven.

The magnitude of the resultant external forces affects essentially both the penetration rate and the greatest depth possible. As shown in Fig. 2.3a, the pile will begin to sink when the soil load — including the dead load of the pile — exceeds a certain critical value σ_0 depending on the soil properties, on the pile size and the vibration system. *The driving rate is at its maximum for a given value σ_{eff} beyond which the penetration rate decreases again. Outside of a certain range — extreme values of the ratio G/P_g of resultant external forces to the exciting force — the penetration stops altogether.*

In Fig. 2.4 driving rates are plotted against the vibration amplitudes of the driven element, for tip resistance values obtained in different soils. The theoretical relationship between driving rate and amplitude has been confirmed by experiments.

The correctness of the theory of an initial sinking threshold and relationship between the sinking rate and the vibration amplitude being proved,

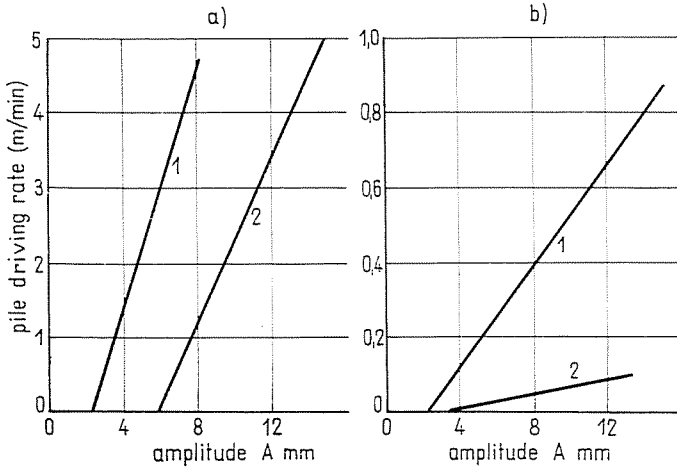


Fig. 2.4. Pile driving rate vs. vibration amplitude

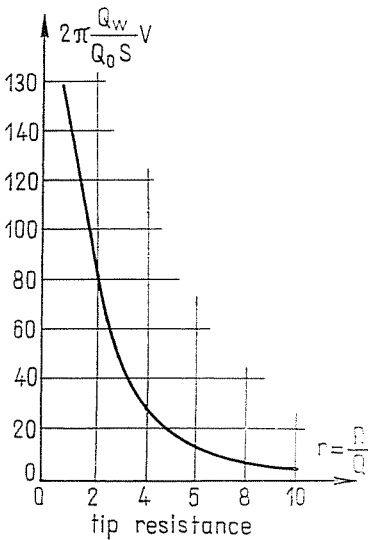


Fig. 2.5. Effect of tip resistance on the penetration rate

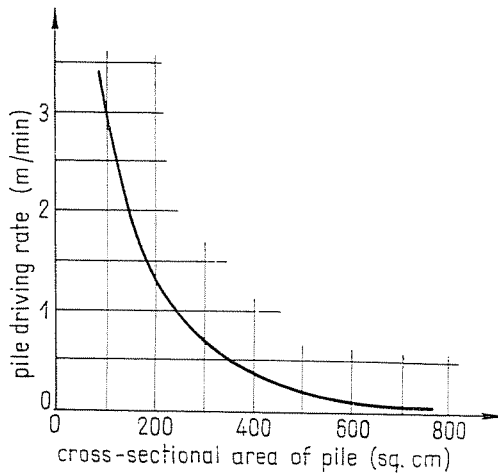


Fig. 2.6. Rate of wooden pile penetration as a function of the cross-sectional dimension

it seems obvious that the proportionality factor between driving rate and vibration amplitude depends on the magnitude of tip resistance. In Fig. 2.5 the change of the proportionality factor is plotted against the tip resistance of the soil. The driving rate is seen to decrease substantially with increasing soil tip resistance. Supposing the increase in tip resistance to be proportional to the cross-sectional area of the pile to be driven, Fig. 2.5 may be considered

to give the relationship between the driving rate and the cross-sectional area of the pile. Experimental data plotted in Fig. 2.6 confirm theoretical relationships shown in Fig. 2.5. Both rate and depth of driving being substantially reduced along the increase of the soil bearing capacity, therefore the use of vibrators is practically limited to the case of relatively low tip resistances. This is why vibrating hammers are especially important in practice, suiting to overcome high tip resistances.

