Wedged Piles under Light Structures

Pieux expansés sous des structures légères

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ABSTRACT: Contemporary geotechnical investigations tend to concentrate on the construction of big, heavy buildings and a lot of progress has been made in determining the best technologies and calculations for the piles generally used under such buildings. On the other hand, when planning light structures, a lot of money is often wasted on unnecessary concrete, earthworks and labour. In Estonia, wedged piles 1.5 to 3 m in length have been used for the past 30 years in the construction of light structures (2-3 storied buildings, store-houses, agricultural structures etc). The use of such piles allows for 30-60 per cent lower costs and speeds up the 0-cycle process about two times. The behavior of wedged piles in soils has been well researched, including the processes accompanying pile driving (soil compaction and the squeezing out of excess earth) and the impact of those processes on the formation of pile bearing capacity. The pile tests allow us to evaluate the bearing capacity of piles based on the information gained in the course of pile driving, as well as CPT tests in various soils. The latest investigations have concentrated on evaluating the cooperation between piles and the raft, allowing for more cost-effective foundations.

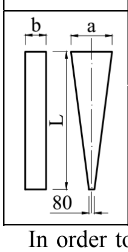
RÉSUMÉ : Les recherches géotechniques portent aujourd'hui généralement sur la construction de bâtiments importants par la taille et le poids, et des progrès considérables ont été accomplis pour déterminer les meilleures technologies et les meilleurs calculs concernant les pieux couramment utilisés sous de telles constructions. En revanche, les projets de structures légères donnent souvent lieu à des dépenses inutiles en béton, terrassement et main d'œuvre. En Estonie, des pieux expansés d'une longueur comprise entre 1,5 m et 3 m ont été employés durant les trente dernières années pour la construction de structures légères (immeubles de deux ou trois étages, entrepôts, structures agricoles, etc.). L'utilisation de ces pieux s'accompagne de coûts inférieurs de 30 à 60 % et accélère le process 0-cycle par un facteur 2. Le comportement des pieux expansés dans les sols a été bien étudié, y compris les processus accompagnant l'enfoncement du pieu (compactage du sol, expulsion de la terre en excès) et l'impact de ces processus sur la formation de la capacité portante du pieu. Les tests conduits permettent d'évaluer la capacité portante des pieux sur la base de l'information recueillie au cours de l'enfoncement et des essais CPT menés dans différents sols. Les dernières recherches ont porté sur la coopération entre le pieu et la semelle, permettant des fondations d'un meilleur rapport coût-efficacité.

KEYWORDS: wedged pile, bearing capacity, load test, CPT, dynamic test, the settlement of the building.

1 INTRODUCTION.

The attention of geotechnics has been on the foundations of buildings founded in complex geotechnical conditions. Relatively little attention has been placed on the lighter and easier civil engineering works that have been constructed in satisfactory conditions in the past few years. The foundation costs of these buildings are, however, at times disproportionately large and often accompanied by a higher need for labour and material.

Table 1. Wedged pile dimensions and consumption of materials

Drawing	Dimensions of pile			Weight	Consumption of materials	
	L mm	a mm	b mm	Kg	Steel kg	Concrete m3
	1500	470	300	300	12,4	0,12
	2000	600	300	510	14,3	0,21
	2500	730	300	760	34,0	0,31
	3000	860	300	1060	62,4	0,43

In order to avoid this, Estonia has been using wedged piles since the end of the 70s. The drawings and measurements of the most commonly used wedged piles are given in Table 1. The wedged piles are driven into the soil with a diesel or hyrdohammer to the predetermined depth. The bearing capacity of the pile is verified by the dynamic test on the basis of the measured equivalent (the settlement of the pile from one hammer blow). This allows one to verify the quality of the works.

The wedged piles are mainly used in the soils shown in Figure 1. These include sands, tills and over consolidated clays. Wedged piles are also used in places where there is a 3 m thick stronger soil layer on top of weak soils, for example, or sand on top of weak clays. Due to the cooperation of wedged piles and stronger soil, the point load is divided over the large area of the weak soil (Mets and Tammemäe, 1988).

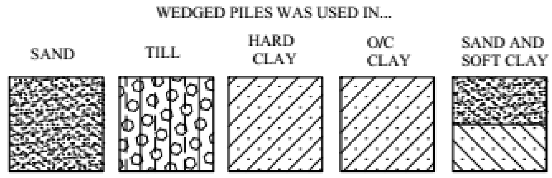


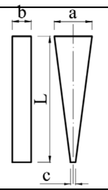
Figure 1. Suitable soils for wedged piles.

