FIELD PERFORMANCE OF DRIVEN ENLARGED-TIP PILES

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Recent experience is presented on the performance of piles with a precast enlarged tip in a variety of soil profiles in the New York City area. The design, construction, and use of one version of enlarged-tip pile are described, along with the conditions under which it may be used to advantage. Although more costly than conventional piles, enlarged-tip piles are used economically where they are significantly shorter than conventional piles or of higher capacity, thus allowing pile substitutions of one for two or one for three. Wave equation analysis of pile driving has made it possible to predict very closely the appropriate hammer size, cushioning material, and driving resistance necessary to produce specific pile capacities with various combinations of pile tips and stems. Soil bearing capacity theory helps to explain why field performance of enlarged-tip piles is markedly superior to that of conventional piles, especially in loose granular soils. Case histories illustrate the range of conditions under which these piles have proved effective.

•CERTAIN precast concrete bulb piles have been shown to be advantageous in Europe, particularly in soil profiles where piles of conventional prismatic form must extend to great depths to reach bearing (3). Franki-type piles (labeled PIFs and bulb piles in the United States) are also enlarged-tip piles but are cast-in-place rather than precast. Precast enlarged-tip piles have heretofore been little used in the United States; however, during the past 3 years considerable experience has been obtained in the New York City area in a variety of soil profiles with a pile having a precast enlarged tip. The design, construction, and field performance of the TPT (tapered pile tip) pile (1) are described here along with the conditions under which it may be used to advantage.

IDEALIZED SOIL PROFILES

Three generalized soil profiles in which TPT piles are useful are shown in Figure 1. A deep deposit of loose sand is shown in Figure 1a. Such a deposit occurs in Brooklyn, where conventional piles of 50-ton capacity or more must be driven to depths of 50 to 100 ft or more to reach bearing. However, both TPT piles and Franki-type piles have been driven for capacities of 100 tons or more at less than half the depth of conventional piles.

A 3-layer soil system is shown in Figure 1b. The overlying fill may be strong and incompressible, but the underlying compressible layer dictates that foundations be carried to or through the third layer, the loose sand. Such a condition occurs in Rockaway (Queens), where a strong upper layer is predrilled. Conventional piles achieved 60-ton capacities at a depth of 70 ft, whereas TPT piles achieved capacities of 150 tons at a depth of 50 ft.

Another 3-layer soil system is shown in Figure 1c. The upper layer is too weak and compressible to function as a bearing layer; thus, bearing must be obtained in the underlying sand or stiff clay strata. Figure 1c shows conditions in a portion of Queens. In one case, 50-ton conventional piles drove through the sand layer to depths of 90 to 100 ft, whereas a TPT pile achieved 50-ton bearing in the sand at a depth of 58 ft.

The significant feature of these idealized conditions is that a TPT pile was able to achieve bearing in a suitable granular soil layer with relatively shallow penetration, whereas conventional piles were much deeper. Further, the bearing capacity achieved with a TPT pile can be double or triple that of normal conventional piles.

From the economic standpoint, the TPT pile is more costly per unit of length than conventional piles. As a consequence, the conditions under which TPT piles are economically used are where they are (a) significantly shorter than conventional piles; (b) of higher capacity, allowing pile substitutions of one for two or one for three; or (c) combinations of (a) and (b). Franki-type piles are a direct competitor for precast TPT piles. Experience to date has been that productivity, approximately double that of the Franki system, favors the TPT.

THE TPT PILE

Schematics of the TPT system are shown in Figure 2. For high load capacities, a steel pipe mandrel (Figure 2a) is used to drive a precast reinforced-concrete tip. The shaft is a corrugated shell, which is filled with concrete after driving. For low load capacities, a wood or steel pipe shaft (Figure 2b) is attached to the precast tip and then is top-driven rather than mandrel-driven. In both cases, conventional pile-driving rigs and hammers are used. TPT piles may be driven on batters and, where the shaft is to be concrete, may be internally reinforced. Thus, the only significant difference from conventional piles is the tip itself.

TPT piles are available in a variety of sizes. The sizes labeled A through E in Figure 3 have top diameters varying from 29 to 41 in. whereas the tip diameter is 6 in. smaller; the height is 60 in. Generally a 16-in. diameter socket is used for the A through E sizes, and the working load capacities have ranged to 150 tons. These piles have been driven with hammers ranging from the Vulcan 06 (19,500 ft-lb/blow) to the Vulcan 010 (32,500 ft-lb/blow).

