DIGGS Schema Extensions for Encoding and Exchange of Driven Pile Installation Data

Report submitted to ASCE G-I

by

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The GI Deep Foundation Special Project Working Group

Abstract

The DIGGS XML schema standard is being expanded to standardize encoding of driven pile installation data through an ASCE G-I Technical Coordination Council Special Project. A working group analyzed pile driving record forms from 18 State Departments of Transportation, and data from a major southern California infrastructure project to inform the schema development. The proposed extensions encompass:
- Installation objects for concrete, steel-H, steel pipe, and timber piles
- Equipment objects for pile driver hammers, pile caps, cushions, and striker plates
- Construction activity objects for both manual/Saximeter pile driving records and pile dynamic analysis (PDA) data

Future proposed extensions will address pre-installation design specifications, cast-in-place piles, vibratory installations, composite piles, and post-installation testing (CAPWAP, BOR).

These schema extensions enable standardized encoding and transfer of driven pile installation data, enhancing geotechnical engineering analysis, design, planning, construction, visualization, and archiving capabilities.

Introduction

DIGGS is an XML-based standard for exchanging geotechnical and geoenvironmental data. Its modular schema design uses extensible base types to accommodate new data while maintaining core structure and minimizing bloat. Initial development focused on ground investigation data, including borehole construction, sampling, laboratory testing, and in-situ monitoring. Recent DIGGS v2.6 extensions support geophysical data and grouting activities.

In late 2023, the ASCE GI Technical Coordination Council approved a Special Project to expand DIGGS for pile driving data, aiming to enhance data exchange and interoperability within the geotechnical community. A working group formed in March 2024, with Daniel Ponti and Nick Machairas as technical leads, and included ten domain experts who provided guidance and sample datasets (Table 1).

This initial phase focused on driven pile installation, including as-built pile properties, installation equipment specifications, and pile driving records from both manual and PDA (pile dynamic analysis) sources. This phase excludes composite piles, cast-in-place/bored piles, vibratory installations, post-installation testing, and pre-installation design specifications.

Table 1. List of DIGGS Deep Foundation Working Group Participants

Daniel Ponti, (USGS Retired) and Nick Machairas (Haley & Aldrich) Technical Leads
Allen Cadden (Schnabel Engineering), Working Group Coordinator
Andrew Christian Anderson, Univ. Illinois
Derek Dasenbrock, U.S. Federal Highways Administration
Ross Cutts, Schnagel Engineering
Scott Deaton, Dataforensics LLC
Mohammad Hussein, Pile Dynamics, Inc.
Beverly Miller, Pennsylvania Dept. of Transportation
Sarah Mullaney, Pennsylvania Dept. of Transportation
Brent Robinson, Pile Dynamics Inc.
Heather Shoup, Illinois Dept. of Transportation

The new schema objects are defined in the Piling.xsd schema file located in on GitHub in the schema-dev repository at: https://github.com/DIGGSml/schema-dev/blob/main/Piling.xsd.

Full schema documentation can be found at: https://diggsml.org/docs/latest.

The current dictionary of observed properties that can be reported for pile driving and PDA records is located at: https://diggsml.org/def/codes/DIGGS/0.1/pil_properties.xml.

An example DIGGS instance file that encodes both a pile driving record and a PDA record from installation of a steel pipe pile can be found in the Github repository at: https://github.com/DIGGSml/diggs-examples/blob/master/Piling%20Development/CaltransTest.xml

Proposed DIGGS Schema Extensions

Sampling Feature Objects

All as-built piles in DIGGS are Installation objects, deriving from AbstractLinearInstallation (Figure 1). An installation must be associated with another sampling feature that "contains" it. For driven piles, this containing feature is a Sounding - defined as a sampling feature created by inserting a probe or tool into the ground. In this case, the "tool" is the pile itself, and the Sounding represents the space surrounding the pile. Both Sounding and the pile installation objects are modeled geometrically in DIGGS as lines. Figure 2 shows the relation of a sounding to a driven pile and illustrates the geometric properties common to both the Sounding and all specialized pile objects.