The cost of wedged pile foundations is considerably lower (20...60%) than traditional shallow foundations. Using these will considerably lower the intensity of concrete and reinforcement, there are also practically no earthworks and often no need for lowering the water level. The appearance of the construction site and the behavior of the buildings improves significantly – settlement converges (the classical settlement difference between end walls and the central part of the building). There is an especially good effect with using wedged piles in weak clays above sand. A raft foundation practically forms from wedged piles and stronger soil. The load-bearing structures can be supported on the wedged pile foundation and on the surface of the first floor, while the floor and foundations subside the same amount (Mets and Leppik, 2016).

2 THE BEHAVIOUR OF WEDGED PILES.

The behavior of wedged piles when driving and loading them has been studied with standard piles (shown in Table 1) and the pile models shown in Table 2.

Table 2. Pile model dimensions

Drawing	Name	Dimensions				Volume
		L mm	a mm	b mm	c mm	cm³
	KV30/3	300	86	30	8	423
	KV40/3	400	120	30	16	816
	KV40/6	400	120	60	16	1632

During the study of the pile's behaviour, the behaviour of the ground surrounding the pile towards the lateral tilt and vertical tilt was determined. Experiments with standard piles were carried out in till and in silty sand. The soil was squeezed out by the driving of the pile in both soils. The results of the test in the till are shown in Figure 2.

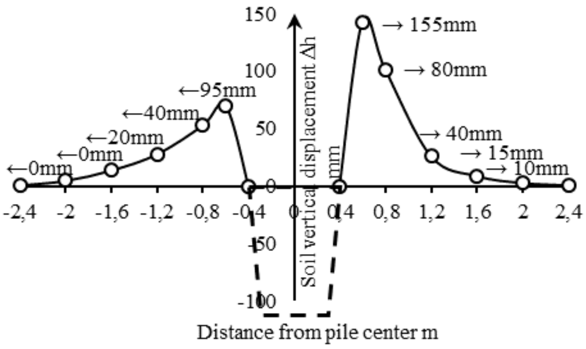


Figure 2. The ground rise around the wedged pile.

There is an active increase area on both sides of the pile, which is practically equal to the width of the upper end of the pile. This is followed by a lower-intensity swelling area, the width of which is practically the width of 2 upper ends of the pile. The comparison of the capacity of the piles and the squeezed out volume is shown in Figure 3.

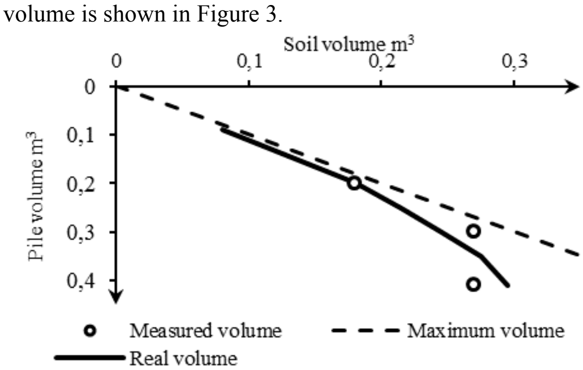


Figure 3. The ground rise around the wedged pile.

The figure reveals that in the case of 2 and 2.5 m piles, the soil volume is squeezed out in the amount of the pile volume. In the case of 3 m piles, the soil's density will also accompany the squeezing out of the soil. This density is characterised by the results shown in Figure 4. The changes of the dry density were examined. Samples were taken 4 m away from one pile to another and from the contact surface of the ground, 0.25 and 0.5 m from the pile. The natural dry density of the till was 17.2...18 kN/m³. Up until the depth of 0.5...1.0 m, it was growing in all measured points 19...19.3 kN/m³. The density of the deepest contact surface remained practically the same, but from 0.5 and 0.25 m from the pile it grew to 2.0...2.1 kN/m³, equaling the maximum density, which was determined by the Proctor method. convergence.

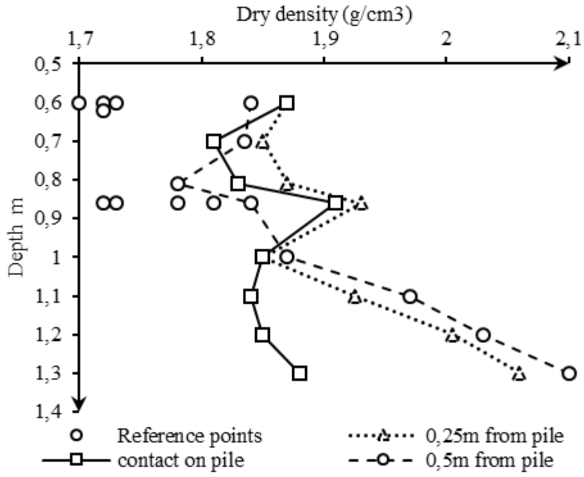


Figure 4. The interdependence of the dry density location in relation to the 3 m wedged pile

The accompanying ground rise of when the pile driven in the dense silty sands is characterized by Figure 5.

