Design and Construction of Starsol Piles

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Use of auger-cast piles has increased dramatically since the late 1970s, when concrete pumping technology enabled piles to be constructed with concrete instead of a sand-cement grout mix. The Starsol rig, introduced into the auger-cast market in the early 1980s, was designed to overcome some of the problems associated with auger-cast piling. The Starsol rig's essential feature is its internal tremie, which constructs a concrete pile shaft of high quality that, in turn, allows for higher concrete working stresses. The Enbesol quality-control system provides real-time pile-construction parameters, enabling rig operators to identify potential problems and rectify them during pile construction. Hard copy print-outs provide clients with a permanent record of a completed pile. Following an independent research project conducted on the load-bearing capacity of the Starsol pile, it was determined the piles could be designed as concrete piles and injected under low pressure.

Auger-cast piles were developed in the United States in the late 1940s. For some 30 years after their introduction, they were constructed using a sand-cement grout mix; but work in Belgium, France, and Holland in the 1960s and 1970s showed that auger-cast piles could be constructed using pumpable concrete mixes. Development of the Starsol piling system was begun in 1980 in an attempt to remedy some of the perceived weaknesses of auger-cast pile construction. This paper describes the Starsol piling rig and pile construction as well as the Enbesol real-time data quality-control logger, and its record-keeping instrumentation. An investigation into the load-bearing capacity of the piles and pile-shaft concrete quality is also detailed.

WHY THE STARSOL SYSTEM WAS DEVELOPED

The conventional auger-cast or continuous-flight-auger (CFA) pile was developed in the United States in the late 1940s. In the early years of the CFA system, engineers found that placing concrete with conventional-size aggregate was more costly than using sand-cement grout, and so for the next 30 years or so, grout piles were the norm (*1*). However, in the 1960s and 1970s, work carried out in Belgium, France, and Holland showed that it was possible to construct augercast piles economically using conventional, pumpable concrete mixes. This discovery spurred the development of a large auger-cast market in Europe. Although considerable problems were encountered in the early stages of the CFA pile's development (*2*), problems rarely were documented. A notable exception was a project at a site in Glasgow in which an engineer and piling contractor worked together to solve several problems (*3*).

Some early problems related to the fact that most of the machines used to drill auger-cast piles had fairly low drilling power, with torques in the 20- to 80-KNm range. Consequently, hard layers frequently could defeat the piling rig. Also, the traditional method of concreting the pile, whereby an auger is raised a few centimeters just before concreting, could disturb the pile base and cause the concrete and soil to mix. The result was often poor pile-base load-settlement characteristics, which are often a feature of auger-cast piles. Finally, if the auger were extracted too rapidly, the soil could collapse and cause necking within the pile shaft. To minimize the problems associated with conventional auger-cast piling, in 1980 a new piling rig was developed: the Starsol system.

DESCRIPTION OF THE STARSOL RIG

At first glance, the Starsol rig looks similar to conventional auger-cast piling rigs (Figure 1). An important difference between them is the Starsol rig's internal tremie pipe, which effectively prevents

