Determination of Economic Driving Depth and of Driving Stresses in Reinforced Concrete Piles

Détermination de l'enfoncement économique et des contraintes de battage des pieux de béton armé

C. SZÉCHY, D.SC., *Professor, University of Budapest, Budapest, Hungary*

SUMMARY

Dynamic bearing force increases with the decrease of penetration sets and deformations. Its maximum value will be attained when the residual part s_r approaches 0. Elastic deformations s_e, however, increase with the dynamic bearing force and therefore will increase with penetration resistance and tend towards a fairly constant maximum value. Thus, beyond the limit where residual penetration disappears, successive driving will not produce any further increase of bearing capacity and the total driving energy will be consumed by elastic deformation leading to a gradual destruction of the pile. This reasonable penetration depth may be obtained either by the maximum value of the specific increase in bearing capacity as related to the utilized driving energy or by the 0 value of the ratio s_r/s_e plotted against penetration depth. The average dynamic compression stress in the pile may be obtained by Hooke's law from the elastic deformation of the pile. With this method the deformation may be measured only together with that of the soil, however. The author describes a method by which the elastic deformation of the pile might be separated from that of the soil when simultaneous measurements are effected at two levels.

SOMMAIRE

La force portante dynamique des pieux battus augmente avec la diminution des refus plastiques et des déformations élastiques, en obtenant sa valeur maxima lorsque le refus s_r tend vers zéro. Au contraire, les déformations élastiques s_e augmentent avec la force portante dynamique et avec la résistance de pénétration des pieux en tendant vers une valeur maxima et constante. Alors, au-dessus de la profondeur où l'enfoncement plastique disparaît, le battage successif ne produit plus d'augmentation de la force portante, mais se dissipe en déformation élastique du pieu provoquant une destruction progressive de celui-ci. La profondeur raisonnable d'enfoncement peut être obtenue par la valeur maxima de l'augmentation spécifique de la force portante reliée à l'énergie du battage utilisable ou par la valeur de zéro du rapport s_r/s_e tracé en fonction de la profondeur de pénétration. La tension moyenne de compression dans le pieu pourrait être déduite directement de la formule de Hooke à l'aide de la déformation élastique, mais celle-ci n'est mesurable qu'avec la déformation élastique du sol. L'auteur donne une méthode de séparation des deux valeurs en les mesurant simultanément à deux hauteurs sur le pieu.

PRECAST REINFORCED CONCRETE PILES are frequently destroyed during driving. The blows destroy mainly the pile head but fissures are quite common in the pile shaft and spalling at the pile tips also occurs. These defects are due both to the improper strength and reinforcement of the piles, and to overdriving.

The problem has been thoroughly investigated by Glanville and his collaborators at the Building Research Station (Glanville, Grime, and Davies, 1935) by an extensive series of experiments. This fundamental research work has elucidated the role of the most important factors which influence the magnitude of driving stresses, on one hand the weight of the monkey, the height of drop, and the elasticity of driving cap and, on the other hand, the cage-like arrangement of reinforcement and the crushing strength of concrete in the pile head. For the determination of the stresses in the pile head produced by a blow, a theory has been also developed based on stress-wave oscillations. The practical use of this theory has been facilitated by the publication of graphs. This method is not widely used in practice, however, because it requires the assumption of several values (chiefly that of the ratio: k/A expressing the elasticity of the blow) which coupled with the approximate assumptions of the theory may lead to essential differences.

The author begins with the consideration that the best approach to the problem may be based upon the actual deformation measurements made during driving. These offer a reliable means of determining the reasonable driving depth and of anticipating excessive driving stresses. Two facts provide a starting point: the sum of residual and elastic deformations is in direct relation to the dynamic bearing load and the elastic deformation alone is proportional to the stresses of the pile.

DETERMINATION OF REASONABLE DRIVING DEPTH

All dynamic bearing formulae begin from the basic energy equation

$$W \cdot H \cdot \alpha = \beta \cdot Q \cdot s, \qquad (1)$$

with W denoting the weight of the monkey, H the height of the drop, α the energy loss factor (friction, eccentricity, impact loss at shock, etc.), Q the dynamic bearing load of pile, s the penetration (both residual set and elastic rebound), and β the factor expressing the losses inherent to penetration (deformation). Expressing all losses with a single $\eta = \alpha/\beta$ factor and considering that the deformation s is composed of a residual s_r and of an elastic s_e portion, resulting from the penetration set and the elastic compression of pile and soil, then Eq 1 may be written in the following form:

$$\eta \cdot W \cdot H = Q(s_r + \tfrac{1}{2}s_e)$$

and

$$Q = (\eta \cdot W \cdot H)/(s_r + 1/2 s_e). \qquad (2)$$

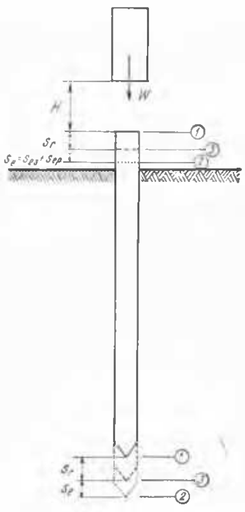

FIG. 1. Displacement of pile under a blow.