2.22. *A practical method to ensure conditions of an efficient pile driving.* Deductions published by the quoted authors are too complicated to be used in practical design. A practical method taking into account the factors affecting pile driving rate and depth has been developed by O. SAVINOV and A. LOUSKIN and can be recommended for choosing vibrators of adequate type and rating, without the risk of major mistakes.

Efficient pile driving requires the following three conditions to be met:

a) *The exciting force of the vibrator must be sufficient to overcome the soil resistance in the greatest depth required:*

$$P_g \geq x_0 \cdot P_{\text{crit}}$$

where

P_g — exciting force

x_0 — a constant taking into account the elasticity of the soil:

for low-frequency vibrators $x_0 = 0.4-0.8$;

for high-frequency vibrators $x_0 = 1.0$

P_{crit} — the force of rupture between pile and soil in the greatest depth.

For piles:

$$P_{\text{crit}} = u \cdot \sum_{i=1}^n \tau_i^k \cdot h_i$$

where

u — perimeter of the pile

h_1 — thickness of strata penetrated by the pile.

For sheet piles:

$$P_{\text{crit}} = \sum_{i=1}^n \tau_i^{k'} \cdot h_1.$$

Values of τ_i^k and $\tau_i^{k'}$ are compiled in Table 2.1.

Table 2.1

Kind of soil	τ_k (pile)			τ_k (sheet pile)	
	Mp/m ²			Mp/m ²	
	timber piles; steel tubular piles	r. c. piles	well piles	light weight	heavy weight
				sheet piles	
Water-saturated sand and soft clay soils	5.9	6.9	4.9	11.8	13.7
As above, but intersected by hard clay stratum or by dense gravel stratum	7.8	9.8	6.9	16.7	19.6
Plastic loamy soils	14.7	17.6	9.8	19.6	24.5
Semi-stiff and stiff clay soils	24.5	28.4	19.6	39.3	49.0

b) The vibration amplitude must adequately exceed the initial amplitude

$$A = \frac{\xi \cdot M}{m} \geq A_{\text{req}}$$

where

- M — moment of forces arising in the rotation axis;
 m — the combined mass of the vibrator, the pile and other rigidly connected parts;
 ξ — 0.8 for reinforced concrete piles and 1.0 in other cases;
 A_{req} — the required amplitude, greater than the critical amplitude.
Proposed values are given in Table 2.2.

Table 2.2

Frequency ranges (min)	Sand soils			Loamy soils		
	300—700	800—1000	1200—1500	400—700	800—1000	1200—1500
Driven element:						
Sheet pile: open end steel tube of up to 150 cm ² cross-sectional area	—	8—10	4—6	—	10—12	6—8
Timber and closed-end steel tubular piles of up to 800 cm ² cross-sectional area	—	10—12	6—8	—	12—15	8—10
Dense reinforced concrete piles of up to 2000 cm ² cross-sectional area	12—15	—	—	—	15—20	—
R. c. tubular piles, soil extracted during sinking	6—10	4—6	—	8—12	6—10	—

c) Resultant forces should be so high as to provide for a suitable rate of pile driving

This condition is satisfied in practice if

$$G \geq \sigma_{\text{req}} \cdot F; \quad V_1 < \frac{G}{P_0} < V_2$$

where

- G — combined weight of the pile, the vibrator and other accessory loads;
- F — pile cross-section;
- σ_{req} — specific load applied on the pile, required to exceed the critical load. Values are given in Table 2.3;
- V_1 and V_2 — for heavy piles $V_1 = 0.4$; $V_2 = 1.0$
 for lightweight piles $V_1 = 0.3$; $V_2 = 0.6$
 for sheet piles $V_1 = 0.15$; $V_2 = 0.5$

