EXPERIMENTS WITH OPEN-END VIBRATED TUBES

by

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1. Scope of the experiments

In the field of pile foundations, recent development has been concentrated on highly mechanized types of bored piles. These pile types with or without steel casing, as Benoto, Bade. Salzgitter, Soletanche, Icos-Veder, Hochstrasser-Weise, etc. find an ever increasing use in engineering practice, whereas driven piles, either precast or cast in situ, seem to be loosing more and more space in this competition. Even the well mechanized Franki, Vibro, Zeiss-Universale cast in situ piles and the conventional precast reinferced or prestressed concrete types – seem to be less and less applied, in spite of the acknowledged fact that their bearing capacity is considerably superior to that of bored piles for the same diameter and length, chiefly when friction piles are concerned.

Their development could chiefly be attributed to the fact that beside the high degree of mechanization, considerably less energy is needed to bring down a thin-walled bore-casing to a given bearing layer, than to drive a solid pile. In the first case, the penetration by the casing is greatly facilitated by the continuous removal of the inner earth core, restricting resistance to the skin-friction of the casing and to the quite low bearing resistance of its cutting rim. Driving a solid pile or casing, however, involves that the soil-mass corresponding to the volume of the driven or vibrated pile is either squeezed laterally or compacted downwards, thus increasing considerably both skin-friction and tip resistance. It is to be admitted of course that this latter procedure improves the bearing properties of the penetrated soil layers and this is why the bearing capacity of driven piles, on an equal base, is always superior to that of bored piles. But this is not an economic and efficient way to increase bearing capacity and can be outweighed by a higher tip resistance on a subjacent more resistant layer – easily available for bored piles.

From this comparison it is apparent that driven piles are competitive with bored piles only when these are made with open end shells (casings). This fact is clearly illustrating the importance of open end tubular piles in the development of driven and vibrated piles.

Both laboratory and field tests have proved [2] that in cohesionless soils *driven tubular piles* may provide the same bearing capacity as solid piles, at a saving of about 30 to 40 per cent in reinforced concrete material at the same rate of driving power, at the cost, however, of slightly increased settlements. The precondition of the development of a bearing inner earth core – overtaking the role of the pile-shoe – is, either that the so-called silo-factor (i.e. the ratio of pile length to the inner diameter of tube: (l/D_b) exceeds 20 or that a slight inner conical taper [5] (1:20 to 1:40) above the open bottom facilitates the formation of a bearing bottom plug.

A special advantage was to be expected from vibration, a process being the more successful and economic in cohesionless soils, the smaller the cross-sectional area and the bigger the relative surface of penetrating element; conditions proper to open end tubular piles.

This promising perspective and the favourable practical results obtained with vibrated large diameter hollow caisson piles [6] have suggested to extend our experiments to the vibration of steel tubes and to make a comparison with driving as to bearing capacity, compaction effects and development of inner earth-plugs.

2. Testing apparatus and method

a) Testing apparatus

All tests were carried out in a steel box 1,30 m deep with a surface area of 1,40 ×1,40 m. It was filled with a fairly uniform grained fine sand to a depth of 0,95 m. A uniform density of sand was secured by manual compaction in relatively thin layers. The original void content n was checked before each test on undisturbed samples taken at a distance of 30 cm from the test tubes. Tests were carried out with three different densities. The loosest condition tested was characterized by a void content $n_1=0{,}346$ $(D_r=0{,}70)$, the medium condition by $n_2=0{,}33$ $(D_r=0{,}80)$ and the densest condition by $n_3=0{,}315$ $(D_r=0{,}91)$. Some additional tests were carried out on a coarser sand and gravel material, which was built in again in a looser condition $(n_{oo}=0{,}25,\ D_r=0{,}66)$ and in a denser condition $(n_o=0{,}20,\ D_r=1{,}0)$. In order to insure a perfect uniformity of soil material, the layers were weighed and compacted down to a previously marked level in an open bottom steel cylinder of 500 mm diameter and 95 cm long, placed in the middle of the test box and withdrawn step by step after the compaction of each layer. This material was always changed before starting a new experiment.

The test tubes were ordinary seamless steel tubes (gas tubes) with the following dimensions:

External diameter D mm	Wall thickness δ mm	Length l mm	Relative wall thickness D/δ	Weight kg	Silo-factor (l/D) rel. to $l=700$ mm
89	4,5	835	19,8	7,53	7,9 (8,75)
70	5	832	14,0	6,71	10,0 (11,7)
60,3	4,15	838	14,5	4,55	11,7 (13,4)
46,0	3,0	835	15,3	2,76	15,2 (17,5)
25,6	1,7	818	15,1	0,71	28,0 (31,5)

Driving was carried out with a 17,34 kg monkey, dropped from a height of 30 cm, whereas vibration was effected with a normal vibrator designed for the compaction of ballast under railway sleepers, with a static weight of 20 kg and with a speed of 2800 to 3200 r.p.m. (46 to 63 Hz).

