Florida Department of Transportation

RON DESANTIS
GOVERNOR

605 Suwannee Street
Tallahassee, FL 32399-0450

JARED W. PERDUE, P.E.
SECRETARY

STRUCTURES DESIGN BULLETIN 22-01
MATERIALS BULLETIN 22-09
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TO: District Directors of Transportation Operations, District Directors of Transportation Development, District Design Engineers, District Construction Engineers, District Geotechnical Engineers, District Structures Design Engineers, District Maintenance Engineers, District Materials Engineers

FROM: Will Potter, P.E., State Structures Design Engineer
Timothy J. Ruelke, P.E., Director, Office of Materials

COPIES: Will Watts, Dan Hurtado, Tim Lattner, Rudy Powell, Carla Perry, Ben Goldsberry, Juan Castellanos, Larry Jones, Rafiq Darji (FHWA)

SUBJECT: Goble Pile Check (GPC) Dynamic Load Testing

This bulletin updates Table 3.5.7-1 of the ***Structures Design Guidelines*** (***SDG***) and Appendix F of the ***Soils and Foundations Handbook*** with respect to the use of Goble Pile Check (GPC) dynamic monitoring equipment to monitor instrumented piles.

REQUIREMENTS

1. Replace Footnote (1) in ***SDG*** Table 3.5.7-1 with the following:

   1. With signal matching analysis of Pile Driving Analyzer (PDA) data, Goble Pile Check (GPC) data or "FDOT Method" analysis of Embedded Data Collector (EDC) data of at least 10% of all Piles in each Bent and Pier Footing. Ensure all soil conditions encountered are analyzed. See Soils and Foundations Handbook.

2. Replace ***Soils and Foundations Handbook*** Appendix F with the following:

Determination Of Acceptance Criteria for Driven Piles

Piles must be installed to not less than the Nominal Bearing Resistance (NBR) in the Plans. For details on the computation of NBR refer to the SDG, chapter 3.

The potential effect of nearby construction activities on pile capacity shall be evaluated using acceptable theoretical methods and engineering judgment. For example, the influence of jetting concrete sheet pile or vibratory installation/removal of steel sheet pile in the vicinity of foundation piles shall be considered, when evaluating foundation performance. Confirmation of pile resistance through set-checks after completion of nearby construction is the preferred alternative. When set-checks are not feasible, potential reductions in pile resistance due to nearby construction can be addressed by implementing revisions (increases) to the NBR, minimum tip elevation, or applicable Plan notes.

The following construction quality control methods may be used to determine pile resistance in the field (see SDG Chapter 3 Table 3.5.6-1 for an exhaustive list):

1. Standard pile driving criteria with dynamic monitoring equipment with Pile Driving Analyzer (PDA) monitored test pile(s) or monitored production pile(s) in projects without test piles, using signal matching software such as CAPWAP, and Wave Equation Analysis. The dynamic monitoring equipment will normally utilize a program, such as the PDA's PDIPlot program described in this appendix, for viewing the results. (The discussions on this method below use the terms 'PDA', 'CAPWAP' and 'PDIPlot' for simplicity.)
2. Standard pile driving criteria (similar to method 1) with Goble Pile Check (GPC) dynamic monitoring equipment monitored test pile(s) or monitored production pile(s) and N_GAPA signal match analyses.
3. Embedded Data Collector (EDC) monitoring of all Test Piles and all Production Piles (100%), using tip and top gauges, or a combination of piles with top and tip gauges and piles with only top gauges. A minimum percentage of the piles in each bent/pier must be analyzed with the FDOT Method post-processing software; see Section 3 of this Appendix.
4. PDA monitoring of all Test Piles and all Production Piles (100%), with CAPWAP analyses on a minimum percentage of the piles in each bent/pier required in Section 4 of this Appendix.
5. GPC monitoring of all Test Piles and all Production Piles (100%), with manual N_GAPA signal match analyses on a minimum percentage of the piles in each bent/pier required in Section 5 of this Appendix.