Both Sounding and pile objects inherit from AbstractLinearSamplingFeature and share mandatory geometry properties:

- referencePoint: The coordinates of the top of the feature
- centerLine: In this case defined by two vertices - one at referencePoint, one at the bottom
- Linear spatial reference system: Enables positions to be referenced by depth from ground surface (Sounding) or distance from pile top (pile)

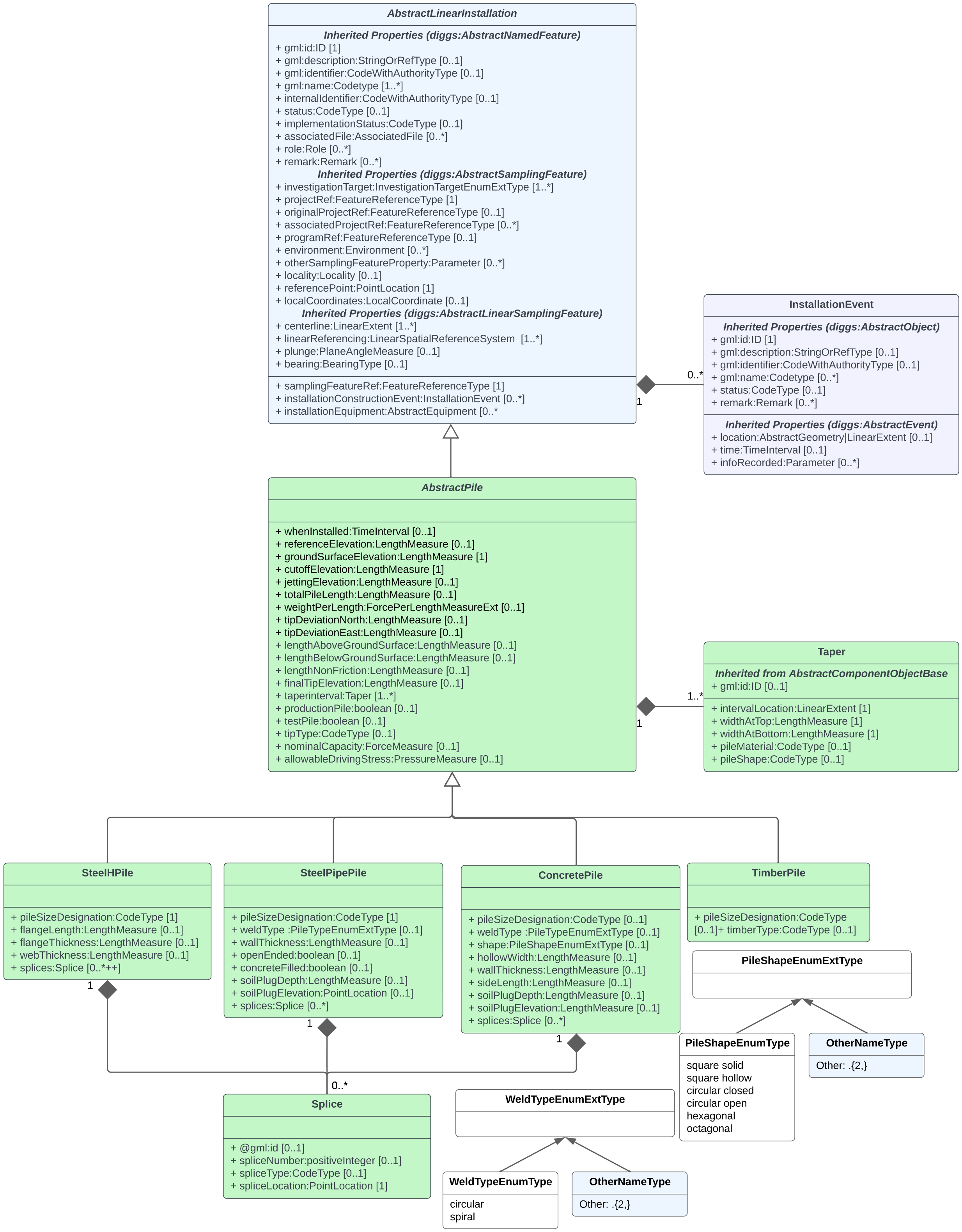


Figure 1. UML diagram illustrating the proposed objects for defining pile installation objects and their associated objects (green). :Light-blue colored objects have been previously developed. In DIGGS, piles are Installation objects that inherit properties from AbstractInstallation, which is a child of AbstractSampingFeature, the parent object of all sampling features. See text for further discussion

