Pile Integrity and Capacity Determined by Redriving

L'Intégrité et la Capacité du Pieu Déterminé par Reconduire

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SYNOPSIS A procedure of redriving 0.36m square prestressed concrete piles up to 82m long was developed where low resistance to driving for substantial depths within the bearing stratum was experienced. Instrumentation and load tests demonstrated the static capacity of the piles in excess of twice the 889kN (100-ton) design load. Dynamic instrumentation during driving was used to locate broken piles and establish redriving requirements for determining the integrity and the adequacy of the piles.

INTRODUCTION

Piles driven through 62 to 77m of low strength clay into consistently compact fine sand encountered highly variable and unpredictable driving resistances at the Metropolitan Syracuse Water Pollution Control Plant. Piles met refusal after only 1m of penetration into the sand and a short distance away penetrated up to 23m with little increase in driving resistance. Driving all 4200 piles to the required resistance in the compact sand layer would have resulted in a large increase in the planned 328km of piling and excessive waste due to unpredictable pile tip levels. Piezometers located in the sand 1.5m or less from piles recorded temporary excess pore pressures that approached the effective vertical overburden stress during driving of piles to low final resistance (Lacy, 1979). Load tests demonstrated adequate static capacity for those piles driven to low final resistance (Lacy, 1979). Additional borings were made to more clearly define the variations in character and the level of the top of the bearing stratum. Very low final driving resistances raised questions of pile integrity even though most had experienced no hard driving.

SOIL PROFILE

The Syracuse, New York site at the southeast end of Onondoga Lake is underlain by 1.5 to 4.5m of granular fill and compressible chemical waste over loose silty fine sand. Deep deposits of normally consolidated soft to stiff silty clay contain occasional random layers of loose fine sand. Compression of these deep deposits under fill loading has caused up to 1m settlement of the surface and shallow supported structures over the last 20 years. Bearing strata underlying the clay consist of an upper layer of very compact silty fine to medium sand in varying thicknesses, underlain by a very compact silt varved with hard clay. A lower very compact silty fine to medium sand extends at least 18m below the silt layer. The sand strata contains zones of medium sand with traces of coarse sand and gravel. In some areas, the upper sand layer becomes very thin or is not present in the 290 by 420m site. Soil properties have been described previously (Lacy, 1979).

PILE TEST PROGRAM

Theoretical analysis of static pile capacity indicated adequate capacity with less than 3m penetration into the bearing stratum. This was confirmed by load test. The piles were prestressed using seven or eight strands of 1.27cm reinforcement to 6.0 and 6.5MPa (880 and 940 psi). Moment resistance splices were spaced generally at 26m intervals. The piles were driven with a Link Belt model 660 diesel hammer with a rated energy of 61kN-m (45,000 ft-lb). When low driving resistance was experienced, the hammer energy was reduced to 37kN-m (27,000 ft-lb) to prevent damage from reflected tension waves. Original driving requirements were a minimum of 50 blows per 0.31m at full energy for 3m within the bearing stratum and 6 blows per 2.5cm for the last 10cm.

Drive Test Piles

Initially-driven piles at wide spacing identified areas where little or no increase in driving resistance was observed as the pile tip penetrated the sand bearing stratum. It was found that an interruption in driving of 10 to 120 minutes while only 3m into the bearing stratum resulted in an increase in driving resistance by as much as 30 times. The decrease in temporary excess pore pressure within the bearing stratum following pile driving corresponded well with the increase in driving resistance.

DYNAMIC INSTRUMENTATION

Uncertainties concerning the integrity of a number of piles driven to low resistance prompted the use of dynamic testing. Tests were performed on 136 previously driven piles (Goble & Associates, 1976 unpublished report) to determine the location and extent of pile damage or to demonstrate a pile was undamaged. The tests were performed several weeks after the piles were initially driven using a pile hammer for redriving. The test procedure consisted of attaching two accelerometers and two strain transducers to opposite sides near the top of the pile. These gauges were connected to a pile driving analyzer for immediate evaluation, with signals recorded on an analog magnetic tape for further processing. This equipment records strain and acceleration waves as they pass through the pile following impact with a pile hammer plus returning waves that rebound from the pile tip. The strain and acceleration waves are usually integrated and presented as force and velocity waves. These waves pass through concrete at a constant known speed. Completely broken piles reflect downward velocity waves in a much shorter time than a longer unbroken pile. A broken pile within the clay layer reflects a markedly reduced return force wave or even a tension wave as there is little tip resistance to pile penetration and a high reflected positive or downward velocity (Rausche, 1979). Fig. 1 shows a pile broken at 22m based on measurements of the distance between positive peaks and a force wave that drops to zero.