1. Standard Driving Criteria with PDA Test Piles or monitored indicator production pile(s) in projects without test piles**, CAPWAP and Wave Equation Analysis**

In this method dynamic load tests are initially performed on test piles or indicator production piles and a resistance factor (ϕ) of 0.65 may be used in the computation of the required NBR. Dynamic Load tests are performed in accordance with Specification 455. Dynamic data are collected on

PDA sensors connected at the top of the pile throughout the entire drive for every impact blow: the early pile driving blows on concrete piles are essential to evaluate wave speed as well as to monitor pile stress. The purpose of this method is to establish a “calibrated” model that predicts the number of blows per foot and stroke combination to achieve a desired resistance. The Driving Criteria based on PDA testing involves the following steps:

a. Estimation of production pile tip elevation based on PDA results, and preparation of selected blow for CAPWAP analysis
b. CAPWAP analysis to confirm PDA results
c. Wave Equation calibration and final wave equation analysis
d. Driving Criteria Letter

a. Estimation of production pile tip elevation based on PDA results, and selection of dynamic data for CAPWAP analysis

Based on the field collected dynamic data, estimate the tip elevation where NBR is achieved. Following the recommendations in CAPWAP’s manual, select a representative blow of good data quality for signal match analysis. Adjust the blow as required and ensure the wave speed is properly determined, the F (force trace from strain gauges) and V (velocity times impedance trace from accelerometers) forces are proportional and the final displacement converges to the measured set.

b. CAPWAP Analysis

- Check that the static resistance distribution makes sense, compare with boring logs and pile driving records to ensure reasonable assumptions are being implemented. Do not expect the automatic search feature to provide an accurate resistance distribution.
- **Match Quality number (MQN):** Make every reasonable attempt to obtain a MQN less than three. Make sure good matching is obtained for both wave and force matching analysis.
- **Resistance:** Ensure resistance is not overestimated throughout the entire first 4L/c portion of the record.
- **Match in blow count:** Make every reasonable attempt to match the observed number of blows per foot for the selected interval.

Once the CAPWAP analysis is performed, determine the equivalent Jc (Case damping) value and compare the CAPWAP capacity with the corresponding PDA capacity. The equivalent Jc is the value that produces the same PDA capacity as the one determined by CAPWAP analysis.

Reprocess the PDA and PDIPLOT based on CAPWAP analysis results (using the Jc value from the previous step and the RMX capacity or proper capacity approach), to tabulate the capacity throughout the drive.

c. Wave Equation Calibration

Using the CAPWAP estimated quake, damping and static resistance distribution, establish a WEAP model based on the test pile or indicator production pile length and properties. Perform WEAP analyses to match the following parameters from CAPWAP and PDA: Energy Transferred EMX (within 10%), Compression Stress CSX (within10%), blow count (within 10% but never below the blows/ft measured in the field) for the capacity and stroke evaluated. Some adjustments may be required to the static resistance distribution, hammer efficiency, cushion, thickness, stiffness, etc. to get an acceptable model.

Verify the model: Refer to the corrected PDIPlot and compare at several depths (near the estimated bearing depth) to check whether the model predicts accurate blow counts for this and other capacities/strokes measurements (use PDIPlot average output per foot or per increment). Refine the model if necessary.

Blow count criteria: On the refined wave equation model, apply production pile lengths and NBR loading conditions to develop a driving criteria. Reduce efficiency for battered piles as appropriate. If the Contractor provides longer piles than the authorized lengths, perform the analysis again to confirm the criteria still applies.

d. Driving Criteria Letter

The driving criteria letter provides the inspector with directions on when to accept piles. The letter should include the pile acceptance criteria based on blow count vs. stroke height results obtained from WEAP analysis, pile cushion details and recommendations regarding the operation of the hammer to avoid damaging the pile while driving. In addition, if the minimum tip elevation is not shown on the Plans, provide a criterion for "firm bearing material" to determine when the minimum pile penetration per 455-5.8 has been achieved. Provide the maximum number of hammer blows that may be applied to pile cushions before they must be replaced and the minimum number of blows a new cushion must be impacted before applying the blow count and refusal criteria. Indicate the minimum stroke or stroke range under which this number of blows must be applied. For more information regarding the driving criteria letter, refer to the Construction Procedures Administration Manual (CPAM, chapter 10.1, sample letters).

e. Additional Considerations

It is important to note that the driving criteria applies to the soil/rock material encountered at the elevation at which CAPWAP analysis was performed. Piles that satisfy the driving criteria within different soil/rock strata need to be evaluated to confirm resistance has been achieved. In addition, driving criteria based on initial drive may not be used for set-check (re-strike) conditions. To develop a valid set-check criteria, dynamic load test data must be available for the same driving conditions and time after initial drive was performed, and the same steps (as initial driving criteria development) followed.