The smaller TPTs, labeled Y, X, and W in Figure 3, have been used with creosoted timber pile stems with 8-in. tips. The timber piles are trimmed to 8 in. at the tips to fit into the socket. Pile working loads up to 30 tons have been proved to date. Hammers of up to 15,000 ft-lb/blow energy have been used for driving.

Analyses of the hammer-cushion-mandrel-TPT system have been made using the wave equation analysis of pile driving. M. T. Davisson, Professor of Civil Engineering, University of Illinois at Urbana-Champaign, has been consultant to the author on many applications of the TPT system. Dr. Davisson has been able to predict very closely the appropriate hammer size, cushioning material, and driving resistance necessary to produce specific pile capacities with various combinations of pile tips and stems. Further, the wave equation analysis provides the dynamic loads on the TPT system during driving; with this information, reinforcement for the tip can be designed on a rational basis. W. L. Gamble, Professor of Civil Engineering, University of Illinois at Urbana-Champaign, has been consultant to the author on design of reinforcement. Both conventional reinforcing steel and wire fiber reinforcement are in use; the wire fiber is presently used only in the Y and X sizes of TPT.

BEARING CAPACITY THEORY

The theoretical reasons for the effectiveness of enlarged-tip piles can be seen by inspection of the bearing capacity formula for shallow circular footings (4):

$$Q = \frac{\pi B^2}{4} (1.2\ c\ N_c) \quad \text{for cohesive soil}$$

and

$$Q = \frac{\pi B^2}{4} (\gamma\ D_f N_q + 0.3\ \gamma\ B N_\gamma) \quad \text{for granular soil}$$

where B = footing diameter. Note that for cohesive soil the ultimate load capacity Q increases directly with the bearing area ($\pi B^2/4$) and is a function of the square of tip diameter. For granular soil, however, Q increases with the square of tip diameter in the first term and the cube of tip diameter in the second term. On the assumption

Figure 1. Idealized soil profiles.

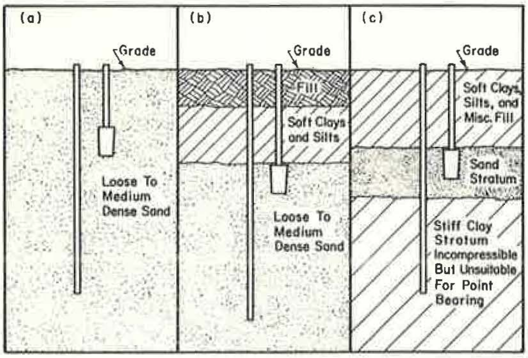


Figure 2. TPT system.

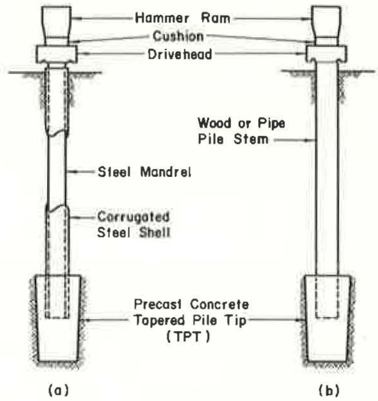
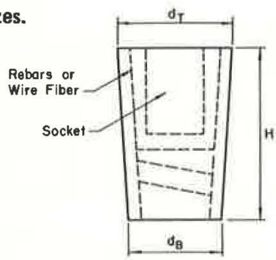
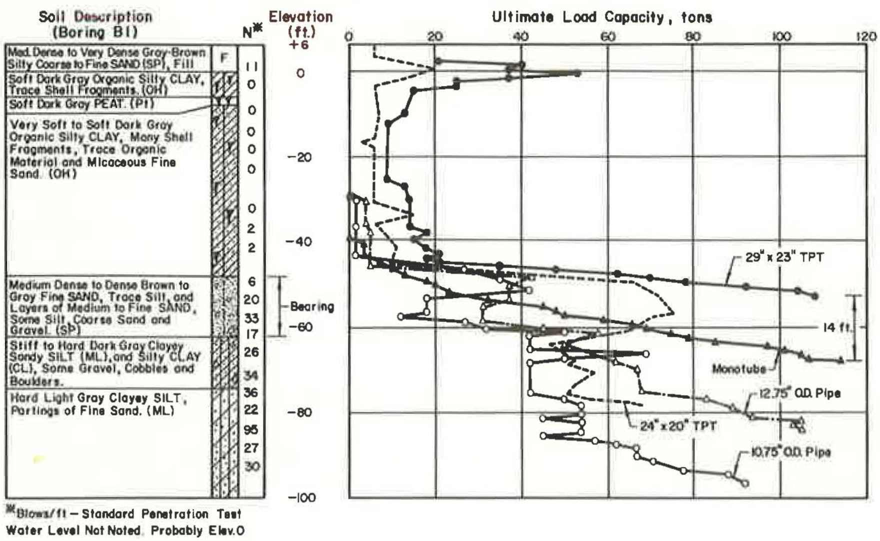


Figure 3. TPT sizes.