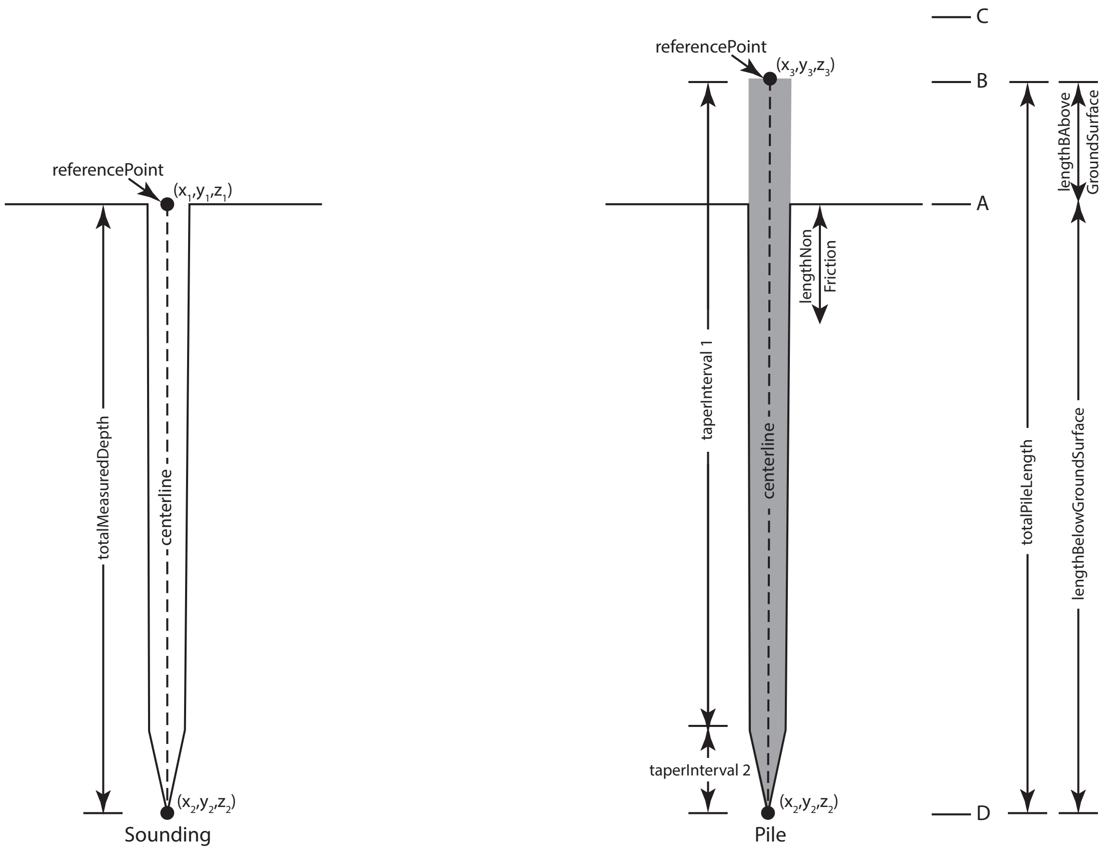


Figure 2. Diagram illustrating the geometric and shape properties of a DIGGS Sounding object and those associated with all specialized pile installation objects. Letters denote the following properties: A – groundSurfaceElevation, B – cutoffElevation, C – jettingElevation, D – finalTipElevation. Both Sounding and Pile objects contain two mandatory geometry properties: 1) a referencePoint point geometry object, and 2) a centerLine linestring geometry object. Both referencePoint and centerLine are represented by coordinate points that are defined in a 3D coordinate reference system (x,y,z)

Common properties for all pile objects include:

- **gml:id** (mandatory attribute) an identifier that complies with NCNAME format and that is unique within a DIGGS instance
- **gml:name** (at least one mandatory) a name identifier
- **investigationTarget** (mandatory) A feature or domain of interest for the investigation(e.g., "Deep Foundation”)
- **projectRef** (required) Project reference (projectRef)
- **samplingFeatureRef** (mandatory) a reference poin=ting to the gml:id of the containing sampling feature

This structure provides a complete framework for defining:

- Unique identification
- Naming and documentation
- Spatial referencing
- Linear geometry representation

- Installation within other features

The following sections detail the specialized pile objects available for describing different pile types.

ConcretePile

The ConcretePile object is used to describe installed piles composed of concrete. In addition to the inherited properties from AbstractPile, ConcretePile contains the following properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_ConcretePile.html):

- **pileSizeDesignation** (optional): A code or name identifying the pile size and other shape parameters. Typically includes diameter and weight/unit length parameters. Intended to come from a controlled list of terms.
- **shape** (optional): The shape of the pile cross section. Values from an enumerated list include:
    - circular closed: A circular pile with a closed cross section
    - circular open: A circular pile with an open cross section
    - hexagonal: A pile with a hexagonal cross section
    - octagonal: A pile with an octagonal cross section
    - square hollow: A square pile with a hollow cross section
    - square solid: A square pile with a solid cross section
- **hollowWidth** (optional): Width of the hollow center of the pile
- **wallThickness** (optional): Thickness of the pile wall
- **sideLength** (optional): Length of one side for square or hexagonal piles
- **soilPlugDepth** (optional): Depth of the soil plug inside the pile
- **soilPlugElevation** (optional): Elevation of the top of the soil plug
- **splices** (optional): List of splice objects that define the physical connections between pile segments

The ConcretePile object provides a complete framework for describing the geometry, dimensions, and construction details specific to concrete piles, while inheriting all the common pile properties defined in AbstractPile such as installation data, elevations, and spatial references.

