Heave of Compacted Expanded Base Concrete Piles

Le Soulèvement des Pieux de Béton à Base Elargie et Compactée

J.I. CLARK P. Eng., Calgary, Alberta, Canada
M.C. HARRIS P. Eng., Edmonton, Alberta, Canada
D.L. TOWNSEND Eng. Edmonton, Alberta, Canada

SYNOPSIS Compacted expanded base concrete piles as originally developed by Franki have been widely used throughout the world. Most applications have been in soil profiles where the piles are predominately in sand or gravel. In Western Canada this pile type is also used in cohesive soils where the shaft is driven through lacustrine clays and silts and the base is formed in dense clayey till. Very high capacity piles are achieved in this profile but often detrimental pile heave occurs. The heave may destroy the integrity of the previously driven shaft or it may separate the shaft from the base thus destroying the normally high capacity of the piles.

Three case histories where detrimental pile heave ranging up to 800 mm has occurred are described. A method of assessing the potential for pile heave is presented along with techniques for rehabilitating piles which have suffered distress as a result of heaving.

INTRODUCTION

Although compacted expanded base concrete piles have been used in Canada for almost 40 years, the problem of pile heave or uplift has emerged in only the last decade. There are several reasons for this. First, the main application of this pile type has been in cohesionless soils and construction in cohesive soils has developed primarily in the last 15 years. Second, increased competition combined with performance specifications has led to designs involving greater capacities and a corresponding reduction in number of piles. This has led to a greater emphasis on load tests which ultimately detect the problem. Finally, it is likely that the problem has gone undetected in other cases but, since the piles have such an exceptionally high shaft capacity, they have performed satisfactorily as friction piles.

The uplift to which a pile shaft is subjected during the driving of an adjacent casing must be resisted since it may structurally damage the pile. The base heave that occurs when the plug is expelled and the base is compacted has not proven to seriously affect the pile capacity as it is pushed up against substantial shaft resistance as is also the case with driven piles (Klohn, 1961).

Pile capacity may be estimated with effective stresses using the design principles shown by Meyerhof (1976). The empirical relationship between capacity, volume of base and total blows for the last charge most commonly adopted is that presented by Nordlund (1970). This relationship, and also the early work of Meyerhof (1960), is applicable to cohesionless soils. As pointed out by Brzezinski et al (1973), it has been rather indiscriminately applied by contractors without special modifications for soils at base level which are not free-draining granular material.

The most common design approach adopted for Franki-type piles is a performance specification. The loads to be carried are specified and the contractor submits a design for which he accepts responsibility and guarantees performance. While this may appear to be the 'safest' approach to the owner or designer, if the contractor's design is not adequate, the impact of additional costs, delays or failures will often at least equally affect the designer and owner. An alternative to a performance specification is a design specification wherein the contractor is told where and how many piles to drive, how deep, in what order and timing and how to construct the pile. The design specification must be complete in every detail and must therefore reflect a thorough understanding of the pile characteristics and soil response to installation procedures. In this case the designer accepts responsibility for the design and the contractor accepts responsibility for proper construction. Irrespective of the contract procedure, the installation methods are critical.

The design specification must ensure that the pile has sufficient capacity, structural integrity and durability. Experience in Canada has resulted in procedures which can be specified to avoid common problems such as soil intrusion, groundwater intrusion and sulphate attack. Soil intrusion in weak or sensitive soils can be prevented by using an inner casing and pouring the shaft as would be done for a poured cast-in-place pile (Brzezinski et al, 1973). Groundwater can be prevented from entering the shaft by careful control of the expulsion of the concrete to ensure that a small plug (about 50 to 100 mm) always remains in the shaft while it is below the water table. Careful control is required since too thick a plug will result in inadequate compaction of the expelled concrete. Sulphate attack can be countered by the use of sulphate resistant cement or in some cases by specifying high strength concrete using normal cement. The specification of water/cement ratio requires close attention for zero slump concrete since the water content must be compatible with the compaction of the concrete as well as being sufficient for cement hydration.