In some special conditions, the pile driving log (and PDIPlot) may indicate an unusually high blow count in upper layers, even though capacity was not obtained. This may occur because soil properties change with depth. For example, a pile driven through soil with large damping properties will require a larger blow count than low damping soils, for the same capacity. This may also occur when the pile cushion has not been fully compressed. Therefore, in some cases it may be necessary to revise the model to ensure piles will not attain a false bearing (meet the blow count requirement without actually achieving the static resistance). There are three choices:

i. Implement a minimum elevation above which the criteria is not applicable.
ii. Establish a blow count requirement that is high enough to avoid stopping in the higher damping soil without bearing. This may be feasible when the test pile shows an increase in capacity with depth and the conservative criteria does not result in unreasonably long production pile lengths.
iii. Establish different criteria for the upper layers to account for the increased damping value of those soils. One set of criteria will be applicable above a predetermined elevation, and the other will be applicable below that elevation.

2. Standard Driving Criteria with Goble Pile Check (GPC) Test Piles or monitored indicator production pile(s) in projects without test piles**, Nguyen_Goble Automated Pile Analysis (N_GAPA)** and **GPC Wave**

In this method dynamic load tests are initially performed on test piles or indicator production piles and a resistance factor (ϕ) of 0.65 may be used in the computation of the required NBR. Dynamic Load Tests (DLT) are performed in accordance with Specification 455. Dynamic data are collected on GPC sensors connected at the top of the pile throughout the entire drive for every impact blow: the early pile driving blows on concrete piles are essential to evaluate wave speed as well as to monitor pile stress. For steel piles, wave speed is a constant and stress limits are high, as such Specifications 455-5.14 allows acceptance based on set-checks or redrives of steel piles. The purpose of this method is to establish a "calibrated" model that predicts the number of blows per foot and stroke combination to achieve the required resistance (establish the driving criteria). The Driving Criteria based on GPC testing involves the following steps:

a. Estimation of production pile tip elevation based on GPC results, and preparation of selected blow for signal match (N_GAPA) analysis
b. Signal match analysis
c. Wave Equation analyses based on the GPC blow and final calibrated GPC wave equation analysis
d. Driving Criteria Letter

a. Estimation of production pile tip elevation based on GPC results, and selection of dynamic data for Signal Match (N_GAPA) analysis

Ensure the material wave speed (WS) is properly determined, the F (force trace from strain gauges) and VZ (velocity times impedance trace from accelerometers) forces are proportional. Do not adjust the replay factor, unless the sensor is incorrectly mounted at an angle on the pile, making the sensor's acceleration smaller than the true pile acceleration.

Based on the field collected dynamic data, estimate the tip elevation where NBR is achieved. Select a representative blow of good data quality for Signal Match analysis: The selected blow shall have similar stroke height (STK), maximum force (FMX), and transferred energy (EMX) to the average of the blows of that foot. This is to ensure that the set of the selected blow will be similar to the average set of that foot. The average set of the foot is the inverse of the measured blow count per foot. Adjust the blow as necessary so that the final displacement converges to the measured set.

b. Signal Match (N_GAPA) Analysis

- Where the pile template creates friction on the pile, implement the "added damping" at that element to model the non-soil friction.
- Check that the static resistance distribution makes sense, compare with boring logs and pile driving records to ensure reasonable assumptions are being implemented.
- **Match Quality Number (MQN):** Make every reasonable attempt to obtain an MQN less than three.
- **Resistance:** Ensure resistance is not overestimated throughout the first 4L/c portion of the record. The simulated or calculated WU shall not be much larger than the measured WU within this portion.
- **Match in blow count:** Make every reasonable attempt to match the observed number of blows per foot for the selected interval.

Reprocess the GPC Review to produce refined signal match (instant N_GAPA or iN_GAPA) results throughout the drive.

f. Wave Equation Calibration

Import the above Signal Match analysis blow into GPC Wave. The import module in the GPC Wave program will bring in all quake, damping, and static resistance distribution into the Wave Equation Analysis.

Verify the model: Refer to the GPC Review and compare at several depths (near the estimated bearing depth) to check whether the model predicts accurate blow counts for this and other capacities/strokes measurements (use average output per foot or per increment). Refine the model if necessary.