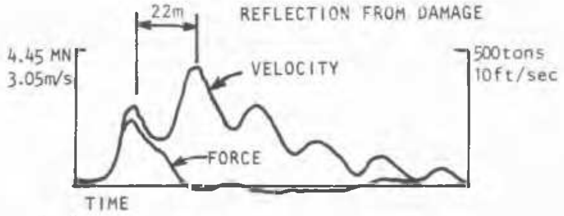

Fig. 1 Record from Completely Broken Pile

Fig. 2 illustrates an unbroken 63m pile with good bearing resistance in the compact sand. The reflected velocity wave is negative (upward) and the reflected force wave is pronounced and compressive at the pile top.

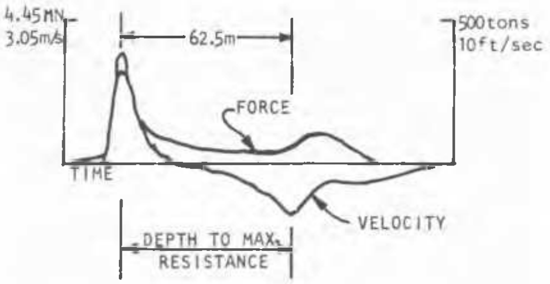

Fig. 2 Record of an Unbroken Pile Showing Location Where Total Resistance is Maximum

As redriving of instrumented piles was several weeks after installation, pile deflection was limited by adhesion of the reconsolidated surrounding clays. Broken and damaged piles sometimes experienced high redrive resistance. It was necessary to use the full hammer energy for stress waves to penetrate to the bearing strata and to limit the number of blows to prevent damage to the pile top.

It was also possible to determine the degree of pile damage expressed as a net reduction in cross sectional area by comparing the relative difference between the reflected force and velocity decrease at the depth of a discontinuity. These damaged areas could be distinguished from minor discontinuities across splices even though damage was often close to the splice.

Results of Tests

While most piles were driven several weeks before testing, two piles had instruments attached before the last section of pile was driven. A continuous record was made of one pile that became damaged and broke during six hammer blows while the pile tip was passing suddenly from compact sand into compact silt at decreasing driving resistance. The pile broke at a depth of 23m or 3m below the upper splice. The data indicates that structural deterioration originated from the splice. The second pile was monitored as it was driven without damage through compact sand into compact silt at low resistance and then redriven one hour later at high resistance as shown in Fig. 3.

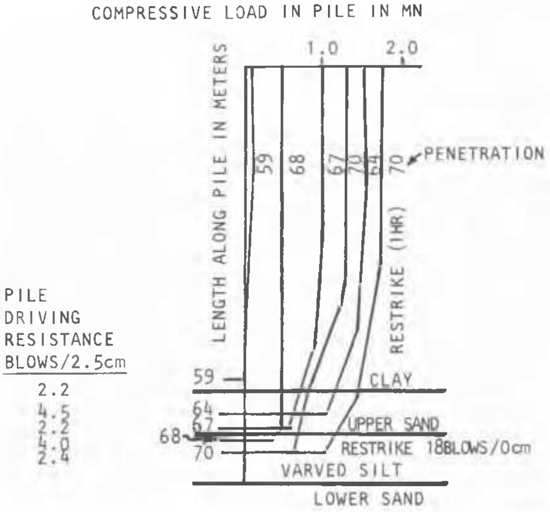

Fig. 3 Resistance Distribution for Pile 333A Tested During Driving

Most of the piles tested were previously suspected of being broken. Several piles that initially drove to high resistance were also tested as controls. The test program showed that only 50 percent of those examined were significantly damaged or broken. Studies to evaluate the

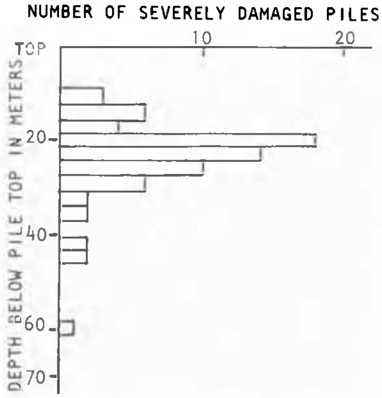

Fig. 4 Damage Frequency Versus Depth

cause of damage showed the predominate location of damage was near the upper splice as illustrated in Fig. 4. Where driving resistance is low, the reflected tension wave is indicated at the pile bottom by a sharp reduction in compression wave travelling down the pile. By the time the reflected wave reaches the upper splice, this section of the pile is in tension. A computer analysis method (Rausche, 1979) was used to estimate tension stresses during driving. This wave equation analysis uses an iterative procedure of comparing computed response based on assumed soil properties with measured response. Fig. 5 illustrates estimated tensile stresses in pile concrete as a pile approaches and penetrates the bearing stratum.