The problem of pile heave due to the driving of adjacent piles has not received adequate attention. Heave or shaft uplift can destroy the structural integrity of the pile by separating it from the base. It can also destroy the competence of the fresh concrete in the shaft. In either case the pile capacity is reduced to a small fraction of that of a non-heaved pile in the same soil profile. Thus, the determination of tolerable heave is the most difficult component of a specified design. As shown by Cole (1972) the specified limit may not be possible for the contractor to achieve and indeed upward movement in excess of that specified may not affect the capacity of the pile.

Most references to pile heave or uplift of compacted concrete piles in the literature have appeared in the last decade (Curtis, 1971; Cole, 1972; Brzezinski et al, 1973; Clark, 1978). Heave of driven piles such as steel or concrete has been recognized for decades and retapping is a common procedure (Klohn, 1961; Hagerty and Peck, 1971). Retapping of compacted concrete piles is much less straightforward. Where the shaft is cased, retapping can be achieved readily but still is not well understood (Brzezinski et al, 1973). Uncased piles present more difficult problems due to special protection requirements at the top of the pile (Curtis, 1971) or due to soil intrusion between the shaft and base as shown later in this paper.

CASE HISTORIES

The three case histories presented in this paper have contributed to the development of design and construction procedures that can be implemented to overcome heave. Each case is briefly described along with the factors that contributed to the development of design and construction specifications. A fourth case, currently under construction, where design specifications were implemented and the results achieved is briefly described.

The pertinent soil properties of the four sites are shown in Table 1.

TABLE 1

REPRESENTATIVE CLASSIFICATION TESTS

	Upper Layer				Lower Layer			
	$w_{\%}$	w_{ℓ}	w_p	N	$w_{\%}$	w_{ℓ}	w_p	N
Library	20	21	15	22	18	35	14	46
Coliseum	40	90	32	12	15	36	16	40
Silo	35	65	25	7	18	35	18	36
Power Plant	30	45	22	12	30	NP	NP	16

1. Library Building

The Library Building is a very heavily loaded structure with a foundation consisting of a central core supported by 132 piles and 24 perimeter columns, 16 of which are supported b 8 piles and 8 by 4 piles as shown in Figure 1. The core piles are 510 mm in diameter and the perimeter piles are 610 mm diameter.

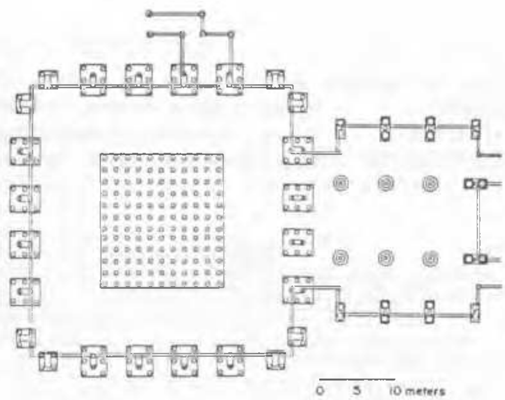

Fig. I LIBRARY FOUNDATION LAYOUT

The pile design was based on a performance specification. The installation procedures followed techniques that had been used extensively in the area but never in the configuration shown because the exceptionally high loads were unprecedented. Extensive heave was recorded but installation of piles was 80 percent complete before consultants were retained to assess the severity of the problem. Maximum upward movement recorded was 810 mm in the central core and 250 mm in the perimeter group.

Subsequent investigation revealed that 200 of the 292 piles were defective and required rehabilitation. The methods of investigation, testing and rehabilitation procedures have been described by Clark (1978).