The tubes driven into the test cylinder had lengths of 500 mm and 700 mm resp. When the required penetration depth was obtained, test loading was carried out by a hydraulic piston mounted in a moving frame of 5 tons capacity.

b) Development of the inner earth-core and the change of void content around, below and within the tubes

Void content changes Δn around and below the tubes have been measured at the spots 1 through 8 indicated in Fig. 1, by means of tin cells 50 ×50 ×50 mm, with their only open sides facing the surface and the tube shaft, respectively. These were carefully taken out when the respective layer was removed after vibration or driving. Later on, the tin cubes were omitted and samples were taken directly in the course of gradual removal of the layers by ordinary brass sampling cylinders, pushed into the carefully cleaned layer surface.

Changes in the void content Δn brought about either by vibration or by driving in the loosest sand material ($D_r=0{,}70$) are indicated in Fig.2. The results are presented in distances d related to the respective tube diameter D, that means that for each tube another reference axis had to be applied as the measurements were taken at constant d values (cf. Fig.1).

Negative Δn values indicate compaction and positive ones loosening; fig. *a)* represents changes due to vibration, and fig. *b)* those due to driving.

As seen, the Δn values obtained around the tube just below (60 mm) the surface, where compaction effects prevail, are rather similar. The maximum decrease in void content is about 3 per cent measured at a distance of $3D$ for

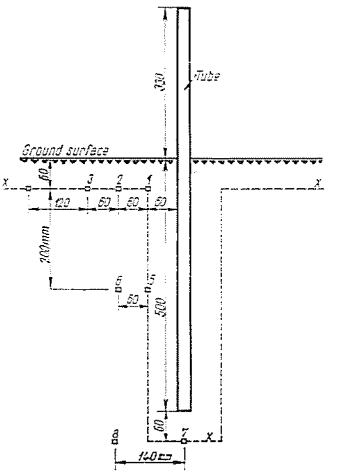


Fig. 1. Location of sampling spots

vibrated tubes; whereas somewhat bigger ($\Delta n = 3$ to 4 per cent) was measured somewhat closer ($2D < d < 3D$) to driven tubes. This can be explained by the fact that at and slightly below the free ground surface the static weight of the lateral soil masses does not counteract the upward directed oscillation movement of the vibrated soil grains and thus the arising larger amplitudes produce a more effective rearrangement of soil grains.

This compaction turned with the depth very soon to loosening, characteristic to the change of void content throughout the soil masses along the shaft of vibrated tubes, attaining values of $\Delta n = 3$ per cent. A similar trend has been observed in the case of driven piles, with the difference however that along the upper half of the tube-shaft compaction still prevailed and a more pronounced loosening arose towards the bottom.

The greatest difference was found below the bottom of the tube where a definite compaction was measured in the axis of the vibrated tubes below tip level, whereas considerable loosening took place below that of driven tubes. This might be explained by the different stress conditions below the respective tubes and by the difference in the resistance of the inner earth-cores. In the case of driven piles a highly resistant earth-core has been produced, which in turn