SteelHPile

The SteelHPile object is used to describe installed H-shaped steel piles. In addition to the inherited properties from AbstractPile, SteelHPile contains the following properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_SteelHPile.html):

- **pileSizeDesignation** (mandatory): A code or name identifying the pile size and shape parameters. Typically references standard H-pile designations (e.g., "HP 200 x 64"). Intended to come from a controlled list of terms such as ASTM A6 H-Piling specifications.

- **weldType** (optional): The type of weld used on the pile. Values from an enumerated list include:

    - circular
    - spiral

- **flangeLength** (optional): Length of the pile flange
- **flangeThickness** (optional): Thickness of the pile flange
- **webThickness** (optional): Thickness of the pile web
- **splices** (optional): List of splice objects that define the physical connections between pile segments

The SteelHPile object provides a comprehensive framework for describing the geometry and construction details specific to H-shaped steel piles, while inheriting all the common pile properties defined in AbstractPile.

SteelPipePile

The SteelPipePile object is used to describe installed steel pipe piles. In addition to the inherited properties from AbstractPile, SteelPipePile contains the following properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_SteelPipePile.html):

- **pileSizeDesignation** (mandatory): A code or name identifying the pile size and shape parameters. Typically includes diameter and weight/unit length specifications. Intended to come from a controlled list of terms.
- **wallThickness** (optional): The thickness of the pipe wall
- **openEnded** (mandatory): Boolean value indicating whether the pipe is open ended (true) or closed ended (false)
- **concreteFilled** (optional): Boolean value indicating whether the pile is filled with concrete (true) or not (false)
- **soilPlugDepth** (optional): Depth of the soil plug inside the pile
- **soilPlugElevation** (optional): Elevation of the top of the soil plug
- **splices** (optional): List of splice objects that define the physical connections between pile segments

The SteelPipePile object provides a detailed framework for describing the geometry, construction details, and fill conditions specific to steel pipe piles, while inheriting all the common pile properties defined in AbstractPile.

TimberPile

The TimberPile object is used to describe installed piles composed of wood. In addition to the inherited properties from AbstractPile, TimberPile contains the following properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_TimberPile.html):

- **pileSizeDesignation** (optional): A code or name identifying the pile size and shape parameters. Typically includes diameter and length specifications. Intended to come from a controlled list of terms.
- **timberType** (optional): A code describing the type of timber used to construct the pile

The TimberPile object provides a straightforward framework for describing timber piles while inheriting all the common pile properties defined in AbstractPile. Its simpler property set reflects the more uniform nature of timber pile construction compared to other pile types.

Equipment objects

All equipment used in pile driving activities derives from AbstractPilingEquipment (see Figure 3), which inherits properties from AbstractEquipment. The following equipment objects have been defined to support pile driving activities:

PileDriveHammer

The PileDriveHammer object describes equipment used to drive piles by impacting the top of the pile. In addition to inherited properties from AbstractEquipment, PileDriveHammer contains the following optional properties (complete online documentation at https:://diggsml.org/docs/latest/Piling_xsd_Element_diggs_PileDriveHammer.html):

- **hammerType**: A code describing the type of hammer being used (e.g., steam/air, diesel, hydraulic, vibratory)
- **hammerAction**: A code describing the type of action the hammer uses (e.g., "single acting", "double acting")
- **ramRatedEnergyMax/Min**: The maximum and minimum rated energy of the ram
- **ramWeight**: The weight of the ram or hammer weight
- **ratedStroke**: The rated stroke length of the hammer
- **totalHammerWeight**: The net weight of the hammer
- **cylinderWeight**: The weight of the cylinder (applicable to double and differential acting hammers)
- **helmetWeight**: The weight of the helmet or anvil, including weight of the striker plate
- **pistonAreaDblActing**: The area of the piston for a double acting hammer
- **smallPistonAreaDifActing**: The area of the small piston for a differential acting hammer
- **blowsPerMinuteMin/Max**: The minimum and maximum blows per minute the hammer can deliver
- **strikerPlate**: Reference to an associated StrikerPlate object
- **hammerCushion**: A property that contains one or more Cushion objects that describe the hammer cushion