Table 2.3

Size and form of pile	σ_{req} Mp/m ²
Steel tubes and other elements up to 150 cm ² cross-sectional area	150—300
Timber piles and closed-end steel tubes, of up to 800 cm ² cross-sectional area	400—500
Reinforced concrete piles up to 2000 cm ² cross-sectional area	600—800

3. Test results obtained with vibrators and vibrating hammers

To substantiate results of theoretical investigations and laboratory tests, numerous field experiments had been carried out with piles used in building. In Fig. 2.4a, data of piles driven into a muddy, saturated sand soil by applying different amplitude vibrations are plotted. The straight line (1) shows the driving rate of a 27 cm diameter timber pile, the straight line (2) that of a closed-end steel tube of 37.5 cm diameter. In Fig. 2.4b the penetration rates into stiff clay of the same size timber pile (1) and steel tube (2), respectively, are plotted.

Test results indicate that *rate and depth* of pile penetration are affected primarily by the *amplitude rather than by the vibration frequency*. Thus, *pile*

driving vibrations should be of low frequency, with a great moment of excentricity providing for vibration of adequate amplitude.

As not only skin friction has to be minimized in pile driving, but also the soil resistance under the pile tip has to be overcome, either heavy vibrators or vibrating hammers should be employed.

Combined use of vibrators and vibrating hammers is expedient also in cases where piles cannot be driven by vibration to the required depth.

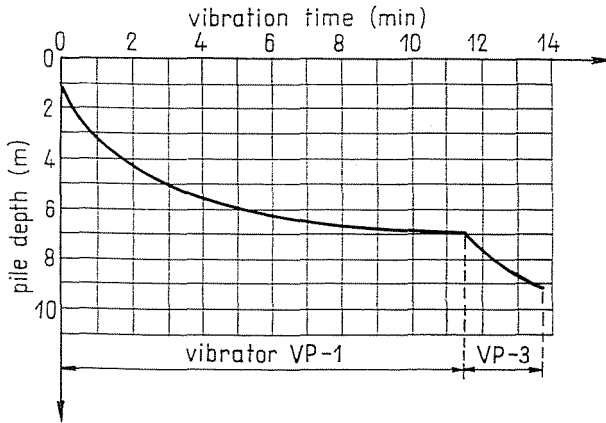


Fig. 3.1. Pile driving by vibrators type VP-1 and VP-3

The use of heavy vibrators is wide-spread for driving large diameter tubular piles and well piles with relatively small resistance at the pile tip.

In Fig. 3.1 the difference in outputs of vibrators VP-1 and VP-3 is plotted for identical soil conditions. Driving the experimental reinforced concrete pile of a cross-section 35×35 cm and a length of 10 m in dry, cohesive sand was begun with a vibrator type VP-1. As it is seen in the figure, the pile could be driven in 9.5 minutes to a depth of 6.7 m. The driving rate was 3.5 cm/min by the end of the driving, for an amplitude of 0.5 cm.

Another pile was driven to a depth of 7 m in 11.5 minutes, the final driving rate being 3 cm/min, for an amplitude of 0.6 cm. The driving depth limit for the given pile dimensions clearly appears from the driving curve which becomes parallel to the time axis.

Subsequently a vibrator type VP-3 was applied on the same piles, producing further penetrations of 2 m in about 2.5 minutes, and 2.25 m in about 2.2 minutes of the first and the second pile, respectively.

In Fig. 3.2 the data for a 40×40 cm reinforced concrete pile are plotted, driven by a vibrator type VP-3 to a depth of 10 m, in 12.5 minutes. The final driving rate was 3 cm/min for an amplitude of 1 cm.

In sand soil with clay and gravel strata a tubular pile of 0.92 m diameter and 6 cm wall thickness was sunk to a depth of 15.5 m, by combined use of a vibrator type VP-1 and of flushing. By vibration alone, without flushing and excavating the interior soil core, the tubular pile could not be driven more than to a depth of 2.5 m. The main technical characteristics for both vibrators are compiled in Table 3.1.