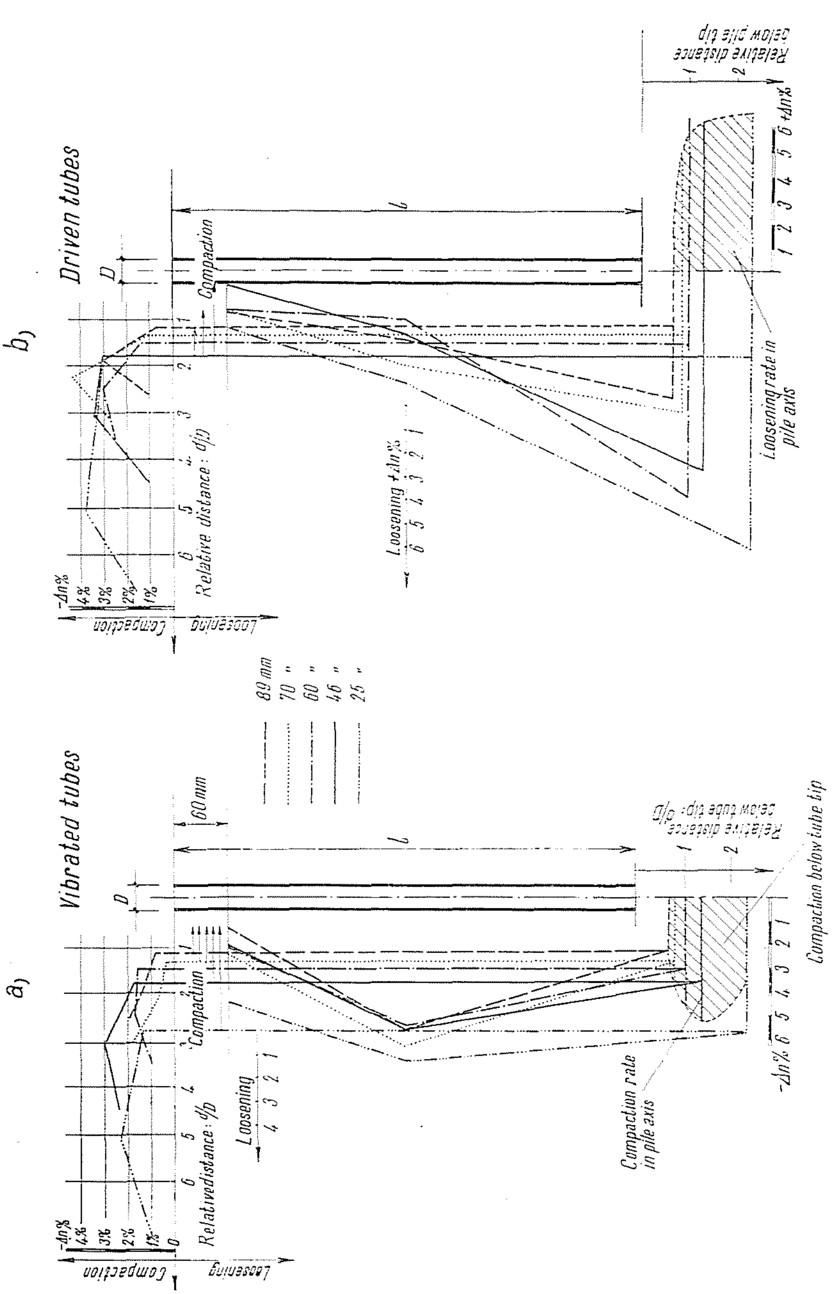


Fig. 2. Changes of void content Δn produced by vibration and by driving, resp.

might lead to plastic deformation of the underlying strata just as *Kérisel* [7] has shown it for solid piles. In the case of vibrated tubes, however, the density of inner earth-core is not so high, as it could produce plastic failure in the soil, it rather represents an elastic yielding support.

When plotting the $-\Delta n$ percentages against the relative depths below the tube tip, their maximum appears at a depth of 1,33 D (i.e. for the 46 mm dia. tube) with a rapid decrease above and below (cf. Fig.2).

As to the density of the inner earth core, it was found that at the tube-bottom, up to a height of about $D/2$, the core became well compacted, whereas overneath the increase of density was but 1/3 to 1/4 of that value. The rate of compaction was the higher, the looser the initial condition of sand material.