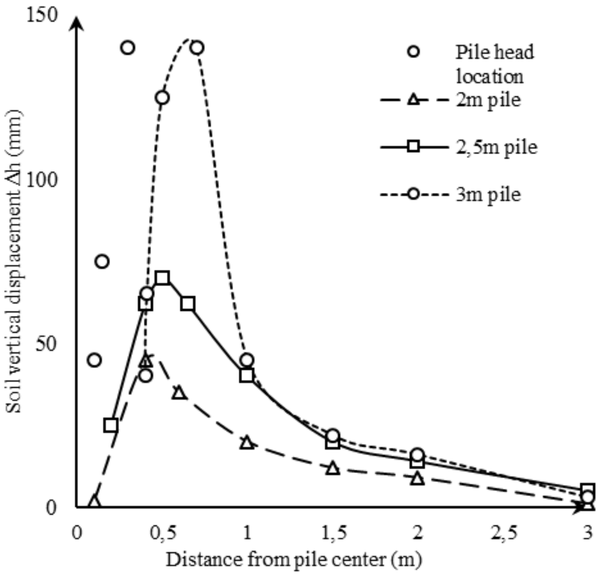


Figure 5. The ground rise in dense sand.

In dense silty sands (natural density level I_D = 0.75...0.87), density level had decreased by the end of pile driving I_D = 0.68…0.71. If you compare the squeezed out soil capacity to the pile's capacity, the latter is 5...10% smaller than the squeezed out soil capacity. Therefore, the wedged piles in dense silty sand make the sand loose during the driving, but because

of the shift formations in the silty sand, the creep level of the sands could also be shifted (Needo *et al.*1991).
Model pile tests were made in loose and dense medium sand. The isolines of the soil rise are given in Figures 6 and 7.

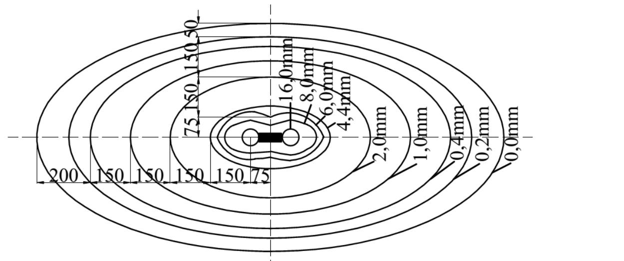


Figure 6. The isolines of the soil rise in dense soil.

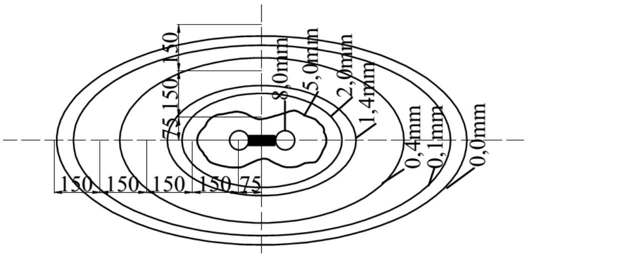


Figure 7. The isolines of the soil rise in loose soil.

The capacity of the squeezed out soil calculated by the soil's isolines exceeded the capacity in the dense sand 4 times and in the loose sand 1.3 times. Two areas can also be distinguished in the squeezed out areas of the model tests: the active squeezing out of the area next to the pile and the immediately surrounding area with a smaller squeezing out activity.
When testing the model piles it appeared that these areas develop during the driving and the characteristics of these areas and their extent remain practically the same for the subsequent tests. (Vares, 2015)

3 THE BEARING CAPACITY OF THE WEDGED PILES

140 pile loading tests have been carried out in different soils in order to evaluate the bearing capacity of the wedged piles. The methodology of characteristic points has been used to interpret the test results, which allows one to bring out the loading levels where changes in pile behaviour occur during the pile loading.