TPT Designation	d_T Inches	d_B Inches	H Inches
Y	17	13	30
X	19	15	30
W	24	20	34
A	29	23	60
B	32	26	60
C	35	29	60
D	38	32	60
E	41	35	60

Figure 4. Ultimate load versus depth, Queens.



*Blows/ft – Standard Penetration Test
Water Level Not Noted. Probably Elev. 0

that deep foundations behave analogously to shallow footings, the fact that Q increases with B^3 is perhaps part of the reason for the excellent behavior of TPT piles in granular soil.

Another feature of the TPT that perhaps adds to its effectiveness is taper of the sides. Taper was shown (2) to increase the bearing capacity of conventional piles in granular soils. In addition, sand densification due to driving was shown to occur below and around enlarged pile tips (3); this raises the effective ϕ-value and the bearing capacity factors N_q and N_γ in the equation, resulting in increased load capacity. Thus, sand densification is another factor that may help explain the excellent behavior of TPT piles in granular soil. Whatever the reasons, the effectiveness of TPT piles is most pronounced in loose sands.

CASE HISTORIES

Three case histories are presented here that illustrate the range of conditions under which the TPT has proved effective.

Queens

Conventional piles of 60-ton capacity were called for in the design of a department store storage facility. The site was covered by a thin layer of fill over approximately 50 ft of peat and organic silty clay. Then a 10-ft strata of medium sand was encountered over a deep bed of hard clayey silt extending to depths beyond 100 ft. A typical boring log is shown in Figure 4.

Six piles were driven and load-tested to failure; in all cases the ultimate load agreed very closely with that predicted by the wave equation analysis of pile driving. This made it possible to convert the driving record for each pile into a plot of ultimate load capacity versus depth. Five different piles were driven in the vicinity of boring B1; their graphs of ultimate load versus depth are shown in Figure 4. Note that the 10.75-in. OD and 12.75-in. OD piles drove through the granular soil layer to depths of 103 ft and 90 ft respectively without reaching bearing of 120 tons (twice the 60-ton design load). However, an 8.5-in. OD by 16-in. OD by 20-ft monotube with a 12.75-in. OD pipe extension reached bearing at a depth of 74 ft. This illustrates the effect of pile taper in granular soils.

A W-size TPT (24 by 20 by 34 in.) also penetrated the granular soil layer but while the tip was in the granular soil achieved approximately twice the load capacity of the pipe piles. A larger A-size TPT (29 by 23 by 60 in.) was driven and achieved the required bearing at a depth of 58 ft. From Figure 4 it can be seen that the A-size TPT was the most effective of the five piles and achieved bearing approximately 14 ft shorter than the monotube pile. It is also obvious that continued driving of the A-size TPT would have produced an even higher bearing value in the granular soil.

Figure 4 shows a comparison of the five piles, illustrating the effectiveness of both pile taper and an enlarged tip.

Brooklyn

A small city (approximately 15,000 population) is under construction in Brooklyn, consisting of 54 apartment buildings varying from 11 to 20 stories each plus 20 parking garages of 5 stories each. Subsoil conditions consist of 15 ft of hydraulic and sanitary fill over 6 ft of loose organic sandy silt. Then a loose to medium deposit of sand is encountered that extends to depths of 100 ft or more. Conventional piles typically achieve 50-ton capacities at depths of approximately 50 ft in this soil deposit.

The first 19 buildings were supported by 120-ton Franki-type piles. Pile capacities were marginal and production was very low, on the order of 4 to 7 piles per day per pile-driving rig. The next 35 buildings were supported on 6,500 TPTs varying in capacity from 90 tons to 120 tons. Production was on the order of 12 to 20 piles per day per pile-driving rig, or more than double that of the Franki-type piles.

The New York City building code places very stringent requirements on high-capacity piles. Fifty-nine load tests on TPT piles were conducted under the New York code; each test pile was loaded to twice design load and held for 96 hours. All tests were successful. The 90-ton piles were driven with the Vulcan "0" hammer (24,375 ft-lb/blow) to resistances varying from 66 to 100 blows/ft; for 100-ton piles the final driving resistance varied from 100 to 120 blows/ft. The Vulcan 010 hammer (32,500 ft-lb/blow) was used to drive the 120-ton piles to final resistances varying from 70 to 90 blows/ft. Penetrations into the granular bearing layer varied from 2 ft to 15 ft, and average pile length was approximately 26 ft.