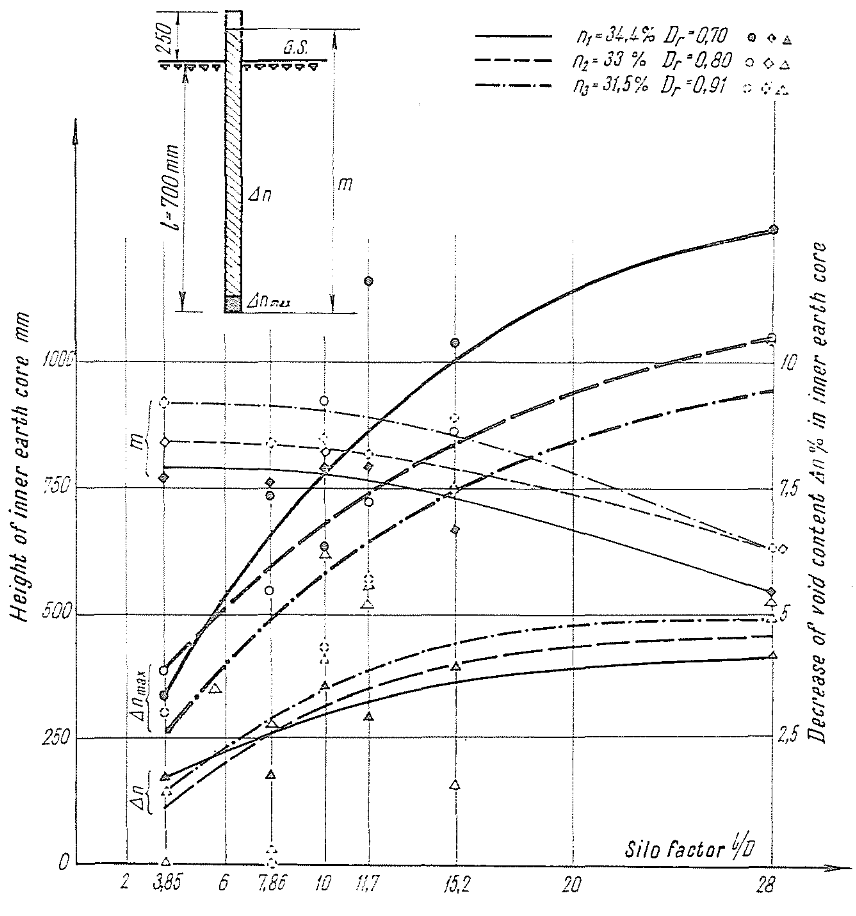


Fig. 3. Variation of the inner earth-core in function of the silo factor

The difference in the increase of density of inner earth cores in tubes vibrated in sand of the investigated loosest condition ($n_1 = 34{,}6$ per cent, $D_r = 0{,}70$) and of the densest condition ($n_3 = 31{,}5$ per cent, $D_r = 0{,}91$) reached up to 12 to 20 per cent in the $\Delta n_{\max}$ values and up to 10 to 15 per cent in the average Δn_a values. The absolute figure is naturally highly dependent upon the silo-factor l/D which may be illustrated by the fact that for the 500 mm long tubes of $D = 89$ mm ($l/D = 5{,}6$), $\Delta n_{\max}$ values of 3 to 4 per cent, and Δn_a values of 1 to 1,7 per cent were measured, whereas for $D = 25$ mm ($l/D = 20$) tubes $\Delta n_{\max}$ and Δn_a ranged from 9,5 to 12,5 per cent and from 4,2 to 5,0 per cent, resp., in function of the initial void content (Fig.3). From the course of the plotted curves it may be concluded that at a ratio of $l/D < 2$ no decrease in the original void content i.e. no core compaction can be produced by vibration at all.

The height of the inner earth-core m is also a function of the silo factor. As seen in Fig. 3, it increases (at first rapidly then only slightly) with the decrease of l/D, and below a certain limit it seems to attain a constant value. The initial void content also affects this height m; namely the higher D_r, the higher will be m.

c) *Bearing capacity of test tubes*

It is already apparent from Fig. 2 that the bearing capacity of vibrated tubes is due essentially to tip resistance while mantle-friction is likely to be negligible. This was proved by the loading tests on 500 mm and 700 mm tubes presented in Figs. 4 *a*. and *b*. respectively. It is seen that the ultimate bearing load plotted versus the cross-sectional area of the tested tubes represents a linear function for all sand densities tested and it is approximately linear in the case of the sand and gravel soils too.

When checking these values theoretically, it appeared that a very good agreement could be found, when here also the tip resistance was taken for the total bearing capacity and it was computed after Rankine's formula, i.e.

$$P = F \cdot l \cdot \gamma \cdot \mathrm{tg}^4(45^\circ + \varphi/2).$$

A fairly safe design may be obtained, when the values of γ and φ are those corresponding to the original condition of the sand test soil and the increase (about 20 to 30 per cent) brought about by the compacting effect of penetration is let to constitute a part of safety.

For sake of comparison, the bearing values of tested driven tubes are also indicated in the diagram. These are about 20 to 25 per cent higher and the increase with the cross-sectional area is more progressive, the share of skin-friction being no more negligible. The differences however decrease with the diameter.

It is interesting to note that the bearing capacity of driven tubes or of vibrated tubes with a closed tip, was more in agreement with Meyerhof's formula for tip resistance, i.e.

$$P = F \cdot l \cdot \gamma \cdot e^{\pi \cdot \mathrm{tg}\,\varphi} \cdot \mathrm{tg}^2(45^\circ + \varphi/2)\,.$$

Another interesting comparison is presented in Figs. 5 *a* and *b* where the bearing capacity of tubes is plotted against their diameter rather than against their cross-sectional area. Values obtained for tubes 500 mm and 700 mm long in the sand and gravel test soils are shown separately.

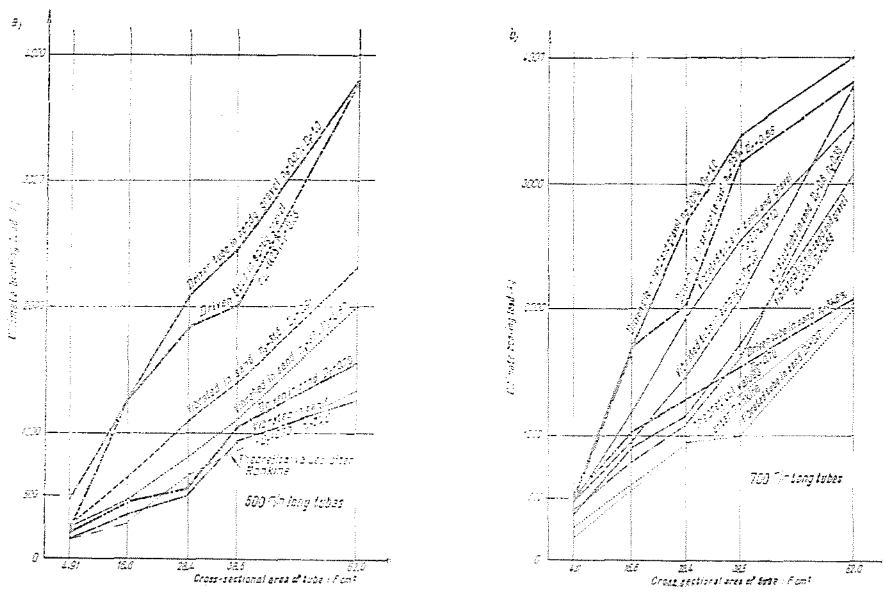


Fig. 4. Experimental bearing values of tubes: *a)* 500 mm long; *b)* 700 mm long

First of all it may be concluded that the bearing capacity of 700 mm vibrated tubes exceeds that of 500 mm long tubes by 40 to 70 per cent i.e. more than proportionally to the rate of length increase. This rate is likely to increase with the tube diameter rather than to depend on the original density of test soil. With driven tubes, however, the rate of increase has been proportional to the length (i.e. 40 per cent).