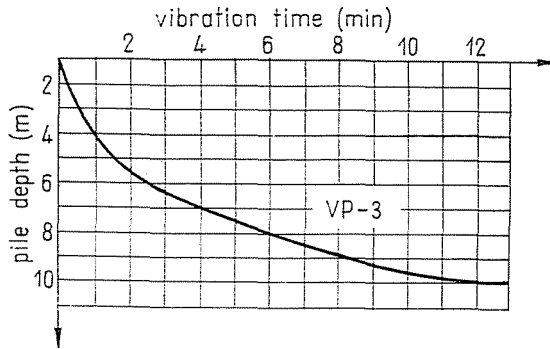


Fig. 3.2. Pile driving by vibrator type VP-3

Table 3.1

Type	r. p. m.	Power kW	Exciting force kp	Weight of machine kp
VP-1	420	60	18 500	4500
VP-3	408	100	44 200	8000

Figures 3.3 and 3.4 may be compared for outputs of a vibrator and a vibrating hammer of the same power. The efficiency of vibrators is seen to be better for small depths, resulting in a driving rate nearly twice that of the vibrating hammers. With increasing depth, however, vibrators soon reach performance limit and cannot drive the pile any further. Nevertheless, vibrating hammers work on efficiently and achieve a much greater depth.

Vibrating hammers are expediently used to drive piles not only of great tip resistance, but also to important depths, where great lateral pressures act upon the pile and vibrators are not efficient any more. The combined use of vibrators and vibrating hammers is primarily justified from economy aspects, namely, motors of vibrating hammers being actually not shockproof, they fail in substantially shorter operation times than those of the usual vibrators.

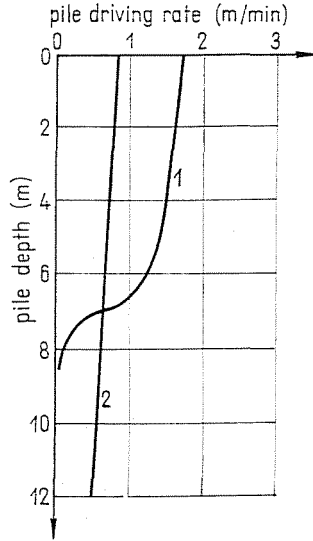


Fig. 3.3. Comparison of rates of pile driving by vibrator and by vibrating hammer, as a function of depth

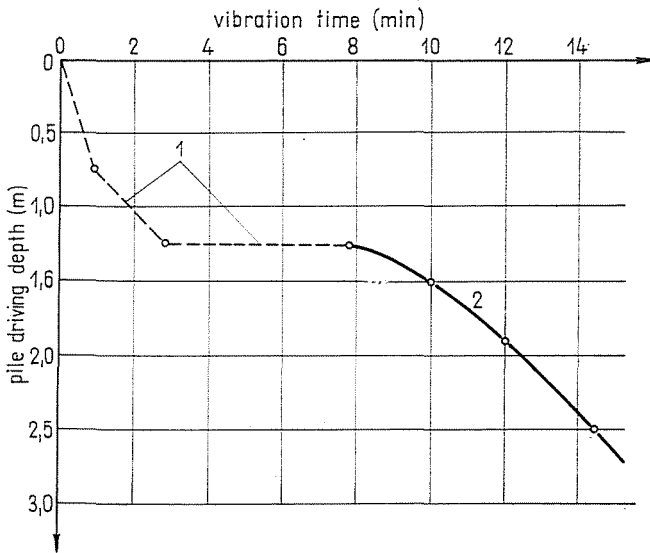


Fig. 3.4. Driving tubular piles by vibration

4. Bearing capacity of piles driven by vibration

From a survey of this study it is evident that the method of pile driving has a decisive effect on the bearing capacity. The soil masses around the pile may undergo structural changes greatly influencing the mechanical properties and the bearing capacity of the soil in relation to the initial static state, inducing either an increase or a reduction. The correct, realistic interpretation and evaluation of the interaction between pile and soil necessitate a comprehensive study of pile foundation problems, and the development of pile bearing capacity theories, taking into account technological and structural features. From the view-point of practical use of pile foundations, any backwardness in whichever of the structural, technological or load bearing theory problems delays the issue of the entire complex of the pile foundations problem.

