3B/25

The Effects of Vibration and Driving upon the Voids in Granular Soil Surrounding a Pile

Les effets de la vibration et du battage sur l'indice de vide de la granulométrie d'un sol autour d'un pieu

by Dr. C. SZÉCHY, Professor, Corr. Member of the Hungarian Academy of Sciences, Technical University for Architecture, Civil and Communication Engineering, Budapest, Hungary

Summary

The author has tested a series of steel tubes of various diameters with open and closed bottoms; they were driven and vibrated into a fine sand in order to compare their bearing capacity in relation to the driving energy imparted to them and to measure the void ratio change near them. It was discovered that open ended tubes are economical only over a certain length-diameter ratio $\frac{L}{D} = 10$. From the void content change Δn measurements it was demonstrated that compaction and loosening of the soil largely depends upon the penetration technique, whether driving or vibration, and upon the form and shape of the bottom plug. The author claims that this differs sensibly from the usual assumptions.

Sommaire

L'auteur présente ses essais faits avec des tubes d'acier de diamètre variable battus et vibrés dans un sable fin. Une série de tubes étaient ouverts, d'autres avaient des extrémités planes et coniques (1 : 1). Le but initial des essais de cette série était d'obtenir quelques informations sur la résistance spécifique des pieux tubulaires, en relation avec le travail de battage nécessaire. On constate une économie de 25-30 pour cent en faveur des tubes ouverts pour un rapport $\frac{L}{D} = \frac{\text{longueur}}{\text{diamètre}}$ du tube dépassant 10. Le changement de volume des pores était aussi soigneusement mesuré au voisinage des tubes battus (Fig. 3-5). On trouva que le compactage et le gonflement obtenus dépendent largement de la technique employée pour la pénétration des tubes ainsi que de la forme de leur extrémité. Les résultats obtenus sont différents de nos concepts habituels.

In a previous paper (C. SZECHY : Tubular Piles, *Acta Technica*, t. XXIV, fasc. 1-2, 1959) the author has described his experiments undertaken with hollow tubes driven into a cohesionless fine sand ($U = 2{\cdot}5$, $\gamma = 1{\cdot}75$ t/m^3, $\varphi = 35°$, $n = 0{\cdot}34$) and tested as bearing piles. As a result of these experiments done in a laboratory with ordinary gas-tubes of various diameters and wall-thickness as well as in the field with spun-concrete tubes; he has reached the following conclusions :

1. The inner earth-core developed in the lower part of the pile during driving — when the ratio of tube-length to tube-diameter exceeds a certain value — performs the same function as a pile shoe.
2. The bearing capacity of these tubular piles is very nearly the same as that of solid piles with flat bottoms although this advantage is gained for the price of somewhat larger settlements.
3. Considerable economy may be achieved when compared with flat bottom solid piles, not only in the material of the pile shaft (about 30 per cent) but also in the driving-energy which may also be about 30 per cent.

As a continuation of this test programme a further series of tests was carried out by the author to discover :

1. Whether any economy in driving energy is obtainable, when pointed piles are used instead of flat-bottom piles.
2. What will be the bearing capacity of a tubular pile and the formation of the inner earth-core, when vibration is applied in comparison to driving ?
3. What changes will take place in the original void ratio of the cohesionless soil near different types of piles ?

The tests were carried out in a steel box with a surface area of 1·40 × 1·40 m and 1·30 m deep. It was filled with fine uniform sand to a depth of 0·95 m. The uniform density of the sand was secured by compaction carried out in relatively thin layers by hand. The original void content was checked before each test from samples taken at a distance of 30 cm from the test tubes. Driving was carried out with a weight of 17·34 kg, dropping from a height of 30 cm. Vibration was effected with a vibrator weighing 20 kg rotating at from 2 800 to 3 000 r.p.m., commonly employed for the compaction of ballast under railway sleepers. The test tubes were ordinary seamless steel tubes (gas-tubes) with the following dimensions:

External diameter mm	Internal diameter mm	Length mm	Weight kg
89	80	835	7·53
70	60	832	6·71
60·3	52	838	4·55
46·0	40	835	2·76
25·6	22·2	818	0·71

All tubes were carried down into the test-sand to a uniform penetration of 500 mm. (With the exception of 89 mm dia. tubes, where the closed bottom types could not be driven down with the available driving apparatus to the required penetration depth.) When the penetration depth was reached, test-loading was carried out by an hydraulic piston of 5 tons capacity — all loads being measured by a dynamometer inserted between the bottom of the piston and the top of the tube. Because it was observed that the density and void-content may be affected by the driving or vibration of previous test piles, final tests were carried out in a soil where uniform density was secured by uniform compaction of sand in a steel cylinder of 500 mm diameter. This was gradually filled in layers and withdrawn step by step as filling and compaction proceeded.

This sand cylinder of 500 mm diam. was removed after each test and replaced by new material of uniform density as described above. All tests were repeated once and their average values are given in the following.