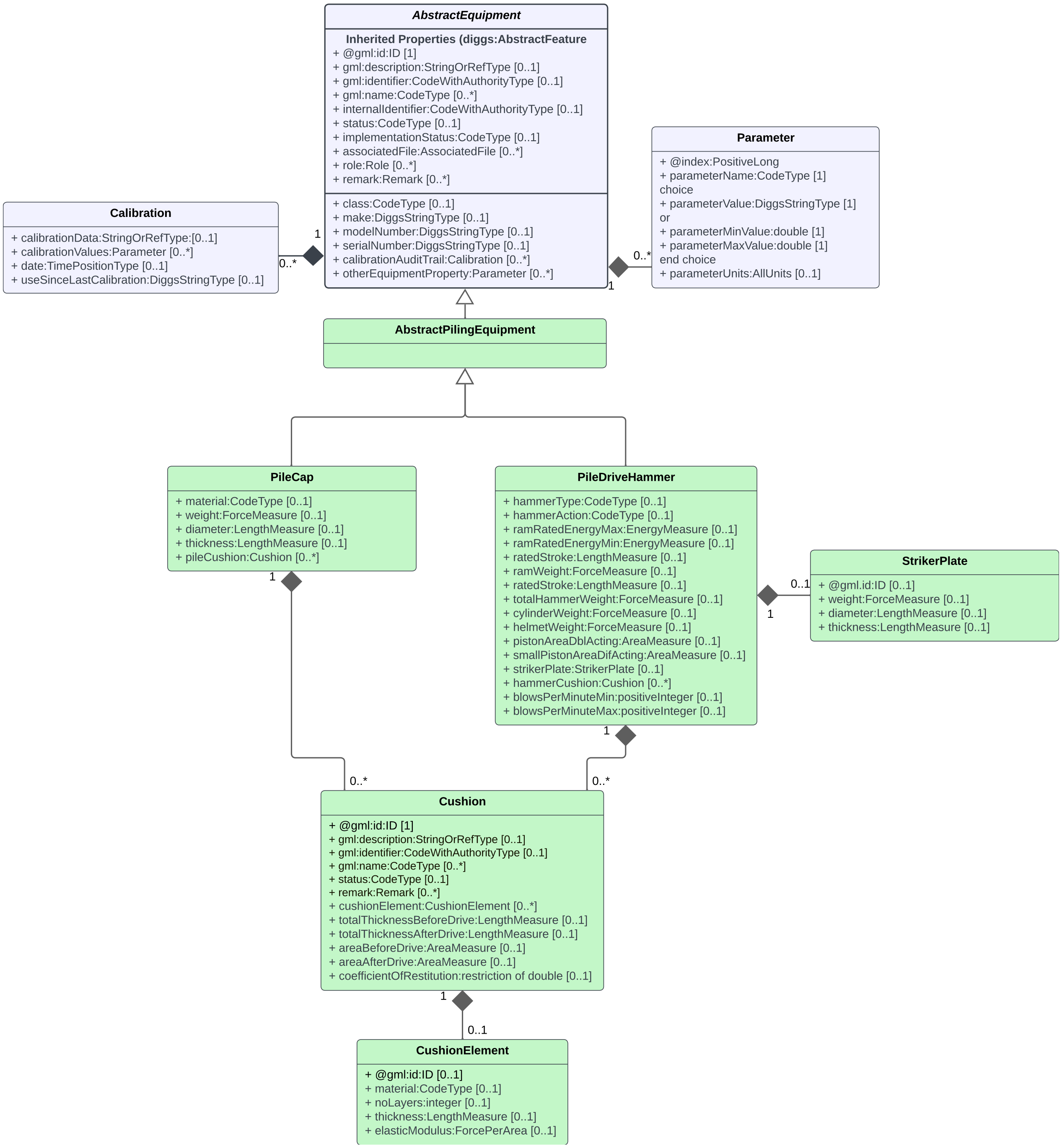


Figure 3. UML diagram illustrating proposed equipment objects use when storing and transferring data from pile driving activities (green). Light-blue colored objects have been previously developed. The newly proposed PileDriveHammer and PileCap objects inherit properties from their parent AbstractEquipment object.