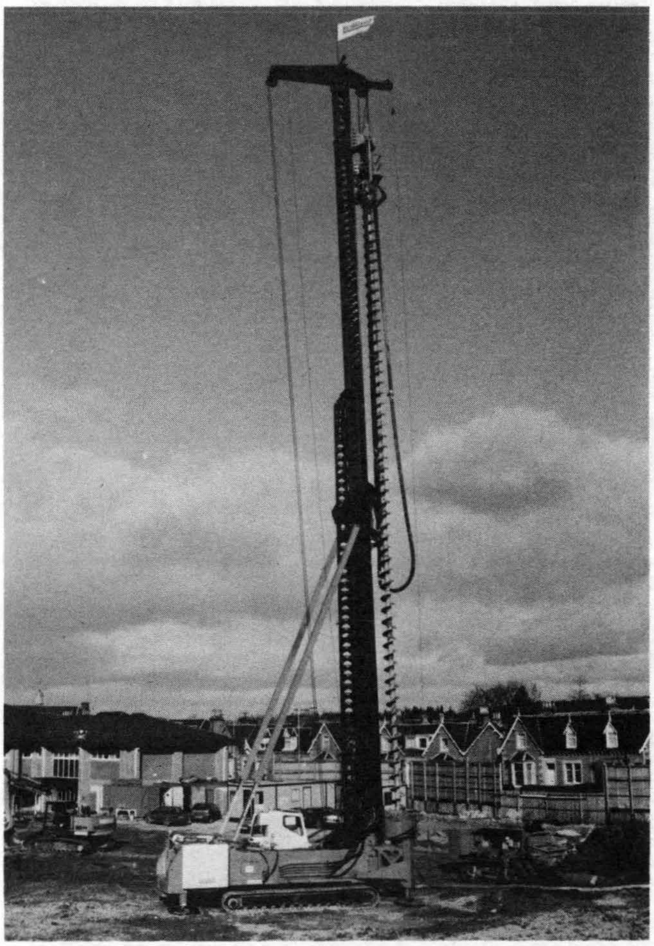

FIGURE 1 Starsol piling rig.

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many of the concreting problems associated with auger-cast piles (Figure 2).

Main features of the Starsol rig (*4*) are shown in Figure 3. Here are the key elements that distinguish it: a hydraulic motor; a continuous-flight-auger around an external tube; a second, central tube sliding inside the first one; a system of hydraulic jacks that allows the central tube to be slid vertically over a length of some 1.5 m; and a spoil-cleaning system. The central tube has two important functions. At its base is a pilot bit or stinger, which can break up tough ground in advance of the main auger. Second, it acts as the concreting tube or tremie.

Depending upon their size, Starsol rigs have torques ranging from 80 to 140 KNm and can produce piles with diameters ranging from 420 to 1420 mm and typical depths of up to 30 m.

STARSOL PILE CONSTRUCTION

Except for the concreting technique Starsol pile construction is similar to that of traditional auger-cast piles.

Drilling

Before drilling commences, a data-logger system is set to "drilling mode" and the hydraulic rams on the drilling head assembly

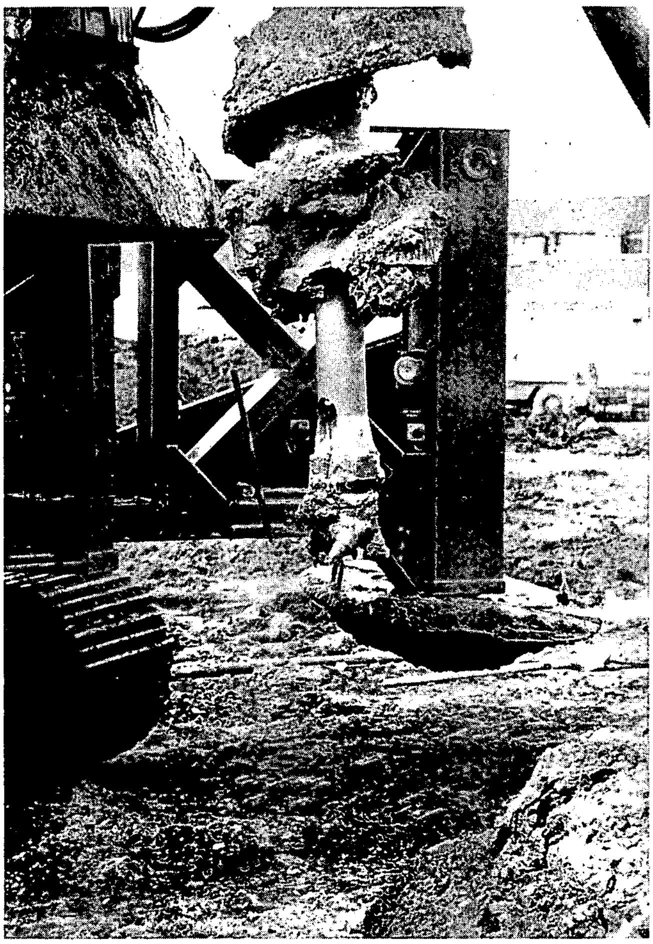

FIGURE 2 Internal tremie pipe.