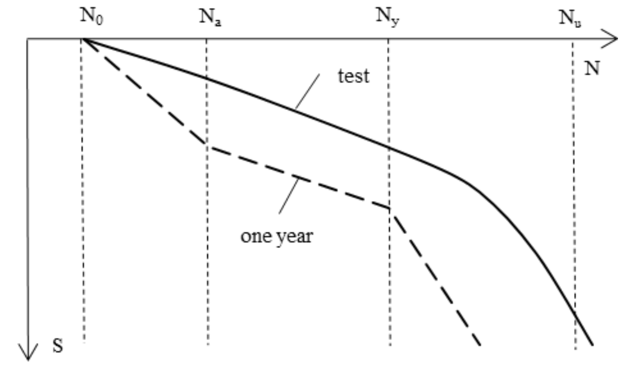


Figure 8. The interdependency between pile settlement and the load S=f(P).

On a conventional curve S=f(N;t) (Figure 8) (settlement depends on the load and time) the following loads have been separated in the course of the tests:

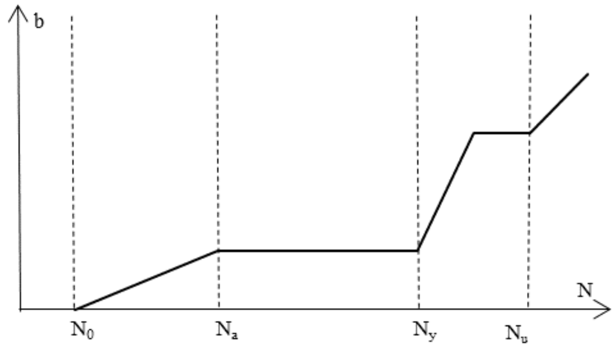


Figure 9. The interdependency between factor b and the load b=f(N) (Formula 1)

1.Load N_a, in which the pile's side resistance is exceeded and the wedged pile starts to compact the surrounding soil with its inclined sides and tip.

2.Creep limit N_y. Between the loads N_a to N_y there is a compaction of soil under the pile and generally the interdependency S = f (N) is linear. In the case of crossing the N_y load, the squeezing out will start from the lateral tilts and from the bottom of the pile's end. Settlement velocities are increasing, but up to the ultimate load, N_u settlements are of a deaccelerated nature – settlement velocity decreases in time.

3.N_u – ultimate load, in which there is a "soil breakage" of the pile foundation. The evaluation of such load during the test is at times complex (especially in till and in over consolidated hard clays). It is considered, that the ultimate load is achieved when the settlement of the wedged pile is 40 mm.

For the evaluation of these points the method of temporality has been applied, which allows one to describe the temporality of the settlements using the following interdependency (see Eq. 1).:

$$S = A \cdot \left(\frac{t}{t_0} \right)^b \tag{1}$$

A – initial deformation; t_o – time for the initial deformation; t – time at the moment, which interests us; b – factor characterising the deacceleration of the settlement.
In order to determine the factors "A" and "b" on every load level, a graph is compiled logS=f(logt).
In most cases the interdependence is linear and allows one to evaluate the initial deformation A, with factor "b" characterising the deacceleration of the settlement's velocity by the line's tilt. Up to the ultimate load the factor is smaller than 1, and it shows that the velocity of deformation is decreasing in time.

The characteristic points are often difficult to assign on the determined curve s = f(N) during the test. But if using the interdependency b=f(N) or calculating with the formula (1), these points are easily evaluated for the 1-year long settlement period.

According to the interdependency b=f(N) b grows from 0 to the load N_a in a linear fashion. From there, it is constant until the load N_y. Crossing N_y, the intermittent growth of the "b" increases, and it should theoretically be 1 in N_f, and the settlement should go from slowing to accelerating (Mets, 1991).
The analysis of the wedge piles' static load tests showed that in the case of wedge piles, the relations between points are constant and on a very high correlation level (0.9):

$N_a = 0.4\ N_y$ and $N_y = 0.5\ N_u$ (2) and (3)

The comparison of the static load test with CPT showed a great correlative interdependency between N_y and q_c, see Figure 10 and a possibility to determine the wedge pile's load capacity based on the CPT tests and reducing the volume of expensive static load tests.

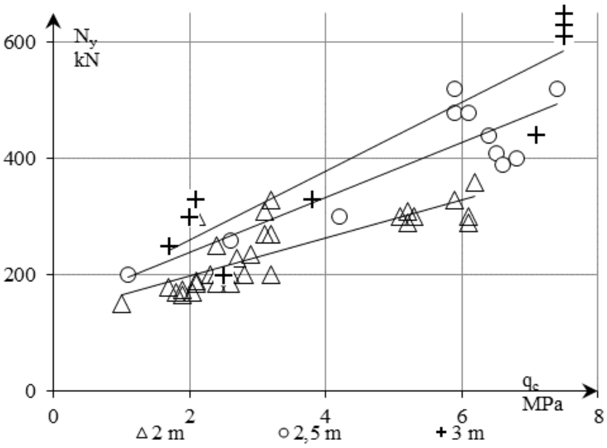


Figure 10. Interdependency between qc and N_y.