The penetration process occurring under a blow is shown in Fig. 1. The pile is brought down first from the initial position 1 to position 2 and then back to the height 3.

A series of field tests has been executed lately under the joint sponsorship of the Ministry of Public Works and the Ministry of Communication in Hungary with a view to determining the cause of failure of various reinforced concrete piles under driving. The field measurements obtained are shown on Fig. 2.

The dynamic bearing capacity of the pile, given by Hiley's formula (Hiley, 1930), as a function of the penetration depth is represented on Fig. 2a. Fig. 2b shows the variation of actually measured residual penetration values s_r and the simultaneously measured elastic deformation values s_e. Fig. 2c displays the "driving diagram" representing the sum of driving energy *versus* pile penetration. At the beginning of the driving process, residual penetration values, s_r are large and thus the dynamic bearing load of pile Q will be small at equal blows ($W \cdot H$ = constant). With the progress of driving, residual penetration value s_r will decrease, however, involving the consequent increase of the Q values. It is clearly demonstrated that with the increase of the Q values the s_e values also increase (although after a certain limit not at the same rate). This is natural, because of Hooke's law:

$$s_e = (Q \cdot l)/(E \cdot A) = \sigma \cdot l/E$$

and from this

$$\sigma = (s_e \cdot E)/l. \tag{3}$$

In this equation, however, s_e comprises the elastic deformation value of both pile and soil ($s_e = s_{es} + s_{ep}$); in practice only its total value may be measured (Fig. 4). A suggestion for their separation will be given later. Also, the "working length," l of the pile is also variable, as will be demonstrated later.

From these basic considerations, however, we may determine the reasonable driving depth of the pile. Namely, with the diminution of the penetration sets, the elastic deformation values s_e must increase according to Eq 2 and beyond a certain limit (when s_r approaches 0) all driving energy must be consumed by this latter factor. This will certainly increase the compaction of the soil under the pile tip but will primarily increase the stresses in the pile. The compaction effect will be soon complete, indicated by s_e approaching a constant value.

In this state the dynamic bearing force Q as well as the average stresses σ of the pile have attained their maximum value according to Eq 2. Any subsequent driving will only increase the impact losses of the blow owing to growing eccentricity and contribute to loosening of the tight fastening of the pile cap, deterioration of its toughness, and a decrease in the efficiency of the transmission of the energy of the blow to the pile shaft; the dissipated energy will consequently be turned to the destruction of the pile head. It is quite clear that the determination of this depth limit is of great practical importance. Based on the field experiments, the author suggests its determination in the following two methods (Fig. 3).

In the first method, when plotting the quotient

$$\Delta Q_i \Big/ \sum_{i=1}^{i} W \cdot H$$

(i.e. the quotient of dynamic bearing capacity increment for a given penetration zone referred to the driving energy consumed for the penetration of this respective zone *versus* penetration depth, we obtain a pronounced maximum at

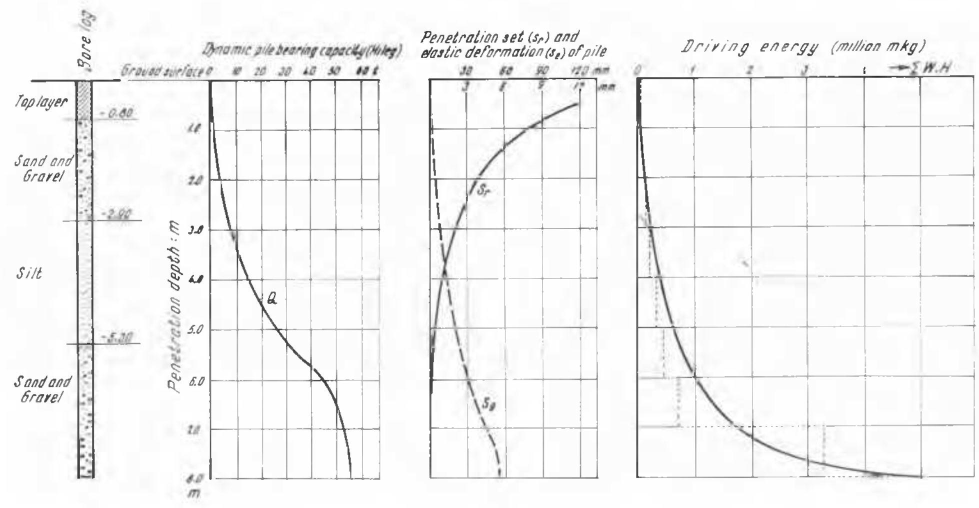

FIG. 2. Typical dynamic bearing capacity, deformations, and driving diagram of the test piles.