Study of the building practice and of the technical literature in highly developed countries proves that up-to-date, highly efficient equipment types are available to drive piles to an important depth in a short time. The bearing theories, however, did not keep pace with the rapid structural and technological development and there are *no bearing theories to take into account the changes of structural and mechanical properties occurring in the soil upon vibration effects, neither reliable formulae for pile load bearing.*

Actual static and dynamic load-bearing formulae, used for pile foundations, are not suitable to determine bearing capacity of piles driven by vibrator or vibrating hammer.

In lack of adequate new design methods, certain correction factors have been applied to some accepted formulae for pile load bearing to determine the actual load capacity. Nevertheless, the important technical facilities provided by either new, up-to-date equipment motivate their practical use.

As indicated by results of comparative experiments, the applied driving method has an important effect on skin friction. In clay soils *the bearing capacity of vibrated-in piles is substantially lower than that of piles driven by ramming.* As an effect of vibration, the soil structure becomes more intensively destructed than in case of driven piles. Under the pile tip a zone of destructed soil structure is formed. After pile driving by vibration, the strength of the soil around the pile — and especially below the tip — is recovered to a smaller degree than in case of ramming.

Contrary to this, in sands vibration increases soil compactness in the domain around the pile and under its tip. This compactness increases the bearing capacity of the pile and the well pile. Therefore, in the Soviet Union, an empirical correction factor α_m , depending on the pile driving method, has been applied to the calculated values for pile skin and tip resistance (Table 4.1).

Factor α_m depends on the diameter of the pile or tubular pile. Piles under 0.8 m diameter are closed-end ones. Thus, soil expulsion intensifies the com-

Table 4.1

Structure type	Coefficient α_m				
	rammed	vibrated			
		sand	fine sand	mud	clay
Pile	1.0	1.1	0.9	0.7	0.6
Tubular pile from 0.8 to 2.0 m	0.9	1.0	0.9	0.7	0.6
Tubular pile over 2 m	—	0.9	0.7	0.6	0.5

paction compared to open-end tubular piles, from which the soil is removed during or after driving. Driving and simultaneous soil removing reduce the bearing capacity of the tubular pile, taken into consideration by the α_m value.

In heavy clays, ramming has to be preferred at present, as the pile bearing capacity decreases substantially upon vibration which is in turn less efficient than ramming. As shown in Table 4.1, the bearing capacity of *vibrated* piles in cohesive soils may be half that of a pile rammed into the same soil.

In sand soils the vibration method is more efficient as it assures an important driving rate and increases to a certain degree the bearing capacity of the pile, as compared to ramming. Thin wall reinforced concrete tubular piles ($d > 0.8$ m) are being driven to considerable depths solely by vibration, because structures of such dimensions cannot be driven by ramming.

Though in the Soviet Union essential types of vibrating hammers have been developed and serial production started, their use is not yet widely spread. *Essentially, both construction and design enterprises object to their use the lack of theoretical methods for safely computing the bearing capacity of piles driven by vibrating hammers.*

In want of a satisfactory number of tests and theoretical experiments, not even an empirical computation method exists to determine the bearing capacity of piles driven by vibrating hammers.

Though vibrating hammers will no doubt be widely spread for pile driving, popularization in this country would greatly be encouraged by comparative and analysing field test series on different types of vibrating hammers, to form a reliable basis for both theoretical and practical work now to be started.

Summary

A detailed analysis is given of factors intervening in the efficient pile driving by vibration.

Vibration frequency has but a small effect on the driving rate, it must not be lower, however, than a value required to cause rupture between pile and soil. That is, vibration frequency has to exceed the critical frequency of rupture.

Pile sinking can only start at a vibration amplitude over a threshold value A_0 . The penetration rate is significantly accelerated by increasing the amplitude. Increasing the amplitude beyond a value A_{eff} has no more influence on the pile driving rate.

For pile driving by vibration it is an important requirement that the sole pressure transmitted by the pile tip exceeds a threshold value σ_0 . Increasing it to a value σ_{eff} favours the increase of the driving rate. Beyond this limit, however, an excessive sole stress may stop the penetration.

An approximation method has been described for assessing the discussed factors and for selecting an adequate vibrator type.

Finally, the effect of vibration on the pile bearing capacity has been examined.

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