This is in accordance with the changes produced in the course of penetration by each process. Namely, skin-friction did not contribute to the bearing capacity of vibrated tubes, however it did to that of driven tubes (cf. Fig.2) and therefore the linear increase with the mantle surface in the latter case is throughout justified. On the contrary, the progressive compaction below tube tip produced by vibration governs the bearing capacity of vibrated tubes and this is likely to grow at a higher rate.

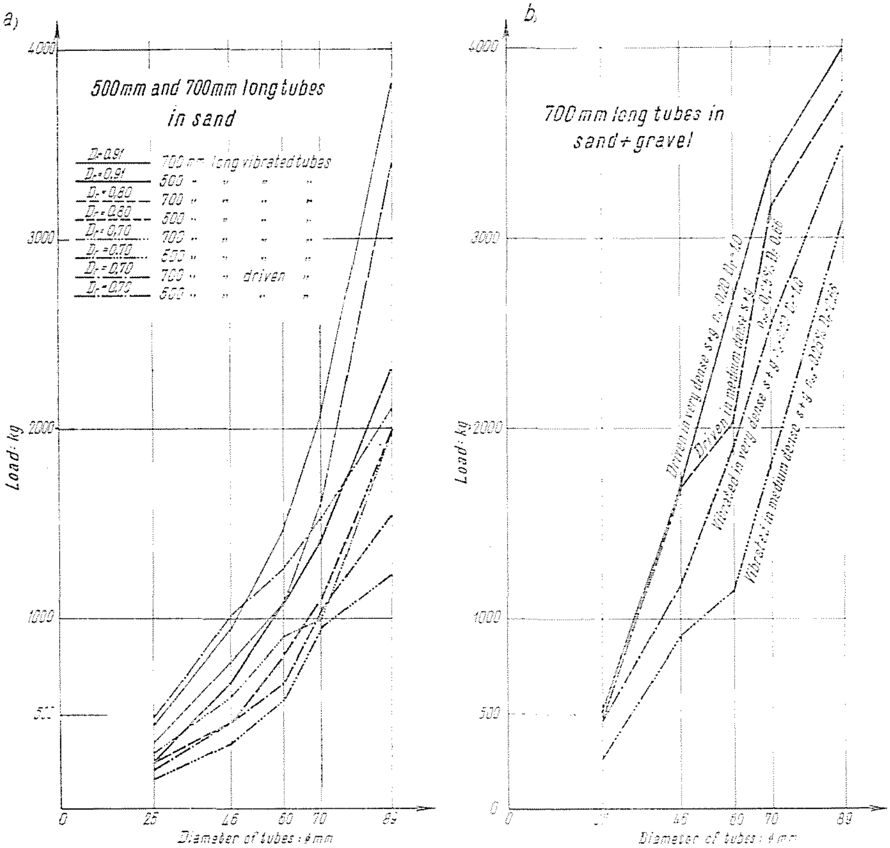


Fig. 5. Comparison of the bearing values of 500 and of 700 mm long tubes in sand (*a*) and in sand and gravel (*b*)

The same trend can be seen in Fig. 5*b* presenting this comparison in sand and gravel test soil for 700 mm long tubes. In addition, superiority of driven piles with the increase of diameter is also seen to diminish.

Finally, figures 4 and 5 give some information also about the influence of soil density upon the bearing capacity of tubes. Evidently this latter increases with the initial relative density of both test soils. The rate of increase is higher in sand with relative density ranging from D_r=0,70 to 0,80 (i.e. n_1=0,346 and

$n_2=0{,}330$), than from $D_r=0{,}80$ to 0,91 (i.e. $n_2=0{,}33$ and $n_3=0{,}315$) for both lengths $l=500$ mm and 700 mm. This is again in accordance with Fig. 3, where the Δn_{max} curves display a greater difference between the lines for $D_r=0{,}70$ to 0,80, than for $D_r=0{,}80$ to 0,91. This leads again to the conclusion that the bearing capacity of vibrated tubes is governed by the rate of compaction produced immediately below and at the bottom part of the tube tip.