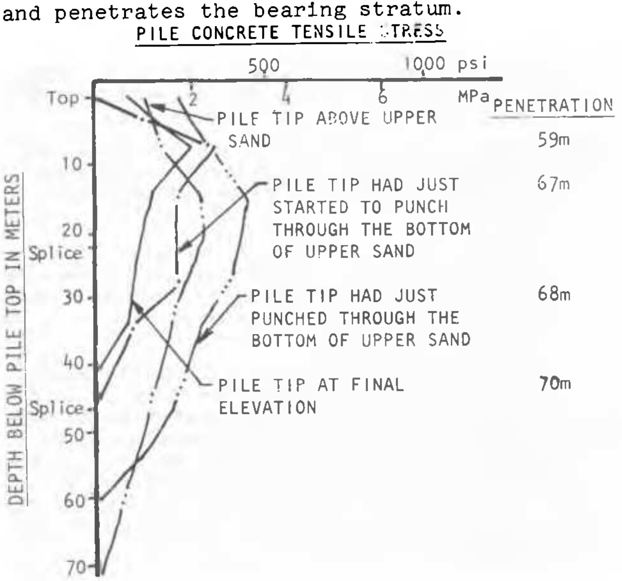

Fig. 5 Pile Tension Versus Depth for Pile 333A

Tension is maximum in the upper part of the pile and increases near the upper splice as the pile tip passes from compact sand into compact silt. Each depth is also shown in Fig. 3 for the same pile along with the soil stratification. This pile was driven successfully to good bearing.

Estimates of Pile Support

Using measured reflected waves, and estimated static and dynamic soil parameters, analyses were made of the distribution of load during driving. Soil parameters were adjusted until the match of computed and measured forces is close, yielding the stress distribution illustrated on Fig. 3. A low pile compressive load was distributed uniformly before the pile tip reached the bearing stratum. A much higher pile force resulted when the pile tip was in the middle of the upper sand layer with most of the load carried in end bearing. As the pile started to punch through the upper sand layer at a depth of 67m, end bearing decreased markedly. The pile load reduced substantially as the pile penetrated the silt layer at a depth of 68m and increased gradually to the final depth of 70m. The pile was redriven after one hour, with an increase in end bearing resistance with very little change in side friction. Pile driving resistance is shown for the depths analyzed. Unit adhesion for the clays above the bearing stratum estimated from these analyses of dynamic loading averaged over the pile length from 16.8 to 19.2kPa (350 to 400 psf) and in one case as high as 43.1 kPa (900 psf). Mobilized unit adhesion under static loading was somewhat higher for similar times after driving. Analysis of the load distribution along several other undamaged piles redriven several weeks after installation produced somewhat similar results:

(i) Piles founded in the middle of the upper sand layer had high end bearing and high side friction in the sand with low mobilized dynamic shear resistance in the clay.

(ii) Piles founded in the varved silt layer had low end bearing, low side friction in the sand layer above and slightly higher mobilized shear resistance in the lower part of the thick upper clay layer, but adequate total capacity which was less than (i).

(iii) Piles extending into the lower sand received primary support on restrike from the upper sand and low total mobilized resistance from the varved silt and end bearing in the lower sand. These piles had the highest total resistance and considerable reserve capacity is indicated in the lower sand layer.

DEVELOPMENT OF REDRIVE PROCEDURE

While dynamic instrumentation was used initially to determine whether previously driven piles were unsatisfactory, a method was needed for the large majority of piles remaining to be installed to establish the integrity of piles whenever driving was terminated at low resistance.

Correlation with Driving Record and Instrumentation

Instrumented dynamic testing has demonstrated that some of the piles driven to low final resistance were broken. Review of the driving records revealed certain correlations with the results of the instrumented testing:

(i) Most of the damaged or broken piles had been driven to a final resistance of less than one blow per 2.5cm.

(ii) Significantly out-of-plumb piles were commonly broken.

(iii) Piles experiencing a very rapid and large drop in driving resistance as the pile tip passed from the upper compact sand into the compact varved silt were frequently broken.