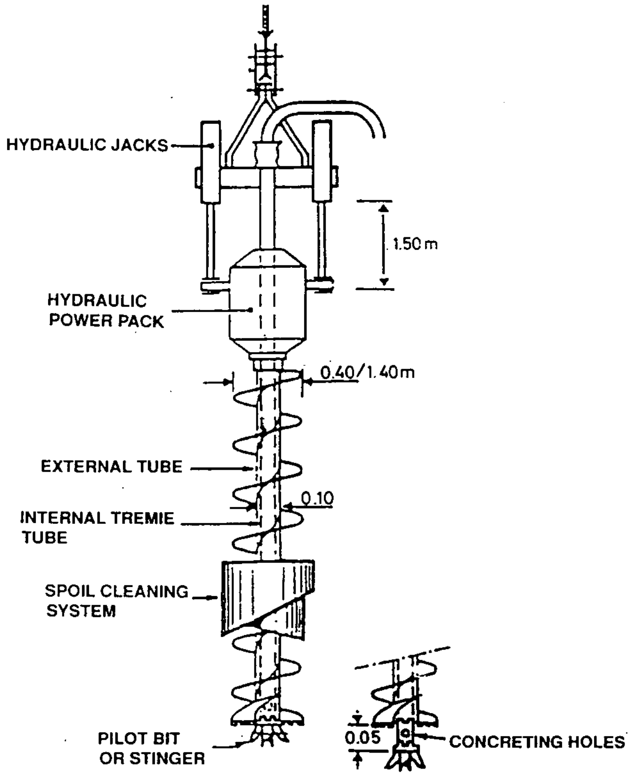

FIGURE 3 Main Starsol features.

are completely opened. At this point, the pilot bit is locked in position immediately below the drilling head of the auger. Drilling begins and the auger and internal tremie turn together, drilling into the ground.

The full drilling torque of the rig is mobilized because of the way the auger blade is designed, with the pilot bit and auger teeth combining over the full surface of attack to cut into the soil. This feature enables the machine to penetrate strata with uniaxial compressive strengths of up to 35 to 50 MPa.

During the drilling phase, the data logger records the torque, advancing speed, and depth. The data are plotted, in real time, on a computer screen in the rig cabin, and the operator can monitor the graphs at any time.

Concreting Phase

During this phase, the main difference between the Starsol method of concreting piles and that of conventional auger-cast piles is observed (Figure 4).

The system is primed by pumping concrete into the internal tremie tube. The rig operator monitors the concrete pressure, and when it is satisfactory the auger assembly, including the rotation table, is raised by two hydraulic rams on the drilling head assembly. During this operation the internal tremie tube and the pilot bit remain at the base of the pile.

As the auger assembly is lifted, two side vents on the tremie pipe are exposed and concrete is injected under pressure at the base of the pile. The auger is lifted in the same manner, until the internal tremie tube is fully extended and the hydraulic rams on

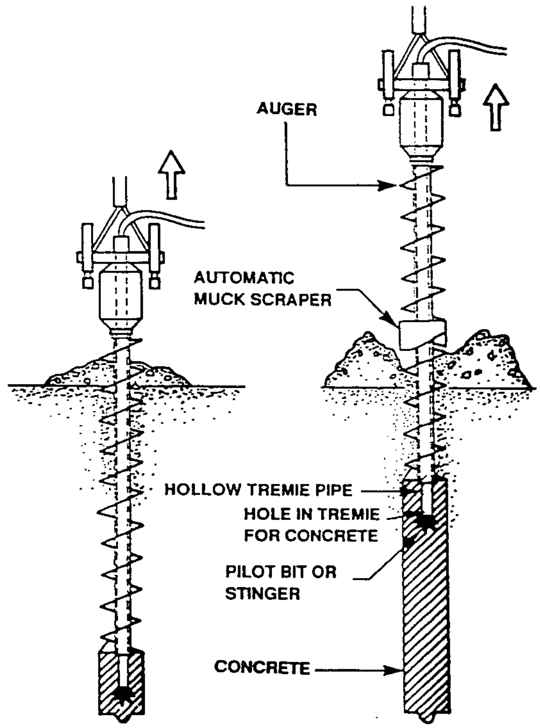

FIGURE 4 Concreting of a Starsol pile.

the drill head assembly are completely closed. When the internal tremie tube is fully exposed, there is approximately 1.5 m between the vents of the tremie and the base of the auger. At this point the internal tremie is locked in position and the whole assembly is raised.

