SELECTION OF A HAMMER FOR HIGH-STRAIN DYNAMIC TESTING OF CAST-IN-PLACE SHAFTS

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Abstract

Hammer details must be appropriately chosen for successful high-strain dynamic testing of cast-in-place foundation shafts (piles). This paper presents results of a wave equation analytical study performed to evaluate the dynamics of a range of hammer-cushion-pile-soil systems. The shafts studied had ranges of diameters, (D), from 750 to 1500 mm and lengths, (L), from 10D to 30D. The range of pile capacities considered represented values commonly encountered in practice. Analysis results suggest as a general guideline that the hammer weight be about 1.5% of the pile static resistance to be verified. This weight is significantly smaller than that required by static testing or by Statnamic.

Introduction

High-strain dynamic testing for evaluating cast-in-place foundation shafts (also known as bored piles, drilled shafts, cast in-situ piles, etc.) is routinely applied world-wide today. Field testing is performed by measuring pile strain and acceleration records under impact of a falling mass. Typically, at most, two to four impacts are applied when testing a cast-in-place shaft. The literature contains many cases where high-strain dynamic testing of cast-in-place shafts was performed for foundation design and/or construction control in conjunction with, or as replacement to static loading tests (Rausche and Seidel, 1984; Balthaus et al., 1985;

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Prebaharan et al., 1990; Lee et al., 1991; Townsend et al., 1991; and Jianren and Shihong, 1992).

The well established technology of high-strain dynamic testing of driven piles is readily adaptable for evaluating cast-in-place shafts. The Pile Driving Analyzer® (PDA) and CAPWAP® methods are used for data acquisition and analysis, respectively (Rausche et al., 1994; Hussein and Likins, 1995). Testing of cast-in-place shafts closely resembles testing of driven piles during restrike some time after initial installation. Testing results include information on pile structural integrity, pile static resistance, pile-soil load transfer and pile load-movement relationships. Advantages over other types of static and quasi-static testing include very low cost, minimal pile preparation and the speed of testing. Shafts can be systematically or randomly selected at any time after installation to receive a dynamic test.

Selection of a proper hammer size is essential for successful high-strain dynamic testing of cast-in-place shafts. Hammer weight, drop height, and cushion details must be appropriately chosen so that hammer impact causes sufficient pile movement to mobilize the required soil resistance, and to assure that dynamic stresses in the shaft will not impair its structural integrity. The hammer apparatus must be constructed in a way to facilitate mobility around job sites and assure a uniform impact to the pile. Naturally, the smallest satisfactory hammer weight is the most desirable.

Wave Equation Analysis

The wave equation analysis has long been used to rationally analyze the pile driving problem (Smith, 1960). In the context of foundation engineering, the term "Wave Equation" refers to computer programs that simulate and rationally analyze the dynamics of impact pile driving. Each component of the hammer-cushion-pile-soil system is discretely modeled and numerically analyzed. Wave equation analysis is generally done to optimize the driving system and pile for given soil conditions prior to start of construction, and/or to evaluate the pile bearing capacity and driving stresses given field observations during initial pile installation or restrike.

The following is a general summary of parameters needed for a conventional wave equation analysis, with emphasis on GRLWEAP™ (Goble Rausche Likins and Associates, 1995):

Hammer:	model of hammer or weight and shape of rams for diesels, combustion chamber information, ram fall height and efficiency
Cushions:	area, thickness, elastic modulus and coefficient of restitution

Pile helmet:	weight
Pile/Shaft:	length, area, density and elastic modulus all as a function of depth
Soil:	static resistance value and distribution, quake and damping values along the pile shaft and at the toe.

GRLWEAP contains advanced modeling techniques and special analysis options that make it particularly suitable for dynamic analysis of cast-in-place shafts under hammer impact. Some of these features, such as the "constant capacity, variable stroke option" and the Smith-viscous soil damping model, were utilized in this study.

This paper presents results of a wave equation analytical study using GRLWEAP to evaluate the dynamics of hammer-cushion-shaft-soil systems. Analysis results indicate that minimum hammer and cushion sizes required for successful high-strain dynamic testing of cast-in-place shafts are related to shaft size and soil resistance values.

Analysis Details

The shafts studied had diameters (D) ranging from 750 to 1500 mm, each analyzed with lengths (L) corresponding to values of 10D, 15D, 20D, 25D and 30D. Table 1 presents actual lengths analyzed for each diameter size. The lower bound value of 10D was chosen as a short shaft. Shafts with even lower L/D ratios have no tension stress problems. The 30D cases represent relatively long shafts associated with each diameter size.