(iv) Piles that experienced a marked drop in driving resistance when the pile tip was at other levels and the decrease in resistance differed from the performance of adjacent piles were usually broken.

(v) Piles that had been redriven, within a day after initial driving, to resistances above six blows per 2.5cm were unbroken and founded in adequate bearing soil.

(vi) Piles redriven several days or weeks after initially driven were sometimes damaged or broken even though redriving resistances were greater than six blows per 2.5cm.

Rapid Adhesion of Clays Above Bearing Stratum

It was observed that the deep clay, which became disturbed around the pile during driving, rapidly developed adhesion to the pile after driving was stopped. This was particularly noticable after the first two sections of pile were driven to a 52m depth six to 21m above the bearing stratum. Piles were left for several hours or overnight while adjacent piles were driven. The piles had initially penetrated the clay at 3 to 6m per blow increasing to 5 to 10 blows per 0.31m at the 52m depth. When driving resumed, much higher resistances were observed, especially for the first 0.31 to 0.92m. Driving resistances were plotted versus the time period over which driving was interrupted for a number of piles driven to this level as shown on Fig. 6.

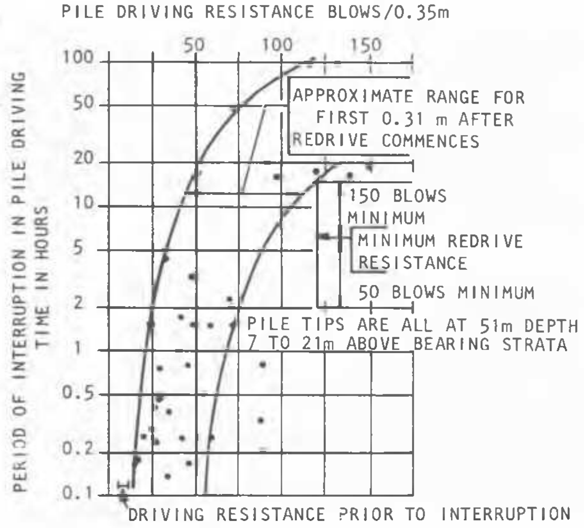

Fig. 6 Redrive Resistance Versus Time With Pile Tip in Clay

Even a delay of 15 minutes to an hour while the pile was spliced resulted in a marked increase in driving resistance for the first 0.31m of driving with progressively reduced driving resistances for continued driving, eventually approaching the original low values. The wide variation in driving resistance is a result of erratically positioned layers of sand and silt that tend to reconsolidate around piles much more rapidly than the dominant clayey material.

Criteria were developed to permit acceptance of piles driven into the bearing stratum at resistances less six blows per 2.5cm. These requirements are shown on Fig. 6. Redriven piles had to obtain at least ten blows per 2.5cm between two and 18 hours. A minimum total of 50 blows was required for redriving between two and six hours while a minimum of 150 blows was required for redriving between six and 18 hours. The higher number of blows permitted piles driven at a rate of ten blows per 2.5cm to be driven more than 0.31m. Prolonged redriving often resulted in pile breakage.

Production Pile Driving

Pile driving continued during testing, evaluation and several modifications in drive and redrive requirements using three to five rigs. The site was divided into three areas of similar foundation characteristics to permit pile driving to proceed in areas of consistent conditions.

CONCLUSIONS

Development of redrive criteria for this site has:

(i) permitted the use of piles driven to low resistances by redriving the piles to show, primarily, that the piles were not damaged or broken;

(ii) demonstrated that redriving piles, to confirm increased static resistance following dissipation of pore pressures from pile driving and to determine pile integrity, must be based on rational criteria resulting from tests and analyses;

(iii) shown at this site that the deep deposits of low strength clay have a substantial time dependent effect on redrive resistance;

(iv) illustrated the effectiveness of instrumented dynamic testing in understanding pile driving and redriving records. This testing was critical to development of the redrive procedure;

(v) provided an example of highly variable pile driving resistance in compact soils. Development of satisfactory methods of installing reliable foundations required close cooperation between the contractor, owner and engineers permitting the project to be completed economically with minimum possible rejected piles and without significant delay.

The completed structures have been in service for two years with measured settlement well within the range of elastic compression of these concrete piles between the pile top and the bearing stratum with insignificant differential settlement.

REFERENCES

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Rausche, F. and Goble, G.G. (1979): Determination of Pile Damage by Top Measurements, Behavior of Deep Foundations, ASTM STP 670, pp 500-506