Concreting continues using the tremie. A real-time data logger enables an operator continue to control the concrete pressure (at a minimum, 10 kPa), which ensures the integrity of the pile concrete. The injection of concrete under pressure gives a sound contact between the ground and the concrete over the whole pile shaft.

Auger Cleaning

As the auger is extracted, spoil remains attached to the flights. An auger-cleaner clears the flights and deposits the soil on the ground to the side of the excavation.

After completing the concreting, when the auger and tremie are fully extracted, the rig moves back from the pile position in order to allow access to the pile head.

An excavator quickly removes the spoil that accumulated around the cast pile. The rig is cleaned and prepared to construct the next pile.

As with any tremie technique, contaminated concrete is brought to the surface and must be removed before a reinforcement cage can be inserted. The concrete is removed with an excavator. Then a funnel, with approximately the same diameter as the pile, is inserted in the top of the pile shaft as preparation for the next phase of construction.

Insertion of the Reinforcement Cage

It is possible to position either individual bars or reinforcement cages in the pile. A simple system has been developed that can be used to assist cage placement. With this method it is possible to place long reinforcement cages; the longest inserted to date is 24 m. The reinforcement cage can be inserted either with the aid of the rig or a service crane.

QUALITY CONTROL DURING CONSTRUCTION: ENBESOL DATA-LOGGING SYSTEM

The data-logging system is used to supply a real-time record and ongoing quality-control mechanism during pile construction.

Quality control starts when drilling begins. As the auger penetrates the ground, the rate of advance and the torque mobilized are measured and recorded. In the concreting phase, the pressure and volume of concrete are measured and recorded. This real-time monitoring constitutes a preventive model for quality control: if anomalies occur, the pile can be immediately redrilled.

During the drilling phase, measurement of the penetration rate helps indicate the stiffness of the strata encountered. When these data are examined in conjunction with the torque measurements recorded by the drilling head, an operator gains a pretty good idea of the ground qualities.

In the concreting stage, concrete pressure and volume are measured by the data logger. Pressure is clearly indicated, both in positive and negative values. The software translates this data into a graph representing the ratio of real to theorical volume. The ratio should be over 1.0; in practice it is generally between 1.15 and 1.2. Furthermore, sharp variations on the concrete curve can be observed and avoided; the rig operator is able to control them by varying the lifting speed of the auger and tremie tube.

The concrete-pressure sensor is located at the swan neck at the top of the tremie tube. Although it would be preferable to measure concrete pressure at the discharge point, the base at the auger during drilling and concreting is too harsh an environment for the concrete-pressure sensors.

The concrete pressure at the point of discharge is given by

$$P_c = P_b \cdot h + P_m - P_f - p_b \cdot h_b - p_w \cdot h_w$$

where

P_c = concrete pressure,
p_b = unit weight of the fresh concrete,
h = height or the auger,
P_m = concrete pressure measured at the swan neck,
P_f = friction loss in the tremie pipe,
h_b = depth of discharge below the surface of the concrete,
p_w = unit weight of water, and
h_w = height of water above the discharge point.

The two final terms of the equation are of relatively minor significance compared with the first three. The only unknown value is the friction loss in the tremie tube. This can either be calculated using fluid mechanics or estimated for a specific concrete and particular machine by pumping concrete through the system before screwing the auger into the ground and measuring the concrete pressure at the discharge point. In this manner, the friction-loss value can be found, and hence the formula can be

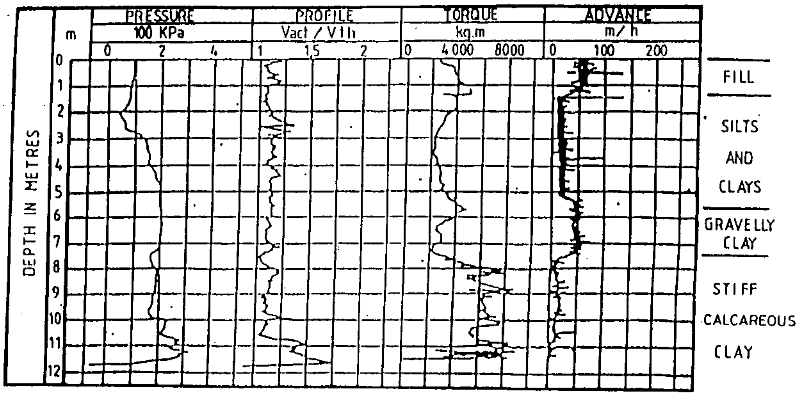

FIGURE 5 Typical Enbesol log.

used to estimate concrete pressure at the discharge point, at any stage of the concreting cycle.

Before lifting the auger to expose the vents at the base of the tremie, concrete is pumped at high pressure to build up a satisfactory head of concrete. The pressures during the whole concreting phase will remain positive, indicating that the tremie pipe is full of concrete. Any anomaly noted can be acted on immediately, and if the situation merits it, the pile can be rebored and the concreting repeated. By monitoring the concrete pressure and the ratio of actual- to theoretical-pile volume, it is possible to reduce concrete consumption without risking the integrity of the pile shaft (*5*).

The Enbesol data-logger system is designed to give a real-time record of pile construction. A print-out provides four graphs—rate of advance, torque, concrete pressure, and volume—all in relation to depth. This information constitutes a substantial part of the pile's record. A typical record is shown in Figure 5.

ULTIMATE PILE CAPACITY OF STARSOL PILES

The ultimate bearing capacity of this type of pile was the subject of an investigation by the Laboratoire Central des Ponts et Chaussées (*6*). Five sites were investigated, as shown in Table 1. At each site, the piles were instrumented using Laboratoire Central des Ponts et Chausées extensometers to determine the load transferred from the pile to the soil at various depths down the pile. A typical set of results, those for the 10.35-m-long pile at Clermont-Ferrand are shown in Figures 6–8.

Ultimate capacity of the piles was determined from these calculations:

1. The load on the pile when the pile settlement was equal to 10 percent of the pile diameter;
2. If the pile settled less than 10 percent of the pile diameter during the test, but the settlement exceeded the Davisson limit (*7*) (defined as the elastic compression of the pile plus 4 mm plus the pile diameter divided by 120), then the ultimate capacity of the pile was estimated using two methods: Chin's (*8*) and Fleming's (*9*) methods. In each case, the pile load corresponding to a predicted settlement of 10 percent of the pile diameter was taken as the ultimate pile capacity.

On the other hand, if the pile did not settle more than the Davisson limit, no attempt was made to analyze the ultimate capacity

TABLE 1 Details of Piles Tested

Site	Soil Type	Net Limit Pressure - Pl* (MPa)	Pile Dimensions Diameter and Length (m)	Estimated Ultimate Capacity (KN)	Curve
COLOMBES	Sand and gravel	2.0-2.6	1.0 x 7.5	3,660	A
STRASBOURG	Gravel	1.6-2.2	0.75 x 4.5	1,950	B
	Gravel	2.2-2.7	0.82 x 5.1	5,400	C
CLERMONT - FERRAND	Sand and clayey silt	0.5	0.82 x 10.35	1,950	D
	Clayey silts	0.5	0.82 x 7.2	-	-
	Cemented sand	2.0-13.0			
PARIS	Sand and gravel	2.0-6.0	0.5 x 15.5	-	-
	Weathered chalk	1.3-1.9			
TOULOUSE	Soft clay	0.45	0.5 x 11.5	4,300	E
	Calcareous clay	4.50			

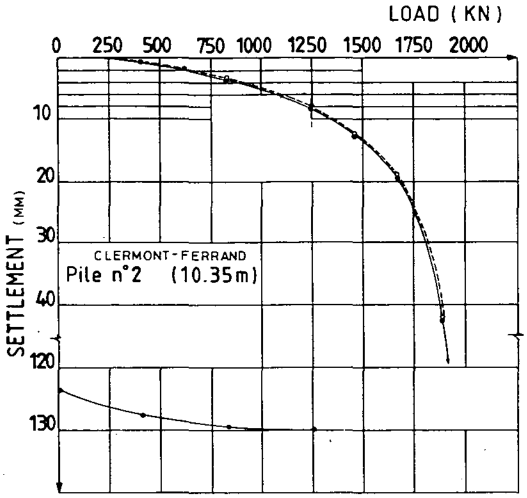

FIGURE 6 Load settlement curve.

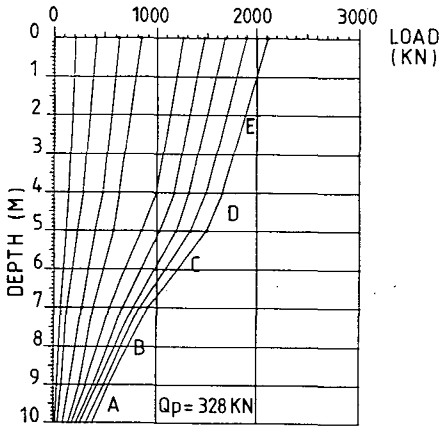

FIGURE 7 Distribution of load along pile length.

of the pile. Figure 9 shows the normalized plots of the five pile tests for which it was possible to determine the ultimate capacity of the piles concerned.

One problem with existing research on the ultimate capacity of the Starsol pile is that it is based mainly on French design practice and the use of a pressuremeter. To enable other engineers to design this type of pile, a review of test data is currently under way with the aim of producing effective stress design methods.

Concrete quality in the piles was monitored by taking concrete cores and testing them some time after pile construction. The results are shown in Table 2.

Results of the load-testing program indicated the following:

- Load-settlement characteristics for this type of pile are similar to those of other piles constructed with different methods; so normal design methods can be applied to piles constructed in this manner.
- Observed ultimate capacities indicated higher ultimate end bearing and ultimate skin friction in Starsol piles than in traditional bored piles. It was believed that these characteristics were the result of good concrete placing via the internal tremie, and minimal disturbance to the surrounding soil because of the boring method that was used.
- High quality, in situ, concrete can be achieved in auger-cast type piles by using the internal tremie system. The system gave the French technical authorities sufficient confidence for them to allow an extra 20 percent compressive stress on the concrete in the pile shaft, an increase from 6 to 7.2 MPa.

On the basis of the load tests, the following design guidelines were proposed.

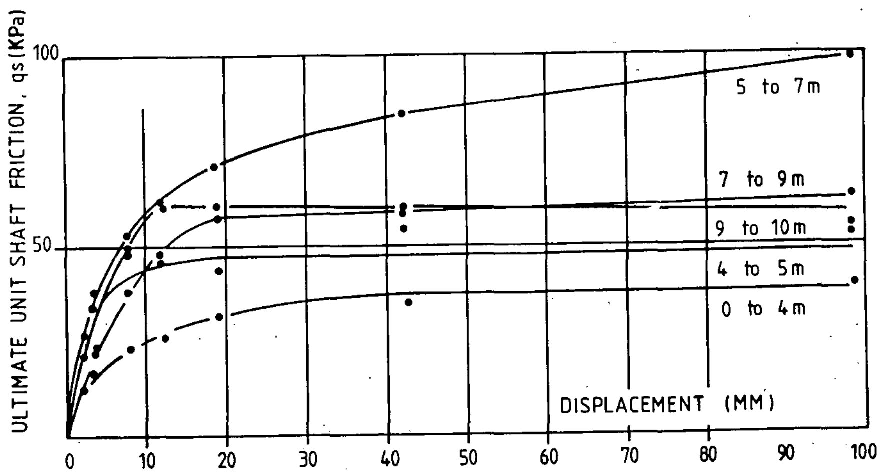

FIGURE 8 Mobilization of shaft friction along the pile length.

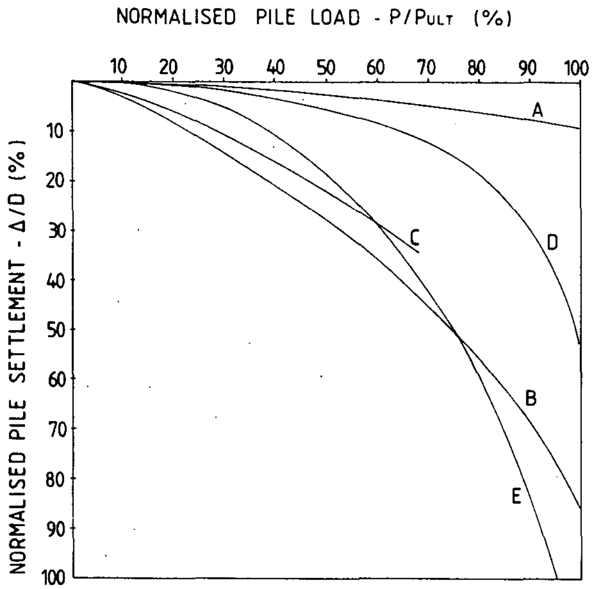

FIGURE 9 **Normalized pile load settlement curves.**

Ultimate Unit End Bearing

The ultimate unit end bearing is given by

$$a_b = K_p \cdot pl^*$$

where

K_p is the end bearing factor and pl^* is the net limit pressure.
Design values for various soil types are shown in Table 3.

Ultimate Unit Skin Friction

The ultimate unit skin friction for various soil types is shown in Table 4. These skin-friction values should be applied to the "real" pile diameter, which is the nominal pile diameter increased by a small factor as indicated below. Note that the range of skin-friction values found during the testing program was very similar to the values obtained using the current French design code (*10*) and the curve for piles concreted under low pressure.

TABLE 2 **Concrete Core Test Results**

Site	Age at Testing (days)	Compressive Strength (MPa)	Young's Modulus (GPa)
Colombes	62	31.40-55.20	19.80-26.30
Elsau	435	31.13-37.39	30.68-39.19
Clermont-Ferrand	350	30.90-50.10	24.48-26.43
Toulouse	128	42.40-51.20	27.00-31.50

TABLE 3 **Design Values for K_p**

Soil Type	Net Limit Pressure pl* (MPa)	K_p
Clayey sand, calcareous clay, clayey silt	0.5 - 4.5	1.2 - 1.4
Weathered chalk	1.3 - 1.9	> 1.8
Sand and gravel	1.6 - 2.7	> 1.8

TABLE 4 **Design Ultimate Unit Skin Friction Values**

Soil Type	Net Limit Pressure pl* (MPa)	Ultimate Unit Skin Friction q_s (KPa)	Increase in Nominal Diameter
Soft clay, clayey silt and loose sand	0.2 - 0.5	35 - 55	1.1
Sand and gravely sand	1.0 - 2.5	95 - 150	1.15
Sandy gravel and gravel	1.0 - 5.0	100 - 200	1.2
Weathered chalk	1.3 -1.9	> 100	1.1
Very stiff calcareous clay	4.5	200 - 400	1.1

TABLE 5 Correlations Between the Net Limit Pressure and U.S. Soil Tests

Soil Type	Pl* (MPa)	Cu (KPa)	N (blows/300mm)
Sand			15 to 20 pl*
Silt			30 pl*
Chalk			10 to 20 pl*
Clay	< 0.3	182 pl*	
	0.3 to 1.0	83 pl* + 30 or 100 pl* + 25	
	1 to 2.5	29 pl* + 85	
			15 to 20 pl*

Correlation Factors

The approximate correlation factors between the net-limit pressure and more common U.S. soil tests (*11*) are given in Table 5. In each case, the net limit pressure *pl** is in MPa.

CONCLUSION

This Starsol piling technique has proven successful in France. Since 1985, 2 to 3 percent of the 100,000 piles constructed to date have been used for highway or railway bridges.

The Starsol rig's internal tremie system in combination with the Enbesol data-logger, quality-control instrumentation has given the French technical authorities sufficient confidence in this piling method to allow an extra 20 percent compressive stress on the concrete in this type of pile as compared with the requirement for conventional auger-cast piles.

Analysis of load tests carried out on the piles indicated that current French standards for piles concreted under low pressure were broadly applicable to Starsol piles, which provide somewhat better pile-loading capacity than do conventional bored piles. A review of available test data is under way to enable the Starsol piles to be designed using effective stress-pile design methods.

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