Blow count criteria: Apply production pile lengths and NBR loading conditions to develop a driving criteria. Reduce efficiency for battered piles as appropriate. If the Contractor provides longer piles than the authorized lengths, perform the analysis again to confirm the criteria still applies.

g. Driving Criteria Letter

The driving criteria letter provides the inspector direction on when to accept piles. The letter should include the pile acceptance criteria based on blow count vs. stroke height results obtained from Wave Equation analysis, pile cushion details and recommendations regarding the operation of the hammer to avoid damaging the pile while driving. In addition, if the minimum tip elevation is not shown on the Plans, provide a criterion for “firm bearing material” to determine when the minimum pile penetration per 455-5.8 has been achieved. Provide the maximum number of hammer blows that may be applied to pile cushions before they must be replaced and the minimum number of blows a new cushion must be impacted before applying the blow count and refusal criteria. Indicate the minimum stroke or stroke range under which this number of blows must be applied. For more information regarding the driving criteria letter, refer to the Construction Procedures Administration Manual (CPAM, chapter 10.1, sample letters).

h. Additional Considerations

It is important to note that the driving criteria applies to the soil/rock material encountered at the elevation at which Signal Match analysis was performed. Piles that satisfy the driving criteria within different soil/rock strata need to be evaluated to confirm resistance has been achieved. In addition, driving criteria based on initial drive may not be used for set-check (re-strike) conditions. To develop a valid set-check criteria, dynamic load test data must be available for the same driving conditions and time after initial drive was performed, and the same steps (as initial driving criteria development) followed.

In some special conditions, the pile driving log (and GPC Review) may indicate an unusually high blow count in upper layers, even though capacity was not obtained. This may occur because soil properties change with depth. For example, a pile driven through soil with large damping properties will require a larger blow count than low damping soils, for the same capacity. This may also occur when the pile cushion has not been fully compressed. Therefore, in some cases it may be necessary to revise the model to ensure piles will not attain a false bearing (meet the blow count requirement without actually achieving the static resistance). There are three choices:

i. Implement a minimum elevation above which the criteria is not applicable.
ii. Conservatively establish a blow count requirement that is high enough to avoid stopping in the higher damping soil without bearing. This may be feasible when the test pile shows an increase in capacity with depth and the conservative criteria does not result in unreasonably long production pile lengths.

iii. Establish different criteria for the upper layers to account for the increased damping value of those soils. One set of criteria will be applicable above a predetermined elevation, and the other will be applicable below that elevation.

3. Embedded Data Collector (EDC) monitoring of Test Piles and Production Piles (100%)

EDC is an approved method for using embedded sensors to monitor pile driving. In this method, dynamic load tests are performed on test piles and all production piles with the EDC system. Sensors are embedded in the pile in accordance with Standard Plans Index 455-003. Test piles may be driven to determine production pile lengths. A resistance factor (ϕ) of 0.75 may be used with this method. No driving criteria are required because achieving the NBR, without exceeding the allowable stress limits, will be determined in the field by EDC monitoring in accordance with either **a.** or **b.** below.

a. EDC monitoring of all Test Piles and all Production Piles, using 100% top and tip gauges.

All EDC piles are monitored in the field using Smart Structures' UF Method. Smart Structures' FDOT Method post-processing software will be used to verify the UF Method results of at least 10% of all piles in each bent and pile footing (minimum one per bent/group) including all test piles. In unique soil conditions such as extreme scour, large uplift loads or high variability soils a higher percentage FDOT Method analyses is required.

b. EDC monitoring of all Test Piles and all Production Piles, using a combination of top & tip gauges and top only gauges.

1. Use top and tip gauges in at least 10% of the piles (minimum one per bent/group) and top only gauges in the remaining piles. All test piles shall contain top and tip gauges. Test piles are included in the 10% minimum. In unique soil conditions such as extreme scour, large uplift loads or high variability soils a higher percentage of FDOT Method analyses is required, therefore, a higher percentage of piles with top and tip gauges is also required.

2. In the field, use the UF Method during driving and confirm pile resistance with the FDOT Method after driving is complete for the piles instrumented with top and tip gauges. Use the Fixed Jc/Case Method with back computed/selected Jc value (as described in the below points) for piles instrumented with top only gauges.

3. For the piles instrumented with top and tip gauges, review the FDOT Method results for at least the first 10 blows in the six inches of the drive qualifying the pile for acceptance and use the Fixed Jc/Max Case Method equation to back compute the damping (Jc) value from the FDOT Method capacity for the representative blow.

4. In the event the back computed Jc value using FDOT method appears to be out of an acceptable range (<0.1 or greater than 1.0), use the UF method capacity and good engineering judgment to determine Jc.

5. When more than one pile in a bent/group must be analyzed, select the highest Jc value of the analyzed piles for the bent/group and/or good engineering judgement to determine which production piles will be based on which Jc value.

6. When the need for set checks is anticipated, the Jc value for set check conditions will be higher than for initial driving. Therefore, the above procedure must be repeated on a set checked pile at the required set-up periods with top & tip gauges to determine the Jc value for set checking a top sensor only pile. When this is not possible use prudent engineering judgement in consultation with and approval by the District Geotechnical Engineer.

4. PDA monitoring of all Test Piles and all Production Piles (100%), with CAPWAP analysis of the percentage of the piles in each bent/pier required in the Specification.

In this method, dynamic load tests are performed on test piles and all production piles. Test piles are driven first to determine production pile lengths, or in cases when the Contractor has chosen to order production piles in advance, the first pile in each bent or pier to verify that the ordered length is adequate. With this method, a resistance factor (ϕ) of 0.75 may be used in the computation of the required NBR. No driving criteria are required as achieving the NBR, without exceeding the allowable stress limits, will be determined in the field by PDA and CAPWAP. CAPWAP analyses are required on at least 10% of the piles in each bent or pier to confirm that the proper damping value, Jc, is used to estimate static resistance of the remaining piles. In unique soil conditions such as extreme scour, large uplift loads or high variability soils, a higher percentage of CAPWAP analyses is required. In addition, piles that meet the criteria at significantly different elevations from where CAPWAP was performed, or tip on a different material type, will require separate CAPWAP analysis. Finally, at least one additional CAPWAP analysis is required for an instrumented re-drive if this has a different set-up time than other piles evaluated in the pier.

5. GPC monitoring of all Test Piles and all Production Piles (100%), with manual N_GAPA analysis of the percentage of the piles in each bent/pier required in the Specification.

In this method, dynamic load tests are performed on test piles and all production piles. Test piles are driven first to determine production pile lengths, or in cases when the Contractor has chosen to order production piles in advance, the first pile in each bent or pier to verify that the ordered length is adequate. With this method, a resistance factor (ϕ) of 0.75 may be used in the computation of the required NBR. No driving criteria are required as achieving the NBR, without exceeding the allowable stress limits, will be determined in the field by GPC and Signal Match analyses. Manual N_GAPA analyses are required on at least 10% of the piles in each bent or pier to confirm GPC results. In unique soil conditions such as extreme scour, large uplift loads or high variability soils, a higher percentage of Signal Match analyses is required. In addition, piles that meet the criteria at significantly different elevations from where Signal Match was performed, or tip on a different material type, will require separate Signal Match analysis. Finally, at least one additional Signal Match analysis is required for an instrumented re-drive if this has a different set-up time than other piles evaluated in the pier.

Determining the Capacity of a Pile from an Instrumented Set-Check

In accordance with section 455-5.10.4, the pile capacity to be reported from an instrumented set-check will be the lowest of:

a. The highest capacity recorded in the set-check
b. The average capacity of the five consecutive blows following the highest capacity blow divided by 0.95
c. The lowest capacity of the remainder of the blows (if any, after the blows in b above) in the set-check divided by 0.90

Note, disregard the last blow, which is typically a low energy blow after hammer was shut down.

Example 1, instrumented set-check w/ minimum blows:	Example 2, instrumented set-check and advance pile:
Blow # Capacity, kips	Blow # Capacity, kips
1. 450	1. 450
2. 600	2. 600
3. 590	3. 590
4. 585	4. 585
5. 580	5. 580
6. 575	6. 575
7. 570	7. 570
8. 277	8. 572
	9. 550
	10. 530
	11. 528
	12. 520
	13. 513
	14. 509
	15. 501
	16. 494
	17. 478
	18. 461
	19. 216
Answer: a. Highest capacity recorded= 600 kips	Answer: a. Highest capacity recorded= 600 kips
b. Average of next 5 blows/0.95 = [(590+585+580+575+570)/5]/0.95= 580 kips/ 0.95= 610 kips	b. Average of next 5 blows/0.95 = [(590+585+580+575+570)/5]/0.95= 580 kips/ 0.95= 610 kips
Answer=600 kips	c. Lowest capacity of the following blows (excluding the last one) = 461/0.90= 512 kips
	Answer=512 kips

BACKGROUND

These revisions should decrease Construction Engineering and Inspection (CEI) costs for dynamic load testing of instrumented piles by providing a third proven test method option, thus creating additional competition.

IMPLEMENTATION

Effective immediately, the use of the GPC dynamic load test method is permitted for all projects that do not have a Modified Special Provision requiring a specific test method to be used.

CONTACT

Larry Jones
Assistant State Structures Design Engineer &
State Geotechnical Engineer
Phone (850) 414-4305
Larry.Jones@dot.state.fl.us

WP/TR/lj