The investigation revealed that the heave affected the piles in two different ways. When the adjacent pile was driven the same day, the integrity of the shaft of the heaved pile was destroyed. The compacted concrete did not bond and sonic tests along the length of the pile shaft showed sections with velocities comparable to gravel (400 to 2,000 mps) and other sections with a velocity in keeping with sound concrete (4,200 mps). When the adjacent pile was driven after at least one day had elapsed the pile shaft maintained its integrity but separated from the base. Analysis of the heave data (available for only the last 40 piles driven) indicated that piles driven about 9 diameters away from the piles driven the same day did not affect the previously driven piles. This is in keeping with later findings published by Cole (1972). The heave records indicated that 50 to 70 percent of the heave occurred as the adjacent shaft was driven and the remaining heave was recorded when the plug was expelled and base was formed. These data were not considered to reflect the actual shaft uplift since those exposed to heave forces the same day they were constructed would absorb part of the heave as the loose and separated sections compressed during the driving of adjacent piles on subsequent days.

Since the shafts were not sound, retapping was not a viable alternative. After exploring several possibilities such as supplemental drilled poured-in-place caissons, steel H-sections and grouting, the latter method was adopted and implemented. Figure 2 shows typical results of load tests for a defective pile, a rehabilitated pile and a pile which had not heaved.

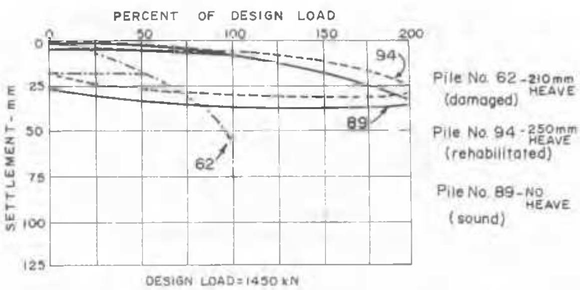

Fig.2 LIBRARY PILES-LOAD TEST RESULTS

The project was delayed for about five months as a result of the uplift problem and cost of rehabilitation was about equal to the initial cost of the foundation. The experience led to the conclusion that piles should not be driven within 9 diameters of a previously driven pile until at least 24 hours had elapsed. It was concluded that much of the uplift could have been eliminated by preboring although this could not be quantified as the contractor elected not to prebore the remaining piles though concern had been expressed.

2. Sports Coliseum

The Coliseum is a large circular arena, approximately 159 m in diameter, supported by 36 columns. Each column was supported by 8 piles, about 8.5 to 10 m long spaced at 3 diameters. The soil profile consists of 6 m to 13 m highly plastic-glaciolacustrine clay of firm to stiff consistency overlying very stiff clay till.

The design was based on a performance specification but recommendations were presented to prohibit driving piles within 9 diameters of a previously driven pile before at least 24 hours had elapsed and to provide 3 metres of embedment in the till to resist heave. In addition the piles were prebored 2 to 3 metres.

Heave was recorded for the piles as new piles were driven. Typically, the heave ranged from 25 to 75 mm with the configuration varying according to driving sequence. Maximum heave recorded was about 90 mm and 50 to 100 percent of the heave occurred during the driving of the casing. Most piles heaved less than 25 mm and those which heaved very little experienced a higher percentage of heave when the base of the adjacent pile was formed.

Load tests were carried out on piles which had heaved 20 mm, 58 mm and 76 mm. The results are illustrated on Figure 3. It can be seen that the pile with least heave had not separated from the base whereas the pile with greatest heave clearly separated. The capacity of this pile is very close to the calculated shaft friction capacity. The third pile performed satisfactorily for the design load. It was set at a higher elevation in the till and reflects the less competent bearing properties in the top of the stratum.