PileCap

The PileCap object describes a cap placed on the top of the pile to protect it from damage during driving and distribute the force of the hammer. In addition to inherited properties, PileCap contains the following optional properties (complete online documentation at =https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_PileCap.html):

- **material**: A code describing the material the pile cap is made of
- **weight**: The weight of the pile cap
- **diameter**: The diameter of the pile cap
- **thickness**: The thickness of the pile cap
- **pileCushion**: A property that contains more Cushion objects that describe the pile cushion

Cushion

The Cushion object describes a compressible material placed between the hammer and the pile or between the pile and pile cap to distribute impact force and reduce damage. The Cushion object contains the following properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_Cushion.html):

- **cushionElement**: A property that contains one or more CushionElement objects that describe individual layers or components of the cushion
- **totalThicknessBeforeDrive**: The total thickness of the cushion before driving begins
- **totalThicknessAfterDrive**: The total thickness of the cushion after driving is complete
- **areaBeforeDrive**: The area of the cushion before driving begins
- **areaAfterDrive**: The area of the cushion after driving is complete
- **coefficientOfRestitution**: A value between 0 and 1 describing the energy returned after impact (1 is perfectly elastic, 0 is perfectly plastic)

CushionElement

The CushionElement object describes one element or layer of a cushion. It contains the following optional properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_CushionElement.html):

- **material**: The material the cushion element is made of
- **noLayers**: The number of layers of this element in the cushion
- **thickness**: Thickness of the cushion element
- **elasticModulus**: The elastic modulus of the cushion element

StrikerPlate

The StrikerPlate object describes a plate placed between the hammer and the pile to distribute the impact force. It contains the following optional properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_StrikerPlate.html)::

- **weight**: The weight of the striker plate
- **diameter**: The diameter of the striker plate
- **thickness**: The thickness of the striker plate

All equipment objects inherit common properties from AbstractFeature through AbstractEquipment, including:

- Unique identifier (gml:id)

- Names and descriptions
- Implementation status
- Equipment specifications (make, model, serial number)
- Calibration history
- Associated files and remarks

Activity objects

All of the information about the process of pile installation by driving is contained within activity objects that reference the pile being installed. This is done through the PileDrivingActivity object and its child objects.

PileDrivingActivity

The PileDrivingActivity object incorporates all of the activities of pile driving. It inherits from AbstractConstructionActivity and its associated objects (Figure 4) and contains the complete record of pile installation data. Each installed pile is associated with one PileDrivingActivity object, though this object can contain multiple PileDrivingRecord and PDARecord objects to document the full installation process.

PileDrivingActivity contains the following optional properties (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_PileDrivingActivity.html):

- **totalDrivenLength**: Total length of pile driven below ground surface
- **preDrillDepth** and **preDrillDiameter**: Dimensions of any pre-drill hole
- **plumbCheck**: Boolean indicating if verticality was checked
- **plumbCheckDirection**: Direction of plumb check relative to north
- **hammer**: Reference to the **PileDriveHammer** equipment used
- **pileCap**: Reference to the **PileCap** equipment used
- **totalLengthPlacedInLeads**: Length of pile placed in leads before driving
- **safety**: Boolean indicating whether safety protocols were followed
- **lastBlowsData**: Data from final set of hammer blows including:
  - **lastBlowsDistance**: Distance driven during final blows
  - **blowCount**: Number of blows in final set
  - **averageStrokeLength**: Average hammer stroke length for final set
- **pileDrivingRecord**: Collection of **PileDrivingRecord** objects containing manual or Saximeter records
- **pdaRecord**: Collection of **PDARecord** objects containing dynamic test data including:

