# Long-term behavior of expansive concrete drilled shafts

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The research reported here is a continuation of work reported earlier in which it was concluded that the use of expansive cement concrete increased the side resistance of drilled shafts (bored piles) in stiff clay by as much as 50% over that in normal concrete shafts and reduced the settlement by about 50%. The conclusions were based on tests conducted at a concrete age of about 2 months. A year and a half later, the three shafts (one made with normal concrete and two made with expansive concrete) were tested again and the same comparatively better behavior of expansive concrete shafts was observed. The base capacities of all the shafts increased over this period owing to the consolidation of soil caused by residual base stresses following the initial tests. The shafts were later extracted for visual observation and coring. The compression tests on concrete cores obtained from various depths along the shafts indicated that expansive concrete behaves as a sound structural material in the long term. The gains in strength and stiffness of expansive concrete over normal concrete over a period of 2 years were found to be significant.

*Key words*: base bearing capacity, bored pile, cement (expansive), concrete (structural), drilled shaft, expansion, frictional capacity, long-term behavior, settlement.

La recherche, traitée dans cet article, constitue la suite d'une recherche relatée précédemment et qui avait permis de conclure que l'utilisation de béton avec ciment expansif augmentait d'au moins 50% la résistance superficielle de pieux forés dans de l'argile consolidée et réduisait l'affaissement d'environ 50%. Ces conclusions étaient fondées sur des essais réalisés sur un béton d'environ 2 mois d'âge. Après un an et demi, de nouveaux essais furent entrepris sur les trois pieux (l'un réalisé avec du ciment normal, les deux autres avec du ciment expansif) et la même amélioration fut constatée pour les pieux à ciment expansif. En outre la capacité portante à la base de tous les pieux avait augmenté, augmentation causée par la consolidation du sol due aux contraintes résiduelles à la base provoquées par les premiers essais. On retira ensuite les pieux afin de permettre un examen visuel et un carottage. Les essais de compression sur des carottes de béton prises à diverses profondeurs indiquent que le béton expansif se comporte, avec le temps, comme un matériau structural solide. L'accroissement de la résistance et de la rigidité du béton expansif sur une période de 2 ans fut trouvé plus important que dans le cas du béton normal.

*Mots clés:* capacité portante à la base, pieu foré, ciment (expansif), béton (structural), gonflement, capacité portante par frottement, comportement à long terme, affaissement.

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# Introduction

The research reported herein is a follow-up of work reported earlier (Sheikh *et al.* 1985), in which the short-term behaviors of normal and expansive concrete drilled shafts in stiff overconsolidated clay were compared experimentally. Three shafts, one made of normal concrete and two made of expansive concrete, were tested under concentric compression about 2 months after casting to substantiate results from an analytical model based on the stress path method. It was observed that the use of expansive concrete resulted in higher (up to 50%) maximum side resistance and that the movement during testing was reduced by about 50% in most of the loading range, in comparison with the normal cement concrete shaft.

All three shafts were tested again at the age of 18 months to study the long-term effects of using expansive concrete. It was assumed that 18 months is a reasonably long time-span to evaluate the structural performance of shafts over their useful life. The elapsed time also allowed the concrete to experience maximum possible expansion.

At age 18 months, the shafts were first tested under monotonic compression to failure and then under monotonic uplift loading to failure. They were subsequently extracted from the ground, and concrete cores were taken from various depths along the shafts and tested at an age of 27 months to evaluate the structural integrity of the expansive concrete. It was postulated earlier (Sheikh *et al.* 1983, 1985) that the water content of the clay at or near the interface of the shaft and soil may increase because of the water migration to that region from the soil as well as from the concrete. This leaves the soil softer and weaker at the interface in the case of the normal concrete shaft. Expansive concrete has the potential to exert sufficient pressure to cause the water concentrated at the interface to diffuse into the soil mass. Water content in the soil was therefore measured at various depths in the vicinity of the shafts to study its variation with both longitudinal and lateral location.

From this study, it can be concluded that the beneficial effects of using expansive concrete are evident in the short term as well as the long term. The expansive concrete in the shafts is appropriately confined and acted as a sound structural material during the 27 months of the investigation.