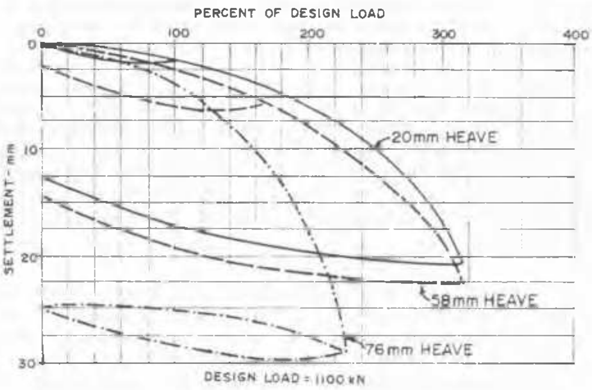

Fig.3 COLISEUM-LOAD TEST RESULTS

The analysis of the results led to the conclusion that piles which had heaved less than 25 mm were satisfactory. Those that had heaved in excess of 25 mm were judged to have separated from the base and would therefore behave as friction piles. Most of the piles had been uplifted less than 25 mm. A typical relationship between pore water pressure and pile driving at a distance away of 6 m (9 diameters) is shown on Figure 4.

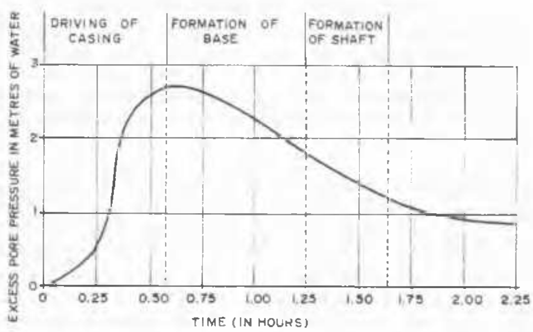

Fig 4 COLISEUM - PORE PRESSURE BUILD UP VERSUS TIME

The pore water pressure developed as the shaft is driven and base expelled may be an important consideration during construction. Brzezinski et al (1973) reports pore water pressure one order greater at a distance of 1.5 diameters from a similar pile in similar soil conditions.

Each group was assessed relative to heave records and where the capacity of individual piles was judged to be less than desired, supplementary piles were installed. The total number of supplementary piles was about 10 percent of the original number of piles.

The experience of this project indicated that the criteria of 9 diameters for driving adjacent piles within 24 hours was adequate for protection of shaft soundness. The preboring appeared to assist in reducing pile heave as did adequate embedment in the till but some shafts did indeed separate from the base. The variation of the top of the till over short horizontal distances led to difficulties in achieving adequate penetration in all cases. Casing resistance was not satisfactory in detecting the top of the till as indicated by subsequent drill holes.

3. Cement Silos

Two structures were involved in the initial stage of this project, each 30 m high. Thus the foundations are required to carry exceptionally high loads when the silos are full. The plan of the foundation and pile locations are shown on Figure 5.

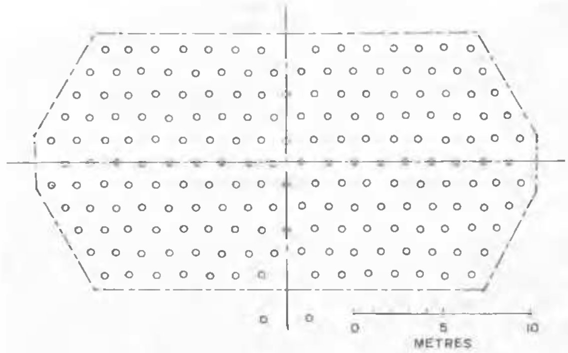

Fig.5 SILOS FOUNDATION LAYOUT

The soil profile consists of firm to stiff glaciolacustrine clay extending to a depth of about 10 m where stiff clayey till is encountered. The till surface undulates about 2 m over the site. The piles were 510 mm in diameter. The specifications placed the onus for design on the contractor with the only constraint being that piles within 9 diameters of each other could not be driven within the same 24 hour period.

Heave was not recorded until about 30 piles had been driven. When leveling initiated at that time indicated pile heave of 70 mm to 250 mm, the project was stopped until the pile performance could be assessed. Load tests were carried out on one of the last piles driven (no recorded uplift) and on a pile which had heaved at least 100 mm. The results are shown on Figure 6. It can be seen that the pile which heaved 100 mm failed in friction before being jacked to where the shaft returned to contact with the base.