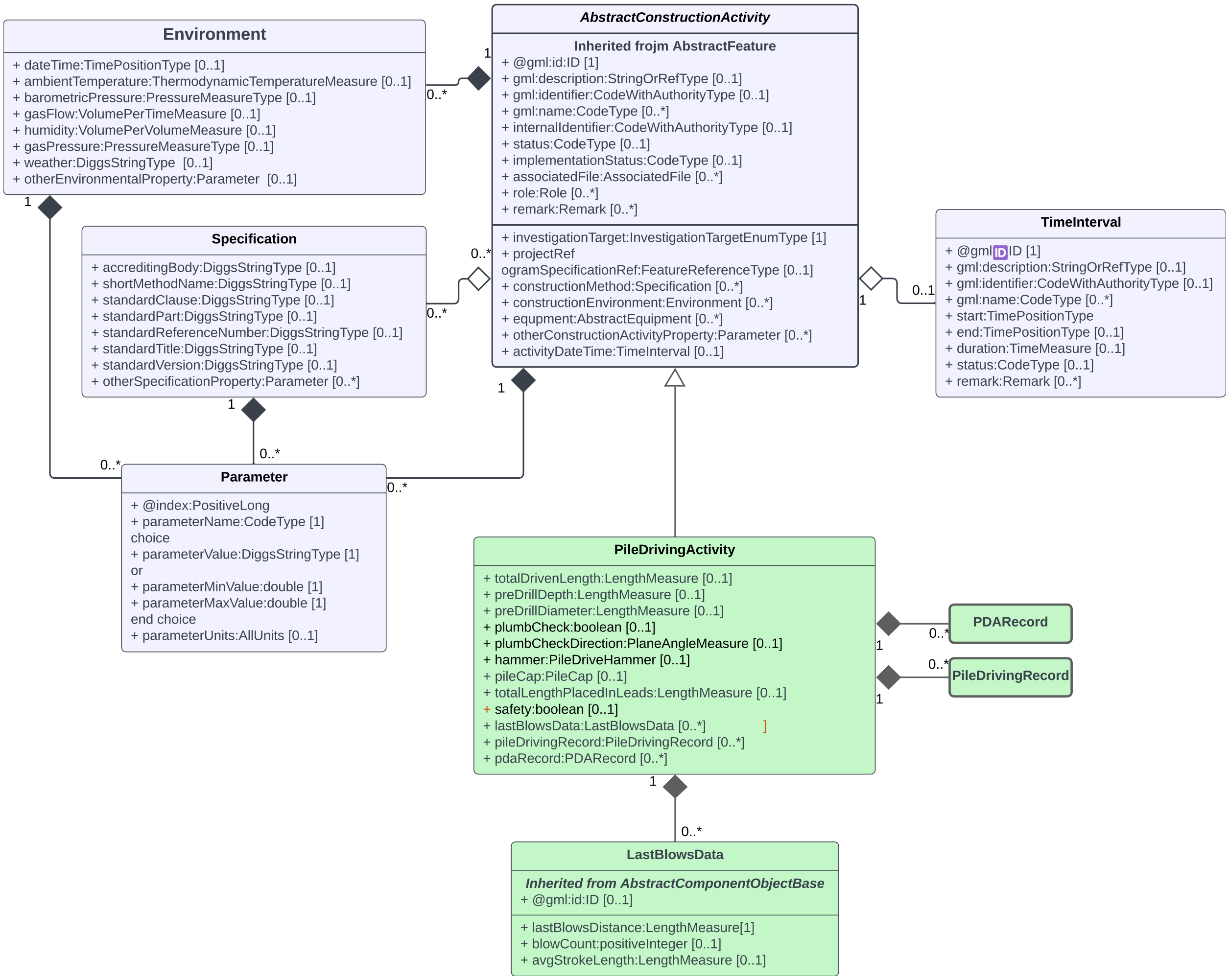


Figure 4. UML diagram illustrating the proposed PileDrivingActivity object and associated objects (green). Light-blue colored objects have been previously developed. PileDrivingActivity inherits properties from AbstractConstructionActivity and contains two objects (PDARecord, and PileDrivingRecord, detailed below) that contain the data collected during installation of the pile.

Details of the PileDrivingRecord and PDARecord objects are discussed below. They, along with PileDrivingActivity provide a comprehensive structure that enables complete documentation of the pile installation process, from equipment specifications through final driving data, in a standardized format suitable for data exchange and analysis.

PileDrivingRecord

The PileDrivingRecord object captures manual or Saximeter measurements taken during pile driving. Like other measurement objects in DIGGS (e.g., Test), PileDrivingRecord contains mandatory location information (pileTipLocation) and results (pileDrivingRecordResults) that follow the GML coverage model (Figure 5).

Key properties include (complete online documentation at https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_PileDrivingRecord.html):

- **recordType**: Indicates if data is from manual observations or Saximeter (from enumerated list)

- **hammerRef/pileCapRef**: References to PileDriveHammer and PileCap objects used during measurement
- **hammerCushionRef/pileCushionRef**: References to Cushion objects used during measurement
- **driveInterval**: Depth interval associated with the record
- **initiationTime/endTime/totalElapsedTime**: Timing of driving sequence
- **associatedPDARecord**: Boolean indicating if PDA testing was performed
- **hammerStartSetting/hammerEndSetting**: Initial and final hammer energy settings
- **pressureAtHammer**: Operating pressure at hammer during driving