The change of void content near the tubes was measured with the aid of small (50 × 50 × 50 mm) tin-cubes left open on their top and at the side directed towards the pile. These were embedded in the test-soil simultaneously when placed and compacted in layers and taken out after the test, when the soil was removed again in layers. Later on regular thin wall brass cylinders were also used for this purpose, test-samples being taken after each test simultaneously with the careful removal of soil in layers — a bottom plate being always slid in underneath the test cylinder before its excavation.

Four different types of tubes were driven to the same penetration depth, and they were as follows :

(a) Bottom end open with vibration;
(b) Bottom end open with driving;
(c) Bottom end closed with a flat plug;
(d) Bottom end closed with a conical plug of 1 : 1 slope.

Test results are illustrated in the diagrams. Fig. 1 shows the ultimate bearing capacity *P* of the tubes, indicating the superiority of closed flat bottom piles. This superiority-related to the bearing capacity of driven open bottom tubes — and ranged from 25 per cent to 35 per cent with a tendency to increase with the diameter. Piles with a pointed tip were then tested, showing a surplus of 0 to 25 per cent, whereas open-bottom vibrated tubes were inferior by about the same amount as related to the standard open-bottom driven tubes. This inferiority was, however, largely due to the vibration time necessary for bringing down the pile to the required penetration depth and nearly disappeared when this exceeded one minute (The usual vibration time was only from 20 to 40 seconds).

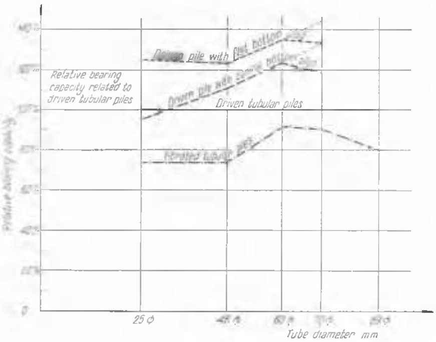

Fig. 1 Relative bearing capacity of various tubular piles.
Force portante relative de divers pieux tubulaires.

Fig. 2 shows the specific bearing capacity of various tubes related to driving energy. This indicates that closed flat-bottom piles are the least economical in this respect. Open bottom tubes are the best for smaller and pointed toe tubes for larger diameters.

From these two diagrams the following practical conclusions may be drawn :

1. The use of flat bottom bearing piles (without a pile-shoe) may be advisable only when the length of available piles is restricted, and when an increase of bearing capacity is required, regardless of the economical use of the necessary driving energy.

2. The use of open-bottom tubular piles will be most economical over a certain limiting ratio of pile-length *L* to tube-diameter *D* and when it is reduced to about $\frac{L}{D} = 10$ it will not offer any relative saving in driving energy, which may however attain a value of 25-30 per cent with a favourable $\frac{L}{D}$ ratio — as already stated in the author's previous experiments (See above).

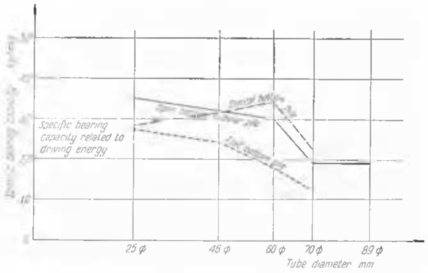

Fig. 2 Specific bearing capacity of tubes related to driving energy.
Force portante spécifique des pieux en fonction de l'énergie de battage.

The results of void-content change measurements are shown in Figs. 3, 4 and 5. Fig. 3 shows the location of spots, where measurements were taken and on Figs. 4 and 5 are indicated

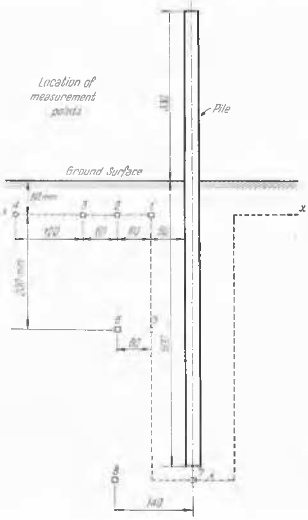

Fig. 3 Location of void content-change measurement points.
Position des points mesurant le changement de volume des pores.

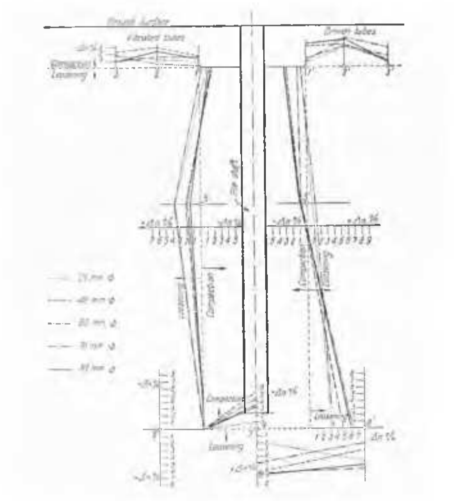

Fig. 4 Diagram of the measured percentage void content changes with open bottom vibrated and driven tubes.

Diagramme des changements du pourcentage mesuré de l'indice des vides pour des tubes à fond ouvert, vibrés et battus.