Two heaved piles were excavated to the base level and showed clean breaks between the base and shaft with separations of 250 mm and 125 mm, corresponding very closely to the heave recorded. The excavations were backfilled and the two piles were retapped. Re-excavation and examination indicated that the two parts of the pile previously separated by a 125 mm break were rejoined and the pile with a 250 mm break before retapping contained compressed soil in a separation of 50 mm. A third pile with a recorded heave of 240 mm could only be retapped 180 mm. This pile was load tested and the results were as shown on Figure 7. Although it was only driven 75 percent of the total recorded heave, this pile showed a substantially better capacity than the pile that failed in friction only as shown by Figure 6.

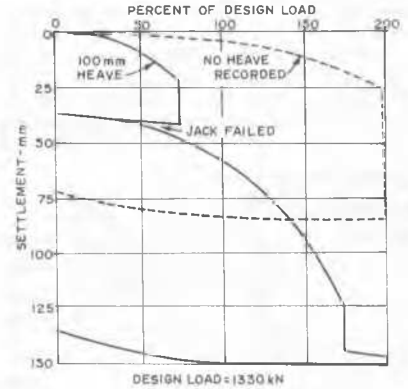

Fig.6 SILOS-LOAD TEST RESULTS

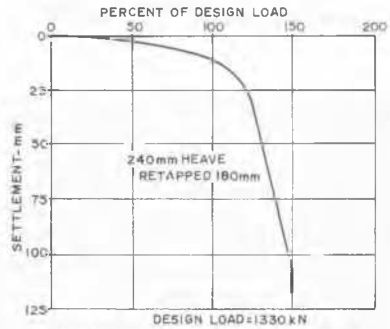

Fig.7 SILOS-LOAD TEST RESULTS

The heaved piles were retapped as much as possible and supplementary steel piles were driven to account for the reduced capacity of the redriven piles. The final retapping procedure consisted of a 1.5 m cap of dense gravel within a casing, and the use of 47.5 kJ of impact energy in conjunction with survey monitoring. For the remainder of the project, it was specified that the piles would be prebored to 6 m and that a tension base would be incorporated to reinforce the connection between the base and the shaft. The usual procedure in completing the pile is to apply two blows of 190 kJ for each 150 mm of shaft. This compacts the shaft and extrudes the concrete into the soil. The procedure was modified by applying one-half the number of blows required to expel the last bucket to form the base to the first bucket (0.15 m^3) of the shaft. The procedure was repeated by further reducing the number of blows by one-half for each charge until a one metre transition between base and shaft was achieved. The configuration of the pile and the usual pile is shown on Figure 8.

The above procedure eliminated pile uplift during the driving of adjacent shafts. However, heave still occurred as the base of the adjacent pile was driven. A maximum heave of 100 mm was recorded and a load test was carried to assess the effect of heave produced by forming the base of adjacent piles. The results of the load test, as shown by Figure 9, are similar to the pile which had not heaved. Thus, the experience with driven piles such as timber or steel where heave induced in the deep founding soil is not detrimental to pile capacity (Klohn, 1961) also holds true for expanded base concrete piles.