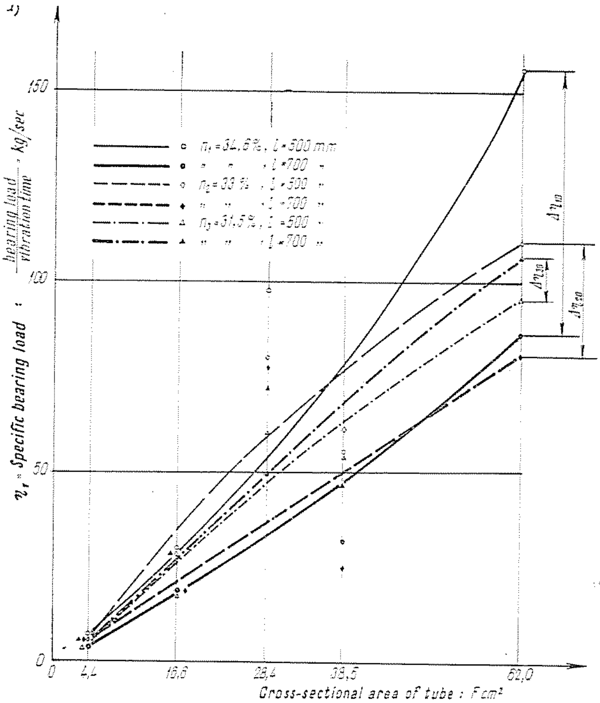
The observations made during the experiments have offered a possibility *to evaluate the efficiency of vibration energy*. The amount of energy was measured by the time of vibration required to bring down the tube to the specified depth. Dividing the ultimate bearing capacity by this time gave a factor of efficiency η_v, similarly an *efficiency factor of driving* was derived by dividing ultimate bearing capacity of driven piles by the total amount to driving energy (of. Fig.7). Efficiency values have been plotted for 500 mm and 700 mm long vibrated tubes for all three densities in sand and for the two densities (n_o, n_{oo}) of sand and gravel. The diagrams 6*a* and *b* show that a higher efficiency is obtained in looser materials and with larger diameter tubes. In addition, the length of the tubes also influences the efficiency, as the specific η values for 500 mm long tubes were higher as a rule than for 700 mm tubes, excepted for the densest conditions, exhibiting an opposite trend. These are indications that *beside the previous factors neither the influence of original soil density nor the magnitude of the oscillating mass can be overlooked.*

The same statement holds also for sandy gravel, only that here the rate of increase is more moderate within the tested range (Fig. 6*b*).

The *efficiency of driving energy* was tested in sandy gravel soil and in a medium dense sand ($n=33{,}5$ per cent) as indicated in Fig. 7. The higher efficiency was obtained also here with looser soils for lengths both 500 mm and 700 mm, the former being again superior. Still the η_d values are much less widely ranged and their plot against the cross-sectional area of tubes shows also a different trend. In sandy gravel soils this variation range was quite small displaying a maximum at about the 60 mm tubes for both lengths, whereas in sand an opposite trend could be observed, namely maxima were obtained with the smallest 25 mm diameter tubes.

This difference clearly indicates the difference between the compacting actions of driving and of vibration brought about around and below tubular piles.

At last it was attempted to determine how tip resistance and mantle friction shared in the total bearing capacity. For this purpose the inner earth core of vibrated 700 mm tubes was removed carefully and reduced to a bottom plug of 40 mm, following the first loading test. Then a second loading test was effected representing practically the share of mantle friction only. Typical test diagrams 8*a* to *c* display that in excavated i.e. hollow condition the bearing capacity of



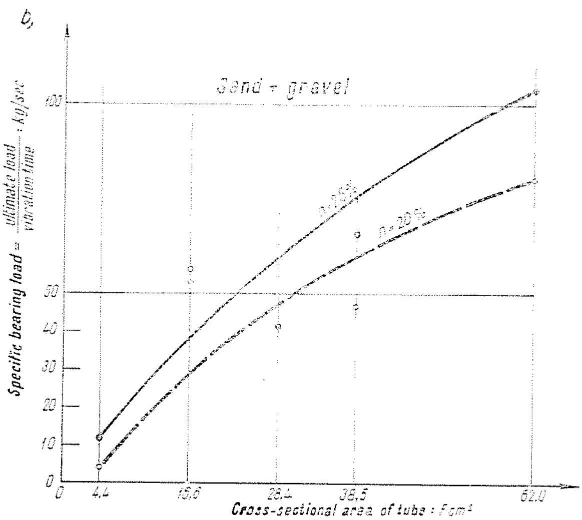


Fig. 6. Efficiency of vibrating energy in function of the cross-sectional area of tubes, *a)* in sand; *b)* in sand and gravel

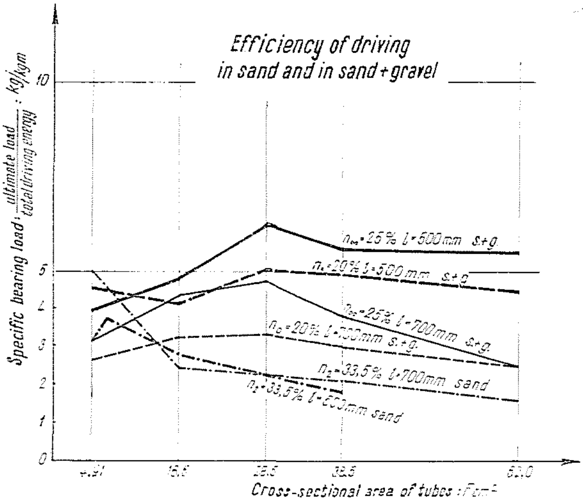


Fig. 7. Efficiency of driving energy in function of the cross-sectional area of tubes