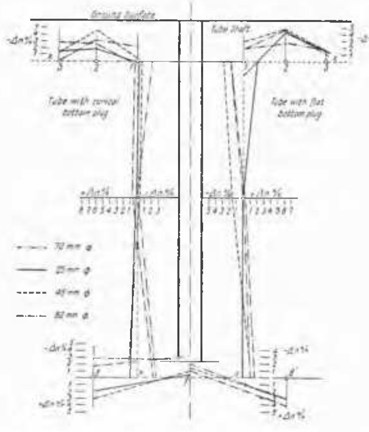

Fig. 5 Diagram of the measured percentage void content changes with driven conical and flat bottom plugged tubes.

Diagramme des changements du pourcentage mesuré de l'indice des vides pour des tubes à fond conique et plat.

the percentage changes Δn in the void-content n values. Where this change was a reduction it meant compaction and the value was plotted towards the pile-shaft or towards the ground surface respectively. Where the change was an increase it meant loosening and the Δn value was plotted on the opposite side of the broken axis x-x. The measurement spots shown in one row were not placed in one vertical plane but located symmetrically along the axis in order not to influence the changes of void content.

The points plotted in the different planes have been connected to each other for better representation.

The comparison of the various Δn figures leads to the following conclusions

1. The change of void content around open bottom tubes differed widely when the tube was vibrated from when it was driven (Fig. 4). There is only one common phenomenon, namely that the void-content just below the ground surface has undergone a considerable reduction extending to about 20-30 cm around the tube. This reduction was greatest at a certain distance from the pile (point 2) and disappeared entirely in the above mentioned distance, but diminished also towards the pile shaft (the same tendency was found at the closed bottom piles (see Fig. 5). A reduction of void content also occured at the upper part of the pile shaft which was considerably greater for driven than for vibrated tubes. (The same difference may be referred to the Δn values below the ground-surface.) A definite loosening was found at about the mid-height of tubes around the pile-shaft, whereas no practical change was found when the tubes were driven. The greatest difference was found to be below the piles. As it can be seen from Fig. 4 a considerable reduction of void content (i.e. compaction), was measured for all vibrated tubes, whereas a still somewhat greater increase of void content (loosening) was measured when the tubes were driven. This latter phenomenon also indicated why the settlement of driven tubular piles was always greater than that of solid or closed-bottom piles. Considering that the degree of compaction may be regarded as a measure of the inner stress conditions, it is also apparent that the bearing resistance of vibrated tubes will be established mainly from point-resistance and that of the driven tubes will consist chiefly of pile shaft friction. This contention is supported by the experience that vibrated tubes had practically no pulling resistance when compared with driven tubes, which have shown a value attaining to 33 per cent of their bearing value.

This phenomenon also proves that the material of the inner earth core must penetrate into the tube mainly from beneath the bottom of the tube. Vibration ensures that this material may be partly supplied from the sides, but driving is not effective enough to destroy the inner arching developed during driving in the upper strata around the tube. The amount of soil intruded into the tube is also much greater owing to vibration than to driving. The inner height of the soil is on average at the same level as the original ground surface and stands even higher in the tubes of larger diameter. The average reduction in void content of this inner earth core ranged from 2·5 to 11 per cent.

On the other hand, the inner level was always lower in driven tubes, the difference increasing with the reduction of inner diameter. The reduction of the original void content was about 6-14 per cent, slightly larger than in the previous case.

2. Fig. 5 shows the percentage Δn values for tubes with closed bottoms; the diagram on the left is plotted for the tubes with a conical bottom-plug (1 : 1 slope), the opposite one on the right side is for those with a flat bottom plug. Here there is some difference in the character of the void content change-lines. The changes just below ground surface are similar to each other and again of negative character. They are somewhat larger near the pile-shaft for the flat-plug tubes. Around the pile-shaft the character of the lines is again different. Whereas there is a reduction at the upper part for the flat-bottom tube, diminishing downwards and slightly increasing at the bottom, the pointed bottom piles

show practically no change at middle height, with a slight reduction towards both the top and the bottom. Under the pile toe there is a definite reduction in void content for both cases, which diminishes towards the sides and probably changes very soon to a slight increase of void-content (loosening). This trend is more marked for flat-bottom than for pointed bottom piles. This clearly demonstrates that both shaft friction and toe resistance must be active with driven closed bottom tubes, although the formation of stress areas around and beneath a pile may be somewhat different from the generally accepted concepts. Namely *the highly compressed stress-concentration areas are surrounded with areas of stress-relief* below the pile toe as well as around the pile shaft and the gradual transition on a greater length cannot be always assumed.

During the tests it was also stated that the original void-content values of the non-cohesive soil have a very great influence upon the bearing capacity of all types of piles as well as upon the building up of stress-concentration areas. With a view to discovering this influence, further series of tests were started in 1960 with three initial void-content values in the course of which the measuring technique was somewhat refined. These tests are not yet finished and will be the subject of a subsequent paper by the author.

All tests were carried out in the laboratories of the University for Civil Engineering and Architecture in Budapest and the author is much indebted for their careful work to the research engineers G. Fazakas and G. Petrasovits and to the laboratory assistants Mrs. T. Tompa and Mr. F. Farkas.