Pile spacing varied from 54 in. to 60 in., depending on tip size. Pile cap sizes varied from 1 pile to 4 piles. Tip sizes driven within a pile cap varied in accordance with the densification produced by the driving of the initial piles in a cap. The maximum tip elevation difference permitted in any pile cap was 10 ft; where the tip difference was more than 5 ft, however, the pile was not stopped until the resistance criterion was doubled. When a pile penetrated more than 2 ft below other piles already installed in the pile cap, the short piles were redriven to assure no loss in bearing capacity. Also, an extensive redriving program was conducted to investigate the possibility of pile relaxation; redriving produced resistances generally equal to or somewhat greater than the original driving resistances, indicating no relaxation.

When the TPT pile is driven, an annular space may remain around the pile stem caused by the penetration of the larger base. Usually this space will be filled immediately with the soil below the water table while the driving is still in progress. Any remaining space is backfilled with granular soil at the completion of driving. To ascertain the lateral stability of the piles, a number of lateral load tests were conducted. Generally usable lateral capacities of 5 tons or more were indicated by these tests, which were conducted with 50 percent of design vertical load on the piles.

A typical soil boring, driving record, and load test result are shown in Figure 5. The B-size TPT (32 by 26 by 60 in.) was driven to 74 blows/ft with the Vulcan 010 hammer, resulting in 4 ft of penetration into the medium-dense sand bearing layer. The pile was intended for 120 tons capacity; therefore it was tested to 240 tons, resulting in gross and net tip settlements of 0.41 in. and 0.20 in. respectively. A retest to 300 tons resulted in gross and net tip settlements of 0.54 in. and 0.25 in. respectively. It is obvious that the pile is satisfactory for working loads up to 150 tons.

The underground utility system for this project is designed on approximately 9,000 20-ton piles. Conventional timber piles driven for 20 tons capacity average 35 ft in length. Currently, Y-size TPTs with timber stems are being driven with a Vulcan No. 1 hammer (15,000 ft-lb/blow) to average lengths of approximately 18 ft. A typical boring, driving record, and load test result are shown in Figure 6. For a final driving resistance of 4 blows/in., the gross and net butt settlements are 0.45 in. and 0.18 in. respectively. It is obvious that the allowable load capacity of the pile is at least 25 tons and probably 30 tons.

The Brooklyn project illustrates the technical effectiveness of enlarged-tip piles. Also, a direct comparison with the Franki-type pile system shows the TPT system to be economically competitive and to require less construction time by a factor or two.

Rockaway

Two 20-story apartment houses are under construction in Rockaway (Queens) at a site within a few hundred feet of the Atlantic Ocean. The soil profile consists of several feet of fill underlain by loose sand, organic silt, and peat to a depth of approximately 27 ft. Then a dense sand layer approximately 7 ft thick is encountered over a 19-ft-thick layer of compressible clayey silt and gravel. The bearing layer is sand, encountered at a depth of 53 ft. Conventional cast-in-place piles achieve a 60-ton capacity at depths of approximately 70 ft in this soil profile.

A total of 450 piles of 150-ton capacity were driven for this project. Three load tests were performed under the relatively severe requirements of the New York City code. All tests were satisfactory. A typical soil boring, driving record, and load test result are shown in Figure 7. Predrilling to a depth of 42 ft and a diameter of 30 in. was performed to assure penetration below the dense sand at a depth of 27 ft. Then, the A-size TPT (29 by 23 by 60 in.) was driven with the Vulcan 010 hammer to

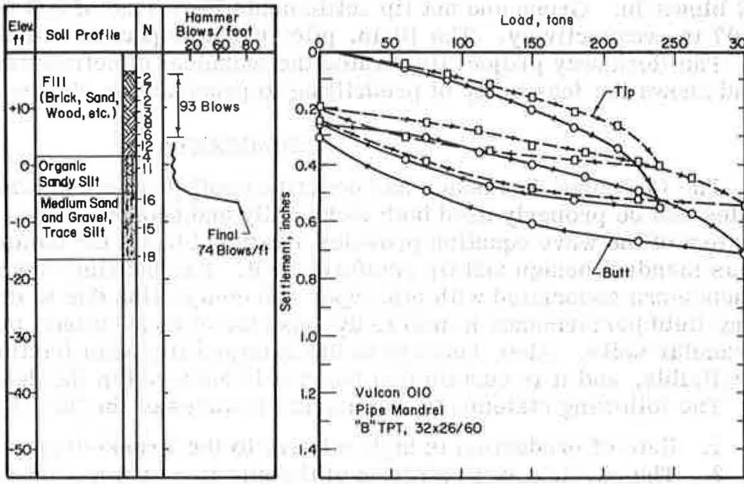


Figure 5. Load test data, B TPT, Brooklyn.