tubes reduced to 15 to 40 per cent – this latter value relating to the smallest 25 mm diameter tubes. The loading diagram for the hollow tubes is quite similar in shape to that of a shearing test, proving that mantle friction is the main bearing component. The comparison of loading diagrams of various diameter tubes shows that the smaller the tube diameter and the denser the original soil, the greater the share of hollow tubes in their total bearing capacity. This share however is not only due to mantle friction, but the thin (40 mm thick) plug left at the bottom will have also a higher resistance in the smaller diameter tube. In soils of equal density the share of mantle friction will increase in proportion with the ratio:

$$\frac{U}{F} = \frac{2r\pi}{r^2\pi} = \frac{2}{r}$$

i.e. at constant tube length l with the silo factor l/D itself. This is also well documented by the diagrams 8*a* to *c* showing that for the smallest 25 mm diameter tubes it amounted to about 45 per cent, whereas it was only 15 per cent for the 89 mm dia. tubes.

A further proof of this relation is presented in Fig. 9 where the share of the bearing load carried by mantle friction is shown in function of the silo-factor $\varkappa = l/D_i$. A fairly linear ratio can be established between the η and $\varkappa$ values, which, in accordance with the above statements and with Fig. 2, may be expressed as

$$\eta(\%) = 1{,}2\varkappa\,.$$

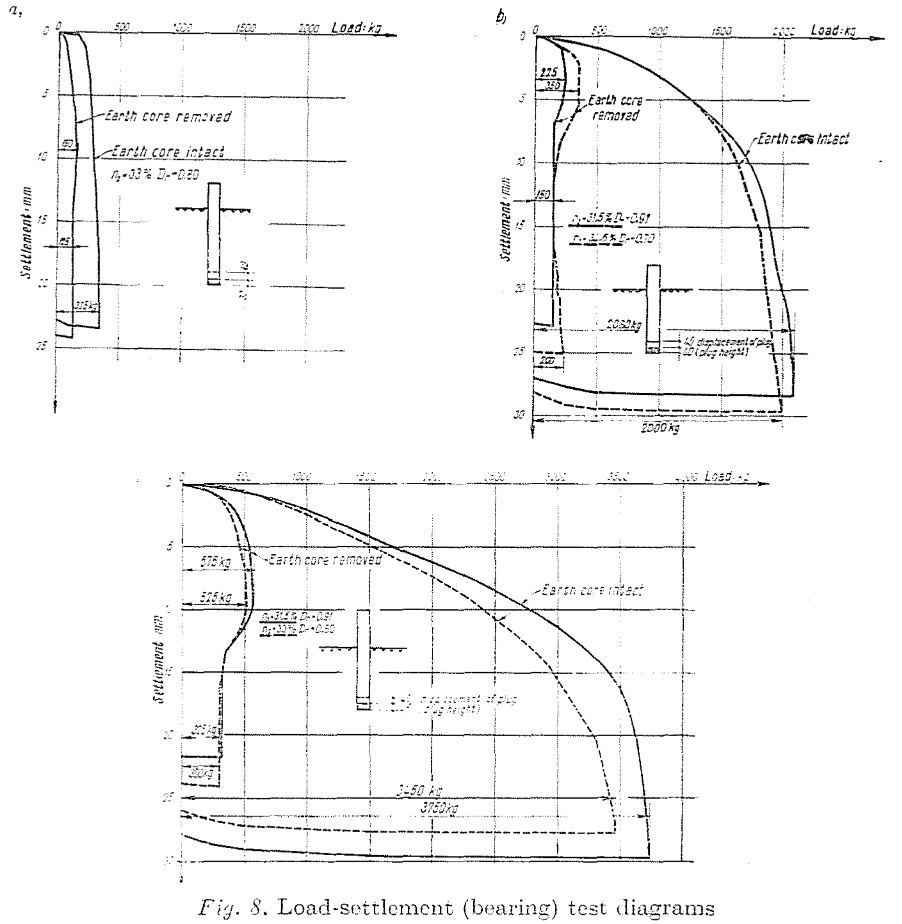


Fig. 8. Load-settlement (bearing) test diagrams of vibrated tubes with earth core intact and removed, resp.

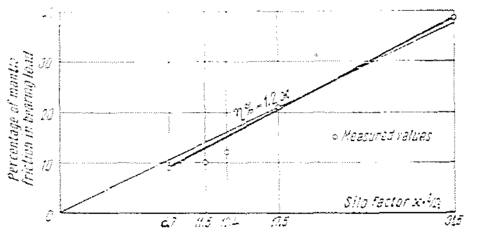


Fig. 9. Share of mantle friction in the total bearing capacity in function of the silo factor

Another experiment helped to plot the distribution of the vertical friction resistance along the inner surface of the mantle shaft. To this effect 70 mm dia. tubes were driven into the sand ($D_r=0,91$) and test-loaded with the inner earth core removed to varying depths. Plotting now the finite differences $\Delta P/\Delta m$ against the height of the earth core produced the distribution diagram of the vertical stresses acting along the inner mantle face (Fig.9). The diagram clearly indicates the predominance of the lower parts of the plug.