For each of the 20 shaft sizes analyzed, three different static soil resistance values were assumed. The static resistances analyzed ranged between 5 and 30 MN. Table 2 includes the three soil static resistance values analyzed with each of the four shaft diameter sizes. In all cases, skin friction was assumed to be 85% of total soil resistance, distributed uniformly over the lower 80% of pile length. Skin soil damping and quake values used in the analyses were 0.66 s/m (Smith-viscous type) and 2.54 mm, respectively. Toe soil damping used was 0.50 s/m and quake values were equal to D/120 (*i.e.*, toe quakes were 6.25, 8.33, 10.42 and 12.50 mm for shaft diameters 750, 1000, 1250 and 1500 mm, respectively). These choices typically represent shafts in cohesive soils with moderate end bearing.

Three different hammer weights were analyzed with each of the shaft sizes and static soil resistances. Hammer weights, W, analyzed ranged between 80 and 480 kN. Table 2 lists the hammer weights used with each shaft diameter. Also included in Table 2 is the ratio of hammer weight to static soil resistance in percent. Hammer weight to soil resistance ratios ranged between 1 and 2.5%. Maximum hammer drop heights used in the analyses were between 2 and 3 m, depending on the size (diameter and length) of the shaft and are included in Tables 3, 4, 5, and 6. In all cases, a hammer efficiency of 75% was used in the analyses. The cushion was assumed to be plywood with an area equal to the shaft area. Cushion thicknesses, t, used in the analyses ranged between 100 and 825 mm, depending on shaft size. Actual values used in each analysis are included in Tables 3, 4, 5 and 6. In the analyses, cushion thicknesses were divided equally between hammer and pile top cushions, separated with a steel striker plate. Striker plates were modeled using the GRLWEAP helmet weights and were set to 5, 7, 10 and 14 kN for the 750, 1000, 1250 and 1500 mm diameter shafts, respectively.

Analysis Results

Results of wave equation analyses performed for shaft diameter sizes 750, 1000, 1250 and 1500 mm are presented in Tables 3, 4, 5 and 6, respectively. Each table includes the computed pile permanent set (SET) in mm and both maximum compression stress (CSX) and maximum tension stress (TSX) in MPa for each analyzed shaft and driving system combination. For example, Table 4 shows that for a 1000 mm diameter shaft, 20 m long with a static soil resistance of 11 MN impacted with a 170 kN ram with a drop height of 2 m using 200 mm cushion thickness, computed pile set, compression and tension stresses are 4.0 mm, 20.4 MPa and 1.9 MPa, respectively. Analysis results of all shaft sizes (diameters (D) and lengths (L)) studied indicate that acceptable sets and stresses result under the following conditions:

a) Hammer weights equal to 1.4 to 1.6% of soil static resistance values,

b) Drop heights corresponding to 7, 8, 9 and 10% of shaft lengths for shaft diameter sizes 1500, 1250, 1000 and 750 mm, respectively (minimum value of 2 m in all cases), and

c) Cushion thicknesses (t) equal to ($L^2/2D$) for (L) less than or equal to 30 m or ($L^2/2D + 150$) for L greater than 30 m where (t) is in mm and (L) in m (minimum value of 100 mm in all cases).

Under these conditions computed pile sets range between 1.2 and 5.6 mm, maximum compression stresses between 13.4 and 28.1 MPa, and maximum tension stresses between 0.7 and 3.8 MPa.

To illustrate the above recommendations a brief study was made for a shaft with 1100 mm diameter and 26 m length, using a hammer weight of

200 kN, a drop height of 2.2 m (*i.e.*, 0.085L) and cushion thickness of 307 mm (*i.e.*, $L^2/2D$). Analysis results for soil static resistances ranging from 9 to 15 MN are presented in Table 7. Alternately, analysis results with a hammer weight of 200 kN and soil static resistance of 13 MN (*i.e.*, hammer weight to soil resistance ratio of 1.5%) at various drop heights from 2.0 to 3.5 m are presented in Table 8. Finally, results of analyses performed to evaluate the effect of varying input hammer, cushion, pile and soil parameters on computed pile set, compression and tension stresses are presented in Table 9.