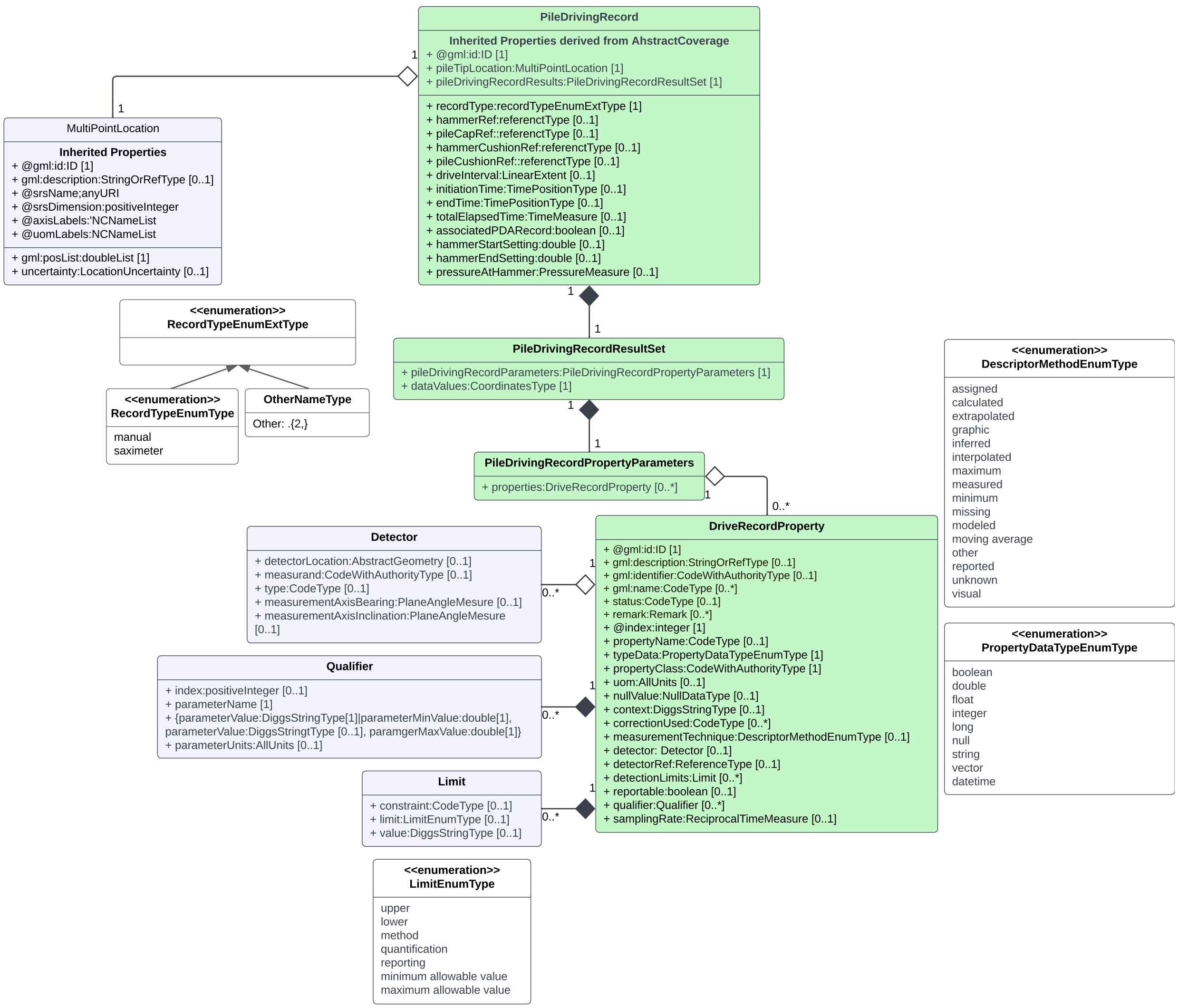


Figure 5. UML diagram illustrating the proposed PileDrivingRecord object and associated objects (green). Light-blue colored objects have been previously developed. The PileDrivingRecord object is structurally similar to other measurement objects, like a Test, where properties observed during pile driving are defined in the DriveRecordProperty object and the actual results recorded in the dataValues property of the PileDrivingRecordResultSet object. See text for further discussion..

The actual measurements are stored in the PileDrivingRecordResultSet object, which contains.

- **pileDrivingRecordParameters**: Collection of DriveRecordProperty objects that define the properties being measured

- **dataValues**: The measured values in a structured data block

Complete online documentation for this object can be found at: https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_ PileDrivingRecordResultSet.html.

The DriveRecordProperty objects are critical for standardization and interoperability. Each property must have:

- **propertyName**: Local name/code used by data provider
- **typeData**: Data type (double, integer, string, etc.)
- **propertyClass**: Standard property identifier from DIGGS dictionary
- **uom**: Unit of measure (following the Energistics Units of Measurement dictionary)

To ensure interoperability, the propertyClass element must use a codeSpace value referencing the DIGGS pile measurement properties dictionary (https://diggsml.org/def/codes/DIGGS/0.1/pil_properties.xml). This dictionary defines standard terms for common pile driving measurements including:

- **blow_count:** Number of hammer strikes per penetration increment
- **pen_increment**: Distance driven for given blow count
- **pen_per_blow**: Penetration per individual blow
- **stroke**: Height of hammer fall
- **energy**: Energy delivered to pile
- **bearