An Experience with Dynamically Tested Piles

Une Expérience avec des Pieux Essayés Dynamiquement

E. SANTOYO Institute of Engineering, UNAM, México
G.G. GOBLE University of Colorado, Boulder, Col

SYNOPSIS An experience with dynamically tested piles is presented. Case method results from field electronic analyzer and CAPWAP analysis accurately predicted the ultimate load static capacity.

INTRODUCTION

Las Truchas steel mill is a fully integrated plant on the west coast of Mexico. It is located near a large deposit of iron ore,near a new associated port facility. The entire development is constructed on the alluvial delta of the Balsas River.

The presence of extensive gravel deposits with lenses of compressible soil,dictated that the major structures of the plant should be supported on deep foundations. Hence, about 2546 driven piles and hundreds of casted piers were needed.

The design of the piles was particularly difficult because the soils could not be successfully sampled and the standard penetration tests produced erratic results. Extensive static load tests were planned in order to prove the safety of the piles. These tests would have been time consuming and the very tight construction schedule did not permit sufficient time for their execution. As a replacement, a dynamic test-pile program completed with static load tests was used. The plant foundation has performed well in the four years since its completion, in the mean time several earthquakes have occured including one of 6.5 magnitude (Richter scale).

SOIL CONDITION

The soil stratigraphy of this alluvial site is very erratic. Granular soils interbedded with variable thickness layers of peat, silt and clay were found up to 30 m deep. Some of these soils were very soft. However, a thick strata of very hard silty clay with sand lenses and boulder layers, was always detected from 30 m up to 100 m depth.

Site exploration was a difficult task. The detection of the soft layer beneath gravel and boulders, required a careful drilling and sample procedures. Undisturbed samples of these materials were obtained using Shelby tubes. When fine granular materials were detected SPT were performed. Whilst in the deep hard silty clays, the Denison and Pitcher samplers were used. Nevertheless, a better quality sample was obtained when the use of the saw-teeth was developed (ref. 1).

FOUNDATION DESIGN

Based on geotechnical information, proper pile depth was selected for each structure, avoiding that pile tips could be over soft layers. As the shear strength of granular materials was very erratic, it was necessary to prove the pile design with load tests.

The first stage of the steel mill required 2546 driven piles of 7 to 14 m long with square sections 40, 45 and 50 cm side. The piles were driven using primarily the DELMAG D-30 hammer. A D-22 was also used on some piles. Due to the large number of piles that had to be driven in a short period of time up to eight crews and hammers were working at one time. Driving in the gravel was very hard so the contractor chose to preauger to the depth of the compressible layers. The holes were kept open by using a mud mixed from the surface soil at the site. This approach was quite inexpensive and it performed satisfactorily.

DYNAMIC DETERMINATION OF PILE CAPACITY

The Case Method was first developed in 1965 in a research project at Case Western Reserve University in Cleveland, Ohio, USA. The method uses electronic measurements taken during pile driving to predict pile bearing capacity. Pile top acceleration, a, and pile top force, F, are measured. The pile was originally assumed to be a rigid body of mass, m. The resistance force of the soil using Newton's Law calculated as

$$R = F(t) - ma(t) \quad (1)$$

where F and a are functions of time (ref. 2).

Further studies including longer piles (more than 60 feet) showed that the pile elasticity could not, in general, be neglected. Assuming a uniform pile and ideal soil behavior the following equation was derived (ref. 3).

$$R = 1/2\ |F(t_1) + F(t_2)| + \frac{mc}{2L}\ |v(t_1) - v(t_2)| \quad (2)$$

were $t_2 = t_1 + 2L/c$ and t_1 is a selected time during the blow; L is the pile length; v, the velocity of the pile top and c, the wave propagation speed through the pile. The soil resistance, R, can be considered to be the sum of a static, S, and a dynamic component, D, so

$$R = R_S + D \quad (3)$$

The "damping force", D, is obtained approximately as

$$D = J\ v_{toe}$$

where J is a damping constant dependent on soil type and v_{toe} the pile toe velocity. It can be shown from wave theory (ref. 4) that the pile toe velocity can be calculated as

$$v_{toe} = 2v_{top} - \frac{L}{mc} R \qquad (5)$$

where v_{top} is the pile top velocity at time t_1. It should be noted that t_1 is chosen when the velocity of the pile top is maximum (time of impact). J is used in dimensionless form after dividing it by mc/L.

Equation 5 is approximately correct for the first 2L/c seconds, after the initial arrival of the stress wave at the toe. The static soil resistance, R_S, is then obtained by subtracting the calculated damping force, D, from the total driving resistance. Thus, the final expression becomes

$$R_S = R - j_c \ |2F(t_1) - R| \qquad (6)$$

where j_c is the dimensionless form of J. In equation (6) all quantities except j_c can be calculated from measurements as defined above.

Over 100 static test piles are available where the necessary dynamic measurements were obtained. From these data the best values for j_c could be determined. The correlation between static capacity measurements and dynamic predictions is shown in Fig. 1.

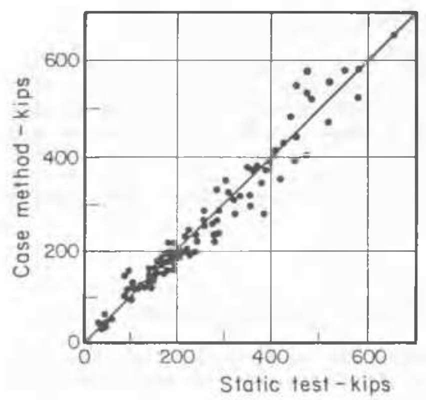

Fig. 1 Correlation between Static and Dynamically Determined Capacities

The Pile Driving Analyzer provides the signal conditioning and computational circuits to calculate predicted pile capacity in real time during pile driving or restriking. Figure 2 shows a schematic of the entire electronic system, including an analog magnetic tape recorder.

Either the measured force or velocity (integrated from acceleration) can be used in a dynamic analysis as a boundary value (both together would not lead to satisfactory results). An analysis can then be performed either in closed form or in a so-called wave analysis procedure, i. e., in a discrete form. Of course it is then necessary to describe the soil resistance forces.

The soil reaction forces are passive and it has been found sufficiently accurate to express them as a function of pile motion only. It is furthermore assumed that the soil reaction consists of a static (elastoplastic) and a dynamic (linear damping) component. In this way the soil model has at each point three unknowns (elasticity, plasticity and viscosity).

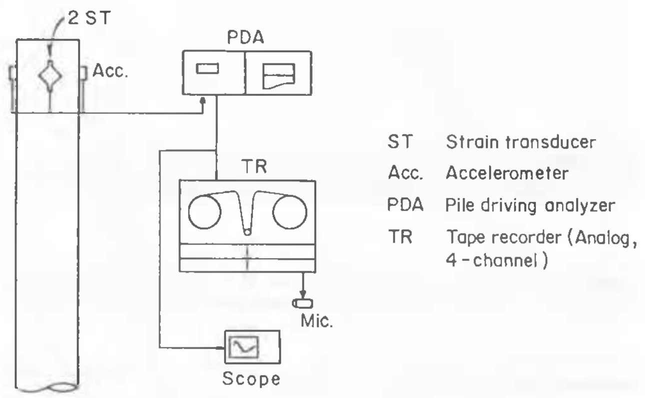

Fig. 2 Schematic of Instrumentation

The dynamic analysis known as CAPWAP (ref 3) is performed after the procedure that was introduced by Smith (ref 5). This procedure divides the pile in a number of mass points and springs. In this method there are three times as many unknown soil parameters as embedded pile elements. First, a reasonable assumption is made regarding the soil parameters, and then the motion of the pile is assumed using the measured pile top acceleration as a boundary value. Output results are not only the pile element motions and soil resistance forces, but also the *computed* pile top force, all as a function of time.

The computed and the measured pile top force will in general not agree with each other. It is necessary to improve this match iteratively by changing the assumed soil resistance parameters. Finally, a computed pile top force will be obtained when an acceptable difference is reached. The corresponding parameters of the soil model are then considered to be the correct values. The results of the CAPWAP analysis are thus the magnitude and location along the pile of both static and dynamic resistance forces. Static computations can be used to predict the static load test curve of the pile.

TESTING PILE PROGRAM

The load test program had three stages: first, the plant area was divided in eigth zones according to their representative soil conditions. A test pile was driven at each zone and statically tested to correlate its capacity with the predicted values. These information was further used to adjust the pile design criteria. Once the construction program was started, 25 service piles were dynamically tested to determine their capacity. Finally a static load test was performed on a dynamically tested pile to verify the dynamic prediction thus reinforcing confidence on the dynamic method.

Dynamic tested piles were selected to cover the entire area of the plant. Some of them were tested at the end of driving while others had been in the ground for some time and were tested by restriking. The results of the test are summarized in Table I. On the entire site the tested piles ranged in strength from 127 tons to 466 tons. Even in a single location such as the Continuous Casting area the strength ranged from 254 ton to 466 tons. All piles showed a large factor of safety to failure.

TABLE I

Pile Test Results

Pile Number	Location	Type	Blow Counts: End of Driving	Blow Counts: Begin of Restrike	Prediction Tons
44	Material Handling	P	20/10 CM	-	372
PA-28	Coal Storage	R	16/10 CM	-	345
128	Pellet	P	31/10 CM	-	305
111	Pellet Coke Plant	P	81/10 CM	68/10 CM	418
373	Bunkers Area Coke Plant	P	431/10 CM	53/1 CM	426
7W-BIS	Lorry Garage Coke Plant	P	35/10 CM	31/1 CM	390
3NW	Quenching Tower Coke Plant	P	33/10 CM D-22	36/3 CM	382
2	Quenching Tower	R	15/2 CM	12/2 CM	252
163-BIS	Power Plant	P	31/10 CM	17/5 CM	314
329	Power Plant	R	28/10 CM	17/5 CM	196
172	Power Plant	R	6/10 CM	19/10 CM	127
31S	B.O.F.	P	21/10 CM	-	186
32S	B.O.F.	P	25/10 CM	-	182
175	B.O.F.	P	48/10 CM	17/1 CM	382
16S	B.O.F.	P	40/10 CM	20/1 CM	377
7S	Continuous Casting	P	40/10 CM	20/1 CM	254
P1-55	Continuous Casting	P	69/10 CM	30/1 CM	431
474	Continuous Casting	P	26/10 CM	-	254
PO-106-C	Continuous Casting	P	32/10 CM	5/1 CM	326
P10- 118	Continuous Casting	P	49/10 CM	10/1 CM	466
P3 - 322	Continuous Casting	P	37/10 CM	11/1 CM	426
PO - 348	Continuous Casting	P	49/10 CM	20/1 CM	308
PO - 439	Continuous Casting	P	62/10 CM	22/1 CM	475
P6 - 355	Continuous Casting	R	33/10 CM	5/1 CM	245
8	Rolling Mill	P	62/10 CM	-	335