Additional Considerations

The above recommended set of parameters can only be as realistic as the representation of hammer, driving system, pile and soil conditions in the analyses on which these results were based. In particular, large shafts with high end bearing components may behave rather differently. While stress levels indicated in Tables 3 through 9 are often acceptable, they should be reviewed considering shaft concrete quality and reinforcement. In any event, proper preparation of the pile top (*e.g.*, the use of a thin casing in the upper pile portion) is necessary to avoid damage during dynamic loading. Furthermore, the static resistance values listed in the results tables may only be mobilized resistances. Large pile sets, *e.g.*, greater than 3 mm, usually indicate that these mobilized resistance values approach the ultimate capacity. Finally, using the results presented and merely recording set, ram weight and drop height is not sufficient to determine a mobilized capacity accurately. Dynamic measurements by the Pile Driving Analyzer® and CAPWAP® analyses are necessary to properly identify the characteristics of test system and soil conditions.

Summary

High strain dynamic testing using a Pile Driving Analyzer can be and has been successfully employed and can result in many benefits for drilled cast-in-place shafts. Wave equation analysis can, and should, be used to design the hammer and cushion details necessary for successful high-strain dynamic testing of these shafts. GRLWEAP incorporates special modeling features and analysis options that makes it particularly suitable for dynamic analysis of drilled cast-in-place shafts. Analysis results of various hammer-cushion-shaft-soil systems suggest the following general guidelines for the selection of hammer and cushion combinations: (1) The hammer weight should be at least equal to 1.5% of the anticipated static test load. (2) The hammer drop height should be approximately 8.5% of pile length (minimum value of 2 m). (3) A plywood cushion thickness of t = $L^2/2D$ (where (t) is expressed in mm and (L) and (D) are in meters) is suggested with a minimum value of 100 mm and an additional 150 mm should be added when pile length exceeds 30 m. It should be emphasized that these suggestions are only meant to be very general guidelines and may not be appropriate if actual conditions vary from those assumed in the analyses. Wave equation analysis should be performed with input variables realistically representing the specific conditions peculiar to each case.

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Table 1: Shaft Sizes, Diameters and Lengths

		Diameter (D), mm			
		750	1000	1250	1500
Length, m	10D	7.50	10.00	12.50	15.00
	15D	11.25	15.00	18.75	22.50
	20D	15.00	20.00	25.00	30.00
	25D	18.75	25.00	31.25	37.50
	30D	22.50	30.00	37.50	45.00

Table 2: Ratios (in percentage) of Ram Weights to Static Resistances

D, mm	750				1000				1250				1500			
Ru, MN		5	6	7		9	11	13		14	17	20		20	25	30
Ram Wt., kN	80	1.6	1.3	1.1	130	1.4	1.2	1.0	200	1.4	1.2	1.0	320	1.6	1.3	1.1
	90	1.8	1.5	1.3	170	1.9	1.5	1.3	260	1.8	1.5	1.3	400	2.0	1.6	1.3
	100	2.0	1.7	1.4	200	2.2	1.8	1.5	300	2.1	1.8	1.5	480	2.4	1.9	1.6

Table 3: Wave Equation Analysis Results, 750 mm Diameter Shaft

L	7.50 m			11.25 m			15.00 m			18.75 m			22.50 m			
t	102 mm			102 mm			150 mm			234 mm			337 mm			
W \ H	2.00 m			2.00 m			2.00 m			2.00 m			2.25 m			
80 kN	5.3	3.8	2.6	5.6	4.0	2.7	5.2	3.5	2.2	4.5	2.8	1.5	4.5	2.7	1.2	SET
	22.6	23.0	23.5	23.6	24.1	24.5	21.0	21.4	21.8	17.7	18.0	18.3	16.5	16.7	17.0	CSX
	0.7	0.7	0.8	1.6	1.6	1.5	2.4	2.0	1.6	2.4	1.7	1.9	2.2	1.9	2.4	TSX
90 kN	6.4	4.7	3.3	6.6	4.9	3.4	6.3	4.4	2.9	5.5	3.5	2.0	5.5	3.3	1.7	SET
	23.5	24.0	24.9	24.5	25.0	25.4	21.8	22.2	22.6	18.4	18.7	19.0	17.1	17.4	17.7	CSX
	0.7	0.8	0.9	1.5	1.4	1.5	2.2	2.0	1.7	2.4	1.8	1.8	2.4	1.7	2.2	TSX
100 kN	7.5	5.6	4.0	7.6	5.7	4.2	7.4	5.3	3.6	6.5	4.3	2.6	6.5	4.1	2.3	SET
	24.2	25.4	26.4	25.3	25.7	26.2	22.5	22.9	23.3	19.1	19.4	19.7	17.8	18.1	18.4	CSX
	0.7	0.8	0.9	1.4	1.4	1.4	2.0	1.9	1.7	2.2	1.7	1.8	2.4	1.6	2.2	TSX
	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7	
	Static Resistance, MN															

L = shaft length, t = cushion thickness, W = hammer weight, H = drop height
SET = shaft set, CSX = maximum compression stress, TSX = maximum tension stress

Table 4: Wave Equation Analysis Results, 1000 mm Diameter Shaft

L	10 m			15 m			20 m			25 m			30 m			
t	51 mm			112 mm			200 mm			312 mm			450 mm			
W \ H	2.00 m			2.00 m			2.00 m			2.25 m			2.70 m			
130 kN	4.5	2.9	1.7	4.6	3.1	1.8	4.1	2.4	1.0	4.0	2.1	0.6	4.3	2.2	0.5	SET
	22.9	23.3	23.8	21.9	22.4	22.8	18.1	18.5	18.9	16.3	16.7	17.0	15.5	15.8	16.1	CSX
	1.4	1.4	1.4	2.4	1.9	1.8	2.3	1.9	2.4	2.9	2.3	2.9	3.3	2.7	3.3	TSX
170 kN	6.7	4.8	3.2	6.9	4.9	3.3	6.2	4.0	2.3	6.2	3.8	1.9	6.7	3.9	1.8	SET
	24.6	25.1	25.6	23.9	24.4	24.9	19.9	20.4	20.7	18.0	18.5	18.7	17.2	17.6	17.9	CSX
	1.4	1.4	1.4	2.3	2.0	1.6	2.6	1.9	2.3	2.6	2.2	2.9	2.8	2.6	3.4	TSX
200 kN	8.4	6.2	4.1	8.7	6.3	4.5	7.9	5.3	3.3	7.9	5.0	2.8	8.5	5.2	2.8	SET
	25.6	26.1	27.0	25.5	26.0	26.6	21.3	21.8	22.2	19.3	19.7	20.0	18.4	18.7	19.1	CSX
	1.2	1.4	1.5	2.1	1.9	1.7	2.5	1.9	2.2	2.6	1.9	2.8	3.0	2.3	3.3	TSX
	9	11	13	9	11	13	9	11	13	9	11	13	9	11	13	
	Static Resistance, MN															

L = shaft length, t = cushion thickness, W = hammer weight, H = drop height
SET = shaft set, CSX = maximum compression stress, TSX = maximum tension stress

Table 5: Wave Equation Analysis Results, 1250 mm Diameter Shaft

L	12.50 m			18.75 m			25.00 m			31.25 m			37.50 m			
t	102 mm			141 mm			250 mm			540 mm			711 mm			
W \ H	2.00 m			2.00 m			2.00 m			2.50 m			3.00 m			
200 kN	4.3	2.8	1.6	4.3	2.7	1.4	3.6	1.9	0.6	3.0	1.0	0.5	3.0	0.8	0	SET
	22.1	22.5	22.9	19.7	20.1	20.4	16.5	16.9	17.2	13.7	14.0	14.1	13.4	13.7	13.9	CSX
	2.2	1.7	1.3	3.5	2.3	2.1	3.8	2.6	2.6	2.8	2.5	2.6	2.1	2.5	3.1	TSX
260 kN	6.6	4.7	3.1	6.5	4.5	2.9	5.7	3.6	1.8	5.0	2.5	0.5	5.6	2.8	0.6	SET
	24.3	24.9	25.4	21.7	22.1	22.6	18.3	18.6	19.0	15.3	15.6	15.8	14.9	15.2	15.4	CSX
	1.8	1.4	1.3	2.7	1.9	2.0	2.7	2.3	2.9	2.5	2.5	3.2	2.5	2.9	3.4	TSX
300 kN	8.0	5.9	4.2	7.9	5.7	3.9	7.0	4.6	2.7	6.4	3.5	1.3	7.1	3.9	1.4	SET
	25.7	26.3	26.8	23.0	23.4	23.9	19.3	19.7	20.1	16.2	16.5	16.8	15.8	16.1	16.3	CSX
	1.6	1.3	1.3	2.7	2.0	1.7	2.7	2.1	2.8	2.5	2.3	3.1	2.8	2.7	3.4	TSX
	14	17	20	14	17	20	14	17	20	14	17	20	14	17	20	
	Static Resistance, MN															

L = shaft length, t = cushion thickness, W = hammer weight, H = drop height
SET = shaft set, CSX = maximum compression stress, TSX = maximum tension stress

Table 6: Wave Equation Analysis Results, 1500 mm Diameter Shaft

L	15.00 m			22.50 m			30.00 m			37.50 m			45.00 m			
t	102 mm			169 mm			300 mm			619 mm			825 mm			
W \ H	2.00 m			2.00 m			2.00 m			2.60 m			3.10 m			
320 kN	5.1	3.2	1.7	4.9	2.8	1.2	4.4	2.1	0.2	3.9	1.2	0.6	4.3	1.3	0.6	SET
	22.9	23.5	24.0	19.3	19.8	20.2	16.4	16.8	17.2	13.9	14.2	14.3	13.5	13.8	13.9	CSX
	2.5	2.0	1.7	4.4	2.9	2.6	4.4	2.9	3.2	3.5	2.8	3.0	3.6	3.0	3.1	TSX
400 kN	7.2	4.9	3.1	6.9	4.5	2.5	6.4	3.7	1.5	5.8	2.6	0.2	6.5	2.8	0.2	SET
	25.0	25.7	26.3	21.1	21.6	22.0	18.0	18.4	18.8	15.2	15.5	15.8	14.8	15.1	15.4	CSX
	2.4	2.0	1.5	3.0	2.3	2.6	3.8	2.8	3.5	2.7	3.0	3.5	3.3	3.4	3.8	TSX
480 kN	9.3	6.6	4.5	8.9	6.1	3.8	8.4	5.2	2.7	7.8	4.0	1.2	8.6	4.4	1.2	SET
	26.8	27.5	28.1	22.6	23.1	23.6	19.3	19.7	20.1	16.4	16.7	17.0	15.9	16.3	16.5	CSX
	2.1	1.8	1.6	2.9	2.0	2.3	3.2	2.7	3.5	3.0	2.7	3.6	3.0	3.4	4.0	TSX
	20	25	30	20	25	30	20	25	30	20	25	30	20	25	30	
	Static Resistance, MN															

L = shaft length, t = cushion thickness, W = hammer weight, H = drop height
SET = shaft set, CSX = maximum compression stress, TSX = maximum tension stress

Table 7: Wave Equation Analysis Results
1100 mm Diam., 26 m Shaft; 200 kN, 2.2 m Hammer

Ru MN	CSX MPa	TSX MPa	SET mm
9	17.4	3.3	8.2
10	17.5	2.9	6.9
11	17.8	2.7	5.7
12	17.9	2.4	4.7
13	18.1	2.2	3.8
14	18.2	2.4	3.0
15	18.4	2.7	2.2

Ru - Static Resistance, CSX - Compression Stress
TSX - Tension Stress, SET - Permanent Set

Table 8: Wave Equation Analysis Results
1100 mm Diam., 26 m Shaft; 200 kN Hammer, 13MN Resistance

H m	CSX MPa	TSX MPa	SET mm
2.0	17.3	2.1	3.2
2.2	18.1	2.2	3.8
2.4	19.0	2.4	4.5
2.7	19.8	2.6	5.1
2.9	20.5	2.8	5.7
3.1	21.3	3.0	6.2
3.3	22.0	3.2	6.8
3.5	22.7	3.4	7.4

H - Hammer Drop Height, CSX - Compression Stress
TSX - Tension Stress, SET - Permanent Set

Table 9: Wave Equation Analysis Results

		SET	CSX	TSX
Hammer eff., %,	55	2.0	15.6	1.9
	65	2.9	16.9	2.1
	75	3.8	18.1	2.2
	85	4.6	19.2	2.5
	95	5.4	20.2	2.8
Stroke, m,	2.0	3.2	17.3	2.1
	2.5	4.6	19.2	2.5
	3.0	5.9	20.9	2.9
Ram wt., kN,	160	2.4	16.5	2.3
	200	3.8	18.1	2.2
	240	5.2	19.4	2.0
Pile Diam., mm,	1000	3.5	21.2	2.9
	1100	3.8	18.1	2.2
	1200	3.9	15.6	2.4
Pile Length, m,	24	3.7	18.1	2.0
	25	3.7	18.2	2.2
	26	3.8	18.1	2.2
	27	3.9	18.0	2.3
	28	3.9	17.9	2.4
Friction, %,	15	2.3	16.2	3.0
	25	2.4	16.4	1.8
	45	2.8	17.0	1.8
	55	3.1	17.3	1.8
	65	3.3	17.6	1.8
	85	3.8	18.1	2.2
Skin Damp., s/m,	0.33	6.1	17.7	3.2
	0.66	3.8	18.1	2.2
	1.00	2.3	18.4	2.6
Cushion t, mm,	250	4.5	19.4	2.4
	300	3.9	18.2	2.3
	350	3.3	17.3	2.1
Cushion E, MPa,	138	2.2	15.6	1.9
	207	3.8	18.1	2.2
	276	4.7	19.9	2.5