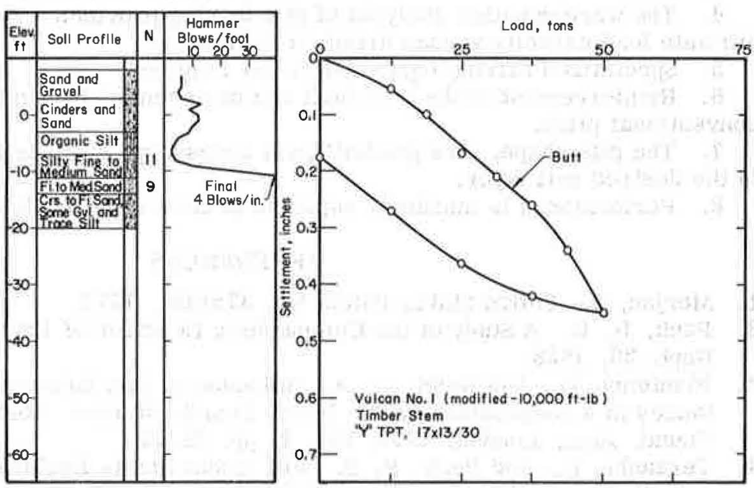


Figure 6. Load test data, Y TPT, Brooklyn.

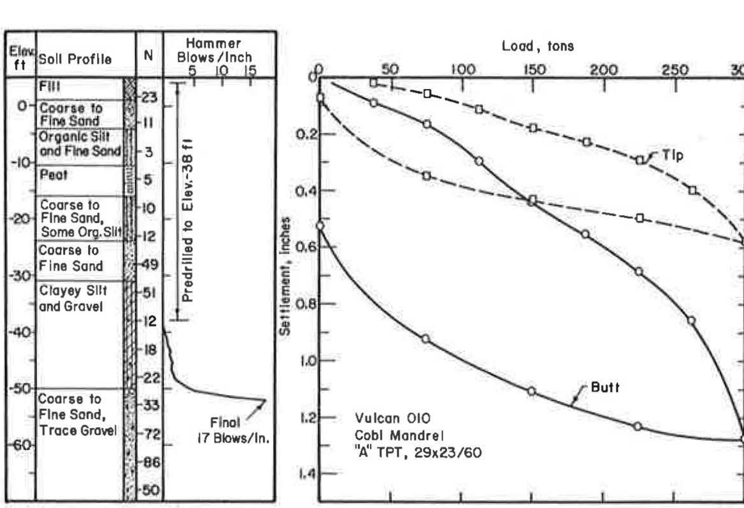


Figure 7. Load test data, A TPT, Rockaway.

17 blows/in. Gross and net tip settlements for a load of 300 tons were 0.58 in. and 0.07 in. respectively. The 16-in. pile shaft was poured with a 6,500-psi concrete.

The Rockaway project illustrates the technical effectiveness of enlarged-tip piles and shows the feasibility of predrilling to penetrate an obstructing soil layer.

SUMMARY

The foregoing discussion has described soil profile conditions in which enlarged-tip piles can be properly used both technically and economically. Analysis of pile driving by use of the wave equation provides a rational basis for hammer and cushion selection plus mandrel design and tip reinforcement. Soil bearing capacity theory, along with phenomena associated with pile taper and compaction due to driving, helps to explain why field performance is markedly superior to conventional piles, especially in loose granular soils. Also, because of the enlarged tip, skin friction on the pile stem is negligible, and it is certain that bearing is achieved in the desired soil layer.

The following statements summarize features of the TPT system described here:

1. Rate of production is high relative to the Franki-type pile.
2. The physical configuration of the pile is a known predetermined quantity, with structural integrity based on a rational design.
3. Field inspection involves the same techniques used for conventional piles.
4. The wave equation analysis of pile driving provides a reliable determination of ultimate load capacity versus driving resistance.
5. Specialized driving equipment is not required.
6. Reinforcement of the pile shaft can be accomplished in the same manner as for conventional piles.
7. The pile shape, plus predrilling if necessary, ensures that bearing is achieved in the desired soil layer.
8. Performance is markedly superior to conventional piles in loose granular soils.

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