P = Prestress
R = Reinforced

The pile selected to verify dynamic prediction was Pile N° P6-355 in the Continuous Casting area. It was chosen because it had a relatively low capacity and, therefore, there was confidence that it could be loaded to failure. The load test setup used had a capacity of 500 tons and the pile was loaded to that level in six cycles. A total pile top displacement of 110 mm was achieved. The load test results are shown in Fig. 3. In the development of the Case Method the constant j_c was selected to give a correlation with static load test results using the Davisson procedure (ref 6) for evaluation of the test. In this approach a line is plotted parallel to the axial stiffness line for the pile. This line is offset by an amount Δ from the load test origin. The Δ value is defined as

$$\Delta = 3.8 + 0.0083D \qquad (7)$$

where D is the characteristic pile cross section dimension (in this case D = 450) and all units are millimeters. The ultimate load is defined as the load where the offset line intersects the load test curve. For this test a defined capacity of 253 tons is obtained. This is in excellent agreement with the dynamically obtained value of 245 tons. It should be noted that the dynamically obtained predictions were determined prior to completion of the load test.

Of course, if other failure definitions were used different values of capacity would be obtained. The Davisson definition is a conservative one and gives ultimate capacities that are lower than most other procedures.

The CAPWAP analysis was also performed on several piles to increase confidence in the Case Method predictions. Agreement between the two dynamic methods was adequate in all the analyzed cases.

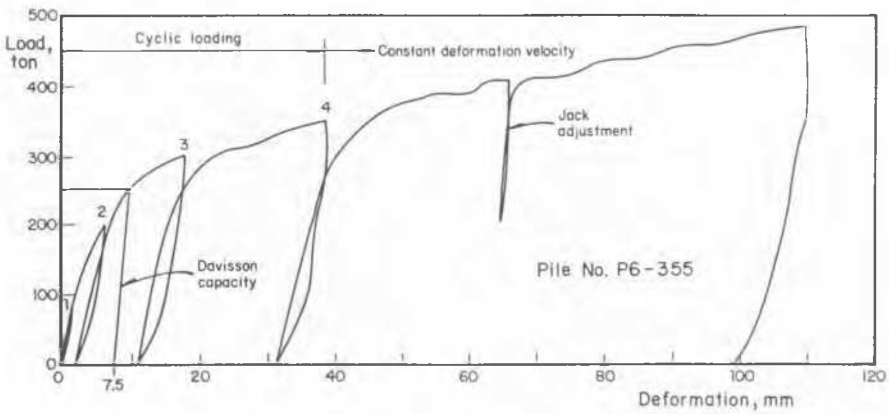

Fig. 3 Static Load Test with Davisson Capacity Determination

CONCLUSIONS

The dynamic test program provided a rapid, inexpensive test to prove the pile capacity. The plant foundation has performed well in the four years since its completion, in the meantime several earthquakes have ocurred including one of 6.5 magnitude (Richter scale).

REFERENCES

Santoyo, E., Jaime, A., Montañez, L.(1981) Non Conventional thin wall samplers. X Int. Conf. on Soil. Mech. and Found. Eng. Sweden

Goble, G.G. and Rausche, F. Pile Load Test by Impact Driving, Highway Research Record N° 333, Highway Research Board

Goble, G. G., Rausche, F. and Moses, F. (1970) Dynamic Studies on the Bearing Capacity of Piles, Phase III, Report N° 48, Division of Solid Mechanics, Structures and Mechanical Design, Case Western Reserve University Cleveland

Goble, G. G., Likins, G. E., Rausche, F. (1975) Bearing Capacity of Piles from Dynamic Measurements, Final Report Submitted to the Ohio Dept. of Transportation, by Dept. of Civil Engineering, Case Western Reserve University, Cleveland

Smith, E.A.L. (1957) Pile Driving Analysis by the Wave Equation, Journ.Soil Mech.and Found.Div. ASCE Vol. 86 N° SM4 (1957)

Davisson, M.T. (1970) Static Measurements of Pile Behavior, Proc. Conf. on Design and Installation of Pile Found. and Cellular Structures. Lehigh Univ. Envo Publ