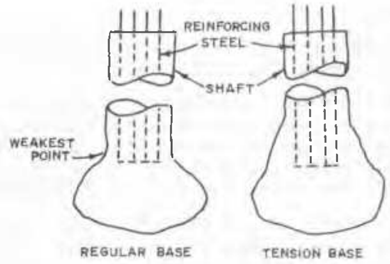

Fig.8 COMPACTED EXPANDED BASE CONCRETE PILES

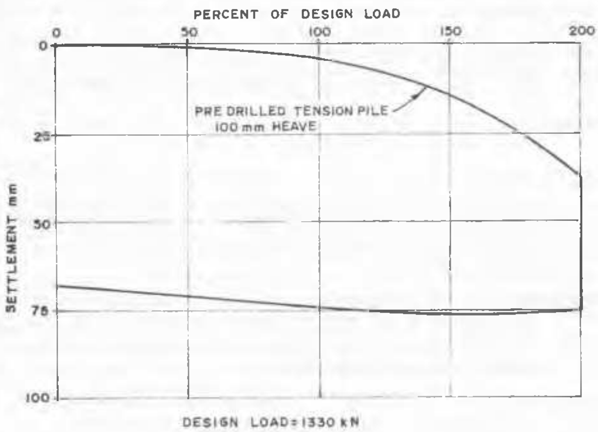

Fig. 9 SILOS-LOAD TEST RESULTS

DISCUSSION

In cohesive soils of the type described in this paper the action of ramming the concrete into the soil results in high shaft capacity. In fact the allowable pile load frequently is governed by the structural capacity of the shaft. As a single, isolated pile the compacted expanded base concrete pile therefore has great attractiveness. In pile groups, however, uplift of the shaft, due to driving adjacent piles, has been shown to seriously reduce the pile load capacity. The data shows that heave which occurs when the plug is expelled and the base compacted does not significantly impair the pile capacity since the upward flow of soil is resisted by substantial shaft resistance, as is also the case with driven piles (Klohn, 1961).

The potential for shaft uplift and separation from the base can be assessed using current concepts of effective stress design. During driving of the casing there is an upward displacement of the soil which tends to pull the shafts of adjacent piles upward. The data and theory indicate that this effect, which depends on pile spacing and soil properties, decreases with increasing depth of driving. At some depth a condition of plane radial strain exists and driving the casing below this depth produces no significant upward displacement of adjacent pile shafts. For the 500 mm to 600 mm shaft diameters commonly used in Western Canada, this depth has been determined by observations to be in the range of 8 to 12 pile diameters and corresponds to the critical depth as described by Meyerhof (1976) for maximum pile shaft resistance. Thus, if the ultimate shaft capacity of the pile above the critical depth exceeds the ultimate shaft capacity of the pile shaft below this depth plus the structural strength in tension of the shaft at its connection to the base (the weakest point) the shaft will separate from the base. It follows then, that as a first approximation, if the critical depth is less than twice the length of the shaft there will not be significant separation of the pile shaft from the base.

If such calculations indicate that shaft uplift could occur then positive measures to reduce uplift are required. Such measures could include preboring and formation of a tension collar to more securely integrate the shaft with the base.

These features were incorporated in a design specification prepared for a major piling project currently under construction. The project is a thermal generating plant requiring approximately 1,200 piles. The soil profile is relatively uniform consisting of 12 m of firm ablation till, with properties as shown in Table 1, overlying medium dense sand. Piles are closely spaced (3 diameters) in groups of up to 20. Thus there is a potential for excessive heave. The specifications developed required that the following criteria be met.

1) Adjacent piles within 9 diameters could not be driven within the same 24 hour period.
2) All piles would be prebored to 6 m immediately prior to driving the shaft the remaining 7 m.
3) The bases would be constructed with the tension collar configuration if recorded uplift exceeded specified limits.
4) The uplift during driving of an adjacent shaft could not exceed 3 mm. No limit was placed on the heave associated with expelling the plug or forming the base of the adjacent piles.
5) The size of base was specified at 0.42 m^3. If the energy required to expel 0.14 m^3 of concrete exceeded 30 blows of 190 kNm before the 0.42 m^3 was achieved, the base construction could terminate at that point.
6) Pile load tests were specified with an acceptance criteria of two-thirds of the allowable deflection at twice the design load as recommended in the Canadian Foundation Engineering Manual (1972). These rigid criteria were adopted because of very low settlement tolerance of the generating units.

The piling for the project is currently 80 percent complete. Uplift has not exceeded the specified limits. All load tests have met the rigid criteria. The performance of a pile subjected to a load test, which is typical of all load tests conducted is shown on Figure 10.

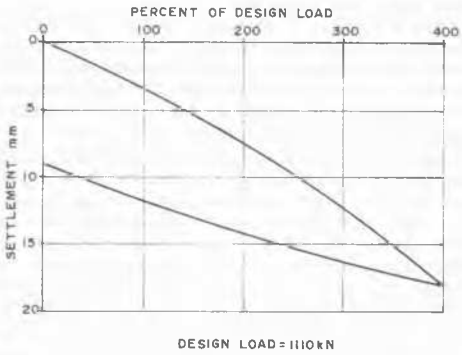

Fig. 10 THERMAL PLANT-LOAD TEST RESULTS

CONCLUSIONS

The case histories reported herein show that reduced capacities of compacted expanded base concrete piles may occur if piles are driven at closer than about 9 shaft diameters. Damage to concrete in pile shafts can be reduced by not driving piles within 9 diameters until the concrete has set for at least 24 hours.

Uplift of pile shafts occurs mainly during driving of adjacent shafts to a depth of 8 to 12 shaft diameters; below this depth the uplift is small. Expelling pile bases can cause significant pile heave but does not result in substantial reduced pile capacity.

For the soils reported on in this paper and as an initial guideline, if the critical depth for maximum shaft resistance (Meyerhof, 1976) exceeds twice the shaft length, special measures to resist shaft uplift are required. They can consist of preboring to the critical depth and the formation of a tension collar at the connection of the shaft to the base. In all cases measurements of pile shaft movement, during shaft and base formation, for adjacent uplift, are essential to quality control. If pile uplift during driving of adjacent shafts occurs, pile load tests to determine pile performance are necessary.

ACKNOWLEDGEMENTS

The work described in this paper was carried out while the authors were employed by Hardy Associates. The co-operation of the particular owners, their general civil engineering consultants and the contractors has developed a better understanding of the use of expanded base concrete piles in cohesive clays overlying cohesive till soils. The authors are grateful for the contribution of Mr. J. J. Vieaux, P. Eng., to some of the case histories described and to the preparation of this paper.

REFERENCES

Brzezinski, L. S., Shector, W., MacPhie, H. L. and Vandervoot, H. J. (1973). An experience with heave of cast in situ expanded base piles. Can. Geotech. J. 10, 246-260.

Canadian Foundation Engineering Manual (1978), Part 3. Deep Foundations.

Clark, J. I. (1978). Failure during construction and subsequent rehabilitation and performance of a dynamically cast-in-place concrete pile foundation. A.S.T.M. STP 670, 209-229.

Cole, K. W. (1972). Uplift of piles due to driving displacement. Civ. Eng. Public Works Rev. London, March 1972, 263-269.

Curtis, R. J. (1971). Constructional control affecting the behavior of driven in situ concrete piles. Proc. Inst. Civ. Eng. Behav. Piles Conf. London. Sept. 15-17, 1970. I.C.E. London 1971, 167-174, 198-199.

Hagerty, D. J. and Peck, R. B. (1971). Heave and lateral movements due to pile driving. Proc.Am.Soc.Civ.Eng. 97 SM11, 1513-1532.

Klohn, E. J. (1961). Pile heave and redriving. Proc.Am.Soc.Civ.Eng., 87 SM4.

Meyerhof, G. G. (1960). The design of Franki piles with special reference to groups in sands. Proc. Symp. Des. Pile Found. 6th Int. Congr. Bridge Struct. Eng., Stockholm 1960, 105.

Meyerhof, G. G. (1976). Bearing capacity and settlement of pile foundations. Journal of the Geot. Eng. Div., Am.Soc.Civ.Eng. March 1976, 196-228.

Nordlund, R. L., (1970). Pressure injected footings. Proc. Conf. Des. & Install. Pile Found. Cell. Struct. Lehigh Univ. 1970, 297-308