The *main conclusions* of the experiments can be summed up as follows:

1. The *level of the inner earth core* in vibrated tubes is – with the exception of tubes with a silo-factor $l/D>20$ – generally higher than the original ground surface; in contrast to driven tubes where it is always lower.

2. *Below the tip of vibrated tubes the cohesionless soil gets compacted*, whereas below driven tubes it becomes loosened. It is just the contrary to the changes in soil condition brought about *along the shaft mantle* of tubes, where *loosening will set in with vibrated tubes and some compaction with driven ones.*

3. It follows from the previous statement that *the bearing capacity of vibrated tubes consists almost exclusively of tip resistance* and may be theoretically computed after Rankine's bearing capacity formula. This is against driven tubes where mantle friction constitutes also a considerable bearing factor, its share being an increasing function of the silo factor l/D. Consequently *the bearing capacity of driven tubes* exceeds that of vibrated tubes by 20 to 40 per cent; *this difference decreasing with the decrease of silo factor l/D.*

4. *Void content, relative density and effective grain diameter* of the cohesionless soil *are also of considerable influence upon the bearing capacity* of both vibrated and driven tubes, as well as upon the level and density of the developed inner earth core.

A linear relationship was found between the bearing capacities of tubes vibrated in sand with the respective D_r values over the limit $D_r>0,80$, whereas below that, bearing capacities increased approximately with the square of the D_r ratios.

The original soil condition affected less the bearing capacity of driven tubes (cf. Figs. 4*a* and *b*).

In sand and gravel the experiments covered only two conditions ($D_r=0,66$ and 1,0) and within this range their effect seemed to be smaller for both vibrated and driven tubes (cf. Figs. 4*a* and *b*).

The height of the inner earth-core in sand increases with D_r just as its average density.

5. The higher the specific bearing capacity produced by vibration, the lower the initial soil density and the larger the tube diameter, i.e. the smaller the silo factor. This factor may be reduced, however, not only by increasing the

tube diameter but also by reducing the tube length. *In conclusion the efficiency of vibration will decrease with increasing tube length.*

6. The specific bearing capacity produced by driving varied with the silo factor in sandy gravel soils in relatively narrow ranges. With lower initial density (D_r=0,66) this effect was in average by about 20 per cent greater than with higher initial density (D_r= 1,0). Previous tests executed in sand of medium density (n=0,335, D_r=0.76) have indicated, however, that the efficiency of driving energy increased with the silo factor, which trend was just opposite to the results obtained with vibration. Therefore the increase of pile length has increased here also the efficiency of driving, by raising the specific bearing capacity (Fig. 7).

7. *The greatest part of the bearing load is carried by the bottom layers of the earth plug for driven tubes (Fig. 9), an effect less evident with vibrated tubes.*

Summary

Experiments on open end vibrated tubes=hollow steel cylinders aimed at throwing some light on the bearing capacity factors of vibrated tubular piles as compared with those of driven ones. These have proved that driven tubes are superior in this respect to vibrated ones and both the formation of the inner earth-core and the compaction and loosening around and below – produced by the different means of bringing down – are

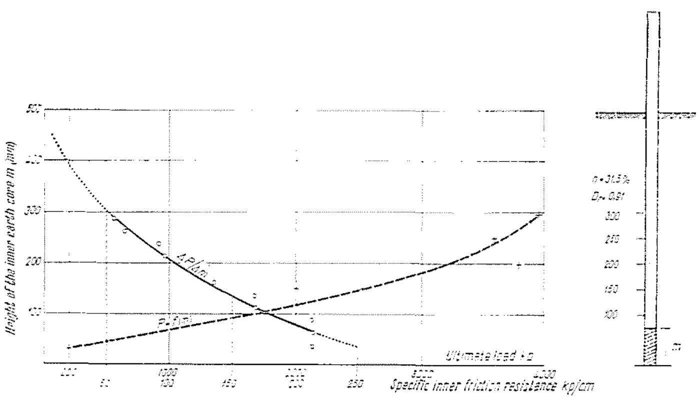


Fig. 10. Distribution of friction resistance along the inner surface of driven tubes

entirely different (Fig. 2). Beside dimensions and ratio of length to inner diameter (l/D_i= $\varkappa$ silo factor), also the relative density (D) of the test soil influences the bearing values. Tubes with a closed tip had still higher bearing capacities, but these test pieces could not be brought down at all with the applied vibrating apparatus except for dimensions below a certain limit (D = 70 mm).

It has been concluded that the bearing capacity of vibrated tubes consists mainly of tip resistance, while mantle friction – in contrast to driven tubes – is likely to be unimportant. Subsequent experiments, with the inner earth-core removed (Figs. 8*a* to *c*), have indicated, however, that the increase of the silo factor ($\varkappa = l/D_i$) increased this share, approaching gradually the behaviour of driven tubes (Fig. 9). These latter experiments have also put a light upon the distribution of friction stresses along the inner earth core (Fig. 10).

The bearing value of tip resistance could be fairly well approached by Rankine's and by Meyerhof's theories (Eqs. 1 and 2).

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