This figure shows that in the case that the soils (cones) have the same strength, the special loading capacity (kN/1m^3) of smaller piles is bigger. This phenomenon was further studied with smaller piles and model piles, and the results are shown in Figure 11.

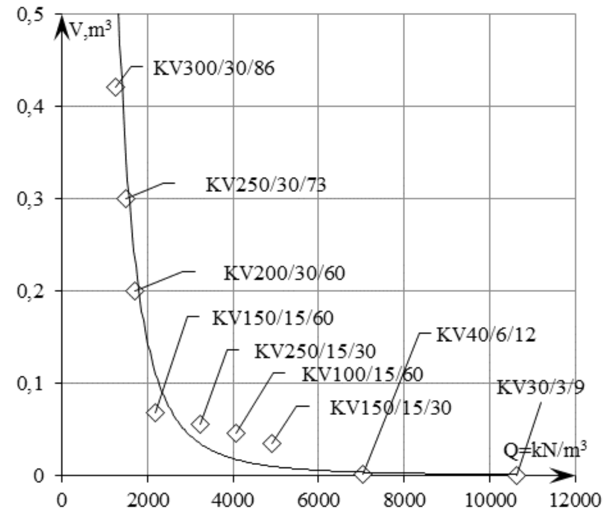


Figure 11. The interdependence between the cone's special barriers and the bearing capacity of one m³ concrete

This graph once again proves what has been stated above, and indicates the future possibilities to use smaller wedged piles to build a foundation for lighter buildings. However, in the case of small wedged piles, it is essential to evaluate the potential risks arising from frost.

For wedged piles with a length of 3, 2.5 and 2 m the effects of frost were investigated during 3 winters with till piles and silty sand piles (both are dangerous frost soils). Study polygons were located in an open field and the snow around the piles was constantly removed. Pile heads were levelled before and after the frost and 2 times in between. At the same time, the depth of frost was also determined, which was 1.05...1.20 m for both polygons. The study showed that none of the investigated piles (there were up to 9 in every polygon) rose due to the frost and measured deformations remained within the measurement accuracy.

The piling set (settlement from one blow) was determined to verify the quality of the pile works. Knowing the impact energy of the hammer, the equivalent can be calculated by using the formula of Gate-Killar or Gersevanov. On the basis of these tests, the dynamic bearing capacity (N_D) of these piles is equal to the creep level determined in the static load: $N_D = N_y$

Gate-Killar's formula:

$$N_D = k\sqrt{0.7Q \cdot h} \cdot \log\frac{25}{e} \qquad (3)$$

k – factor (by set under 5 mm k=3 and set over 5mm k=2); Q – hammer weight in tons; h – hammer drop weight cm; e – set cm.
The analysis of 100 parallel tests showed that on set of 0.1...3 cm Killar-Gate allows one to determine the value of N_D with the accuracy of ± 5…10%. For larger set, the formula underestimates the pile bearing capacity in the extent of –30...50%.
In the usage of the Gersevanov formula on the equivalents 0.1...0.7 cm, pile N_y is overestimated 15…20%. For the equivalents 0.7...2 cm the difference between N_D and N_y is ± 7…12%. For the equivalents over 2 cm, the N_D is 30...50% smaller than N_y.
Today there are over 300 buildings built on wedged piles. Piles driven into till and sand have buildings (barns, warehouses, garages, buildings etc.) with settlements of 1...3 cm and their condition is good.
For a few dozen buildings, the piles have been driven into sands under which there are weak clay soils (C_u =15...30 kPa over consolidated pressure 70 kPa).
The settlement of these buildings depends on the weight of the established buildings and the pressure of weak soils on their upper surface.
For buildings, whose weak soil pressure on the upper surface is smaller than the over consolidated pressure, the settlement is 10...15 cm. If the over consolidated pressure is exceeded, settlements reach over 20...30 cm.
For the buildings founded on wedged piles in sands on weak soils, it is characteristic that the building settlements are even and there are no differences between the outer wall settlements and those in the central part of the building - something that is characteristic to low foundations; also the development of settlement cracks has not been observed.
There are ongoing studies concerning the evaluation of the cooperation between piles and grillage. Model studies have shown that if the pile capacity exceeds the ultimate load, the grillage will start working in the settlement with the length of 2…5 cm and the settlement of the foundation subsides. The usage of cooperation between grillage and piles allows one to reduce the number by 35...60%.

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