## Summary description of test shafts

All three test shafts were nominally 12 in. (305 mm) in diameter and 10 ft (3.05 m) long. Longitudinal reinforcement in each shaft consisted of six No. 5 (area 200 mm<sup>2</sup>) deformed bars, and No. 2 (area  $32 \text{ mm}^2$ ) smooth circular hoops were used at 6 in. (152 mm) spacing throughout the shaft length except at the top, where two spaces were reduced to 4 in. (102 mm). Normal portland cement was used in shaft 1, and shafts 2 and 3 were made of expansive concrete. The expansive cement consisted of a mixture of normal portland cement and an ex-

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FIG. 1. Load-movement curves.

pansive component (Sheikh *et al.* 1983, 1985). The proportion of the expansive component can be adjusted to achieve the desired expansive potential. Expansive cement A, used in shaft 3, contained 40% expansive component, while shaft 2 used expansive cement B, which contained 35% expansive component. The maximum measured *in situ* expansion of concrete in the shafts ranged between 0.10 and 0.15%. The first series of tests (Sheikh *et al.* 1985) was performed 56–57 days after casting. The ages of the shafts varied between 544 and 552 days for the tests reported in this paper.

#### **Compression tests**

The loading arrangement and the test procedure used for these tests were similar to those used earlier. The test data consisted of load and the settlement of the top of the shaft. The strain gages, installed on steel cages before casting and used for earlier tests, were either found to be erratic or did not function at all. These gages, therefore, could not be depended upon for the analysis of load transfer in the shafts. The tests were loadcontrolled, quick tests to initial failure, followed by constant rate of penetration (approximately 10 mm/min) to large displacements. The increments of load were 5 kips (22.2 kN) applied every 3 min. The settlement readings were taken 30 s and 150 s after the specified load was reached. Shaft settlement was measured with the help of two dial gages with a gradation precision of 0.0001 in. (0.0025 mm), mounted on two wooden reference beams resting on soil-supported columns.

The load-settlement curves for the tops of the shafts are shown in Fig. 1, for the present as well as the previous series of compression tests. For the present tests, only 30-s readings are shown. Test results show a very similar trend for both series, but the capacities of the shafts increased significantly over the period of dormancy between tests. These increases are 39, 30, and 48% for shafts 1, 2, and 3, respectively. All the shafts showed improvement over the initial stiffnesses ob-



FIG. 2. Comparison of compression and uplift load-movement curves.

served in the short-term tests. The improvement was highest (about 80%) in shaft 1 and least in shaft 3 (about 50%). The soil at the bottom of shaft 1 was stronger (as evidenced from the CPT tests reported earlier (Sheikh *et al.* 1985)) than that at the bottom of the other shafts. After the shafts were dug out, the soil beneath the bases of all three shafts was observed to be clayey silt with sand seams. The presence of the sand probably allowed the soil beneath the shafts, which was in a state of residual compression after removal of load in the short-term tests, to consolidate and strengthen, which accounts for most of the increased capacity during the June, 1984, loading. This phenomenon was especially prounounced for shaft 1, where a greater frequency of sand seams was observed. The effect of time-dependent increase in base bearing capacity will be described in more detail later.

# **Uplift** tests

One week after the compression tests, the three shafts were tested in uplift. The load was applied to the shafts through the longitudinal bars of the reinforcing cages. After chipping approximately 4 in. (101.6 mm) of concrete from the top of the shaft, an anchor plate,  $20 \times 21 \times 1$  in. ( $508 \times 533 \times 25$  mm) in size, was welded to the reinforcing bars. The anchor plate was then pulled using two 1.75 in. (44.5 mm) diameter all-thread high-strength steel rods. Steel anchor piles used as reactions for the compression tests were also employed as reactions for the uplift loads. The test data consisted of the applied load and the corresponding deformation measured at the shaft head by two dial indicators, again suspended from wooden reference beams. The loading procedure used for the uplift tests was similar to the one used for the three shafts



FIG. 3. Side resistance  $(r_s)$  vs. movement (u).

are given in Fig. 2. Also shown in the same figure are the curves obtained from the long-term compression tests (Fig. 1, June 1984), which relate the side resistance plus base resistance and movement of the heads of the shafts. Only the 30-s readings are plotted in Fig. 2. The uplift capacities, which are assumed to be totally frictional, are 28, 32, and 37 kips (125, 142, 165 kN) respectively for shafts 1, 2, and 3 (after sub-tracting the weight of the shaft). By comparison, the side resistances in compression for the short-term tests were 26, 33, and 36 kips (116, 147, 160 kN), using estimates of residual base loads based on shaft elongation during curing (Sheikh *et al.* 1985). The two sets of values are reasonably consistent, which suggests that similar side resistance values occurred during the February, 1983, and June, 1984, compression tests.

#### Load transfer comparisons

Figure 3 depicts the unit side resistance  $(r_s)$  versus settlement (u) curves obtained in the short-term compression tests (open symbols), including residual shear stresses distributed uniformly over each shaft from the estimated residual base load after curing (Sheikh et al. 1985). The unit side resistance versus upward movement (shown positive) for the uplift tests is also shown in Fig. 3. In developing these latter curves, the total uplift load minus the weight of the shaft was distributed to the upper and bottom halves in the same proportions as were observed in the short-term compression tests. Values of  $r_s$  at values of u less than the elastic rebound displacement of the prestressed soil beneath the base (assumed to be 1.5 mm) are unknown and therefore not plotted. It is clear in analyzing Fig. 3 that side resistance behavior did not degrade measurably in any of the shafts over the period of time between the two sets of tests.

The unit side resistance curves in Fig. 3 were assumed to be applicable for the June, 1984, compressional loadings, and



FIG. 4. Base resistance  $(r_t)$  vs. movement (u).



FIG. 5. Variation of water content with distance from shaft.

base load—settlement curves for those loadings were synthesized from Fig. 3 and the total load—settlement curves in Fig. 1. The resulting curves, shown in terms of net base pressure versus base displacement, are plotted in Fig. 4. Similar curves for the initial set of tests (Feb. 1983) are also shown in the same figure. It is clear from Fig. 4 that a significant difference exists in the maximum magnitudes of net base bearing stresses between the two series of tests. This was due to the apparent high values of initial residual base stresses following the initial tests (approximately 174 psi (1.2 MPa), based on extrapolation of the synthesized base load—settlement curves from the long-term tests to u = 0). These residual base stresses exceeded considerably the preconsolidation pressure of the site soil and allowed the soil to consolidate and strengthen between

GROUND LEVEL							
777777	777777	CONCRETE STRENGTH, f <sup>/</sup> <sub>c</sub> (MPa)					
SHAFT		SHAFT 1		SHAFT 2		SHAFT 3	
	_ 0 m	FEB 1983	MAR 1985	FEB 1983	MAR 1985	FEB 1983	MAR 1985
0		40.8		25.6		22.1	
			40.7	26.2		23.9	
2' -							35.5
			54.7		42.8		
	- 1 m				43.2		35.2
A' -							
6′-							
	-2 m						
			45.0		40.0		39.3
8′ -		40.8	516		47.2		39.2
		40.8	51.0				53.2
			46.5		37.0		33.1
10/ -	— 3 m						
NOTE: 1 MPa = 145 nsi							

FIG. 6. Compressive strength of shaft concrete at various levels and times.

the two series of tests, thus allowing the development of very high base stresses during the second series of compression tests. This increased base capacity therefore apparently produced the primary differences in the short-term and long-term load—settlement curves in Fig. 1.