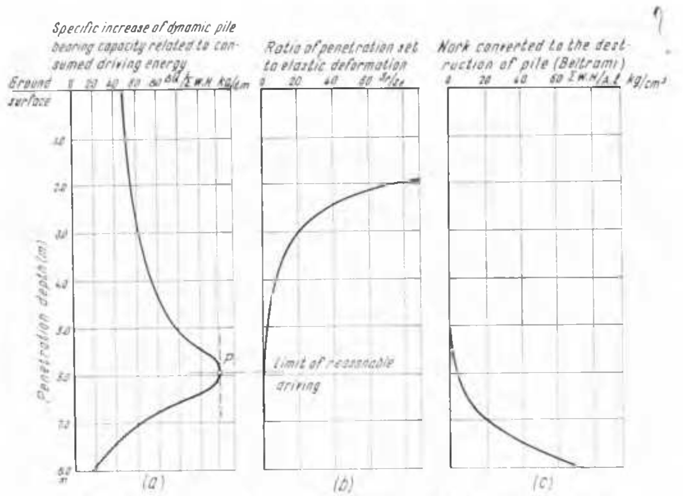

FIG. 3. Determination of the reasonable driving depth.

point P below which the resistance against driving is increasing far more rapidly, than the dynamic bearing resistance (compare Figs. 2a and 2c).

The second method involves plotting the quotient s_r/s_e *versus* penetration depth (Fig. 3b). The critical depth is defined in this case as the point where this ratio approaches zero and the s_r/s_e line approaches a vertical tangent.

Below this point the driving energy does not increase either the bearing capacity or the penetration depth of the pile but is converted entirely to its destruction. It was also observed during the tests, that the destruction can be related to the progress of Beltrami's so-called specific work value. Fig. 3c shows that this value, which expresses the total driving energy $\Sigma\ W\ .\ H$ related to the "working volume" $A\ .\ l$ of the pile, rapidly increases from about this "critical depth." It is clear from the foregoing that this critical depth may be regarded as the reasonable driving depth of a pile.

DETERMINATION OF PILE STRESSES DURING DRIVING

The average stress in the pile shaft might be derived from Hooke's law directly from the correlation

$$\sigma = s_{ep} \cdot E/l, \qquad (4)$$

provided the elastic deformation of the pile s_{ep} could be separated from the measurable total elastic deformation s_e, and in addition, if the variation of the working pile length l could be determined.

The total elastic deformation s_e can be directly measured from Fig. 4 where each wave represents the movement of the pile in time under a blow. However, these measured values contain the elastic deformation of the soil s_{es} as well.

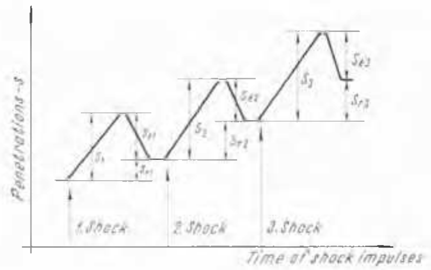

FIG. 4. Typical diagram from deformation measurements.

There are some approximate values for the rough estimation of the elastic compression of soil under the pile tip (*Civil Engineering Code of Practice*, No. 4, *Foundations*, 1954). The large scatter of the values however, expresses the inaccuracy of this estimation.

TABLE I. ELASTIC SOIL COMPRESSION VALUES

		Average stress in pile (kg/sq.cm.)			
Form of compression	Material	Easy driving 35	Medium driving 70	Hard driving 105	Very hard driving 140
Elastic soil compression (mm)	Ground surrounding pile and under pile point	0.13	0.25 to 0.50	0.38 to 0.64	0.13 to 0.38

Some estimated values are also available for the determination of the working length of the pile. It is evidently clear that the deeper the pile penetrates into the soil, the more it will be prevented in its "free" deformation by the skin friction of the surrounding soil mass. Thus l will be always smaller than the total pile length l_0 and its value decreases gradually as driving proceeds, attaining its minimum value at the final penetration depth. Investigations by Schenck and