#### Soil moisture content variation

About a month after the uplift tests were completed, the three shafts were extracted from the ground. During this operation, soil samples were taken at regular depths to determine the effect of concrete expansion on the variation of soil water content with distance from the shaft in the lateral direction. The depths selected were 2.5, 5.0, 7.5, and 9.0 ft (0.76, 1.52, 2.29, 2.74 m) from the top of the shafts. In the lateral direction, a 1/2 in. (12.7 mm) thick layer adjacent to a shaft was cut into four equal parts. Soil samples were taken from each of these parts. The soil at the surface in the vicinity of the shafts had been flooded just prior to sampling, particularly around shafts 2 and 3, which rendered the soil samples from the 2.5 ft (0.76 m) depth unsuitable for evaluating the effects of concrete expansion on moisture variation. Soil samples at 9 ft (2.7 m) depth could not be obtained without disturbance owing to its inaccessibility. Reliable results from the moisture content analysis are therefore limited to the two intermediate depths. These results are shown in Fig. 5. It is apparent that the use of expansive concrete generally resulted in reduced water content in the soil immediately surrounding the shafts. The drier and stronger soil was partly responsible for the increased side resistance of the expansive concrete shafts.

In the case of the normal concrete shaft, the water contents in the soil at and near the interface are higher than those in the surrounding soil, indicating the migration of water to the interface, possibly from the concrete. In the case of the expansive



FIG. 7. Comparison of stress-strain curves of shaft concrete.

concrete shafts, the soil water contents either increased or remained constant as the distance from the shaft increased. This is believed to be due to the pressure generated by the expansion of concrete, which drives water away from the interface.

#### **Concrete strength**

After the shafts were removed from the ground, they were stored at room temperature for about 8 months, following which cores were obtained from various depths. All the cores were tested in compression. The cores were 3 in. (76 mm) in diameter and 6 in. (152 mm) long. The results from these compression tests are shown in Figs. 6 and 7 along with the compression test results from previous cores taken after the short-term tests. Figure 6 shows the strength of concrete along the depth of the three shafts. The coring was done through the shaft ends, and owing to practical limitations, cores could not be obtained from the middle 4 ft (1.2 m) of the shafts. However, it was felt that the properties of concrete in this region can be ascertained with reasonable confidence from samples in the end regions.

The stress-strain curves of concrete from the three shafts are shown in Fig. 7. Each curve indicates an average of at least three cylinder tests. It should be noted that the February, 1983, results for shaft 1 were obtained from 6 in. (152 mm) diameter and 12 in. (305 mm) long cylinders (not cores). Over a period of about 2 years, the strength and stiffness of concrete in all the shafts have increased significantly. The improvement in the case of expansive concrete, however, is much higher than that in normal concrete. The ratio between the strength of expansive concrete and the strength of normal concrete varied between 0.57 and 0.63 in February, 1983. About 2 years later, this ratio increased to a range of 0.75-0.88. The lower ratio was for concrete with higher expansive potential. Whereas the strength and stiffness of normal concrete obtained from the cores adequately represented the properties of concrete in the shafts, the expansive concrete cores underestimated strength and stiffness of concrete in the shafts. This is due to the fact that expansive concrete in the shafts was subjected to lateral confining pressure all the time, which would result in significantly higher strength and stiffness (Sheikh and Uzumeri 1980; Richart et al. 1929). Therefore, the structural behavior of expansive concrete in the shafts in situ is not expected to be much inferior to that of normal concrete.

# Conclusions

This paper presents long-term results from a study on expansive concrete drilled shafts in overconsolidated clay. The short-term behavior of normal and expansive concrete shafts, reported earlier, indicated that the use of expansive concrete resulted in higher (25-50%) side resistance and that the settlement is reduced by about 50% in most of the loading range, compared with values for a normal concrete shaft. That conclusion was based on the tests conducted about 2 months after casting of the shafts. From the second series of tests (com-

pression and uplift), carried out a year and a half later, it was observed that the beneficial effects of using expansive cement concrete remained in effect in the long term. The base capacities of all the shafts in the second series of tests were observed to be significantly higher than those in the first test series. This was due to the increased strength of soil as a result of consolidation caused by the residual base stresses following the initial tests.

More than 27 months after casting, expansive concrete in the shafts behaved as a sound structural material. The ratio between expansive and normal concrete strengths obtained from the tests on unconfined cores varied between 0.75 and 0.88. This ratio at an age of 2 months was about 0.60. The lateral pressure on expansive concrete in the shafts due to in-place restraints is expected to result in better *in situ* concrete behavior than was obtained from the core compression tests.

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