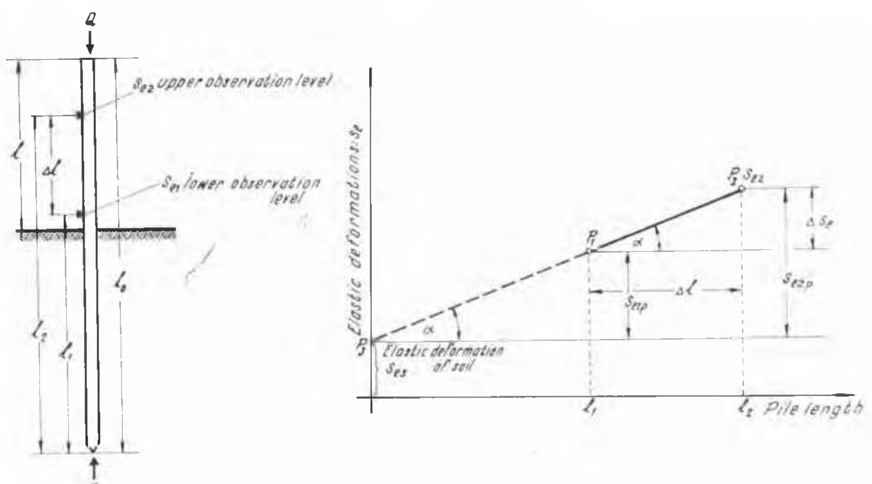

FIG. 5. Separation of the elastic deformations of soil from those of the pile.

Fröhlich showed that the maximum diminution in length ranges from about one-half to one-quarter of the embedded length.

The following method developed by the author offers a possibility of avoiding these uncertainties and obtaining exact values for the determination of average dynamic stresses in piles. The separation of s_{ep} and s_{es} may be effected, when taking measurements from the total elastic deformation *simultaneously at two levels* (Fig. 5). The measured values s_{e1} and s_{e2} must be plotted against their respective distances l_1 and l_2 from the pile tip giving two points P_1 and P_2. Connecting these two points, and extending the line towards the vertical ordinate axis, the distance of the intersection point P_3 from the origin will represent the elastic deformation of the soil, s_{es} and thus $s_{e1p} = s_{e1} - s_{es}$ or $s_{e2p} = s_{e2} - s_{es}$.

The lengths l_1 and l_2 must be working lengths, because it is important from which origin these abscissae are measured. But this difficulty may be set aside when computing the stresses on the basis of the differences, i.e.

$$\sigma = \frac{s_{e2} - s_{e1}}{l_2 - l_1} \cdot E = \frac{\Delta s_e}{\Delta l} \cdot E. \qquad (5)$$

The quotient $\Delta s_e/\Delta l$ appears on Fig. 5 as the tangent of the inclination angle α. We may conclude, therefore, that the steeper the inclination of the grade (i.e., the larger tan α) the greater the stress in pile. Plotting a curve from the various tan α values *versus* pile penetration, we obtain a correlation characterizing the increase of pile stresses with penetration depth (Fig. 6). The same correlation may be obtained from Eq 4 when the elastic deformations of the pile (s_{ep}) would be directly determined from Fig. 5. The obtained values also include the impact effect because the elastic deformations are measured under the dynamic blow. Still, they represent only average values, whereas the distribution of stresses is not uniform along the pile, and excessive values are experienced in the pile head. For the determination of these peak values the use of a majoration factor μ might be advisable, as given in the British *Civil Engineering Code of Practice*, No. 4, *Foundations* (pp. 73, art. 3.83). It is given as $\mu = 2/\sqrt{\nu} - 1$ where ν denotes the second member (expressing impact losses) of Hiley's formula

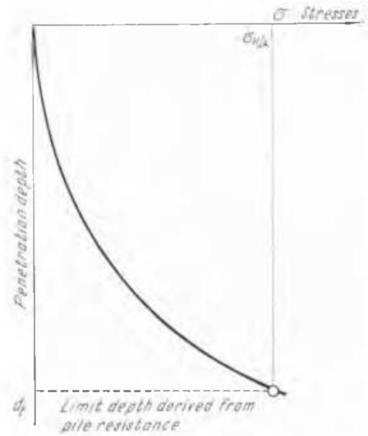

FIG. 6. Determination of the critical driving depth.

$$\nu = (W_r + k^2 \cdot W_p)/(W_r + W_p)$$

with W_r and W_p denoting the weight of ram and pile respectively and k the shock factor for which tabulated values, ranging from 0.32 to 0.50, are given by Hiley (1930).

The check of a given pile may be effected now, by computing the limit bearing stress σ_H of the cross-section of the reinforced concrete pile and dividing it by μ. The intersection of this σ_H/μ vertical line with the σ line will give us the penetration depth at which the destruction of the pile head may be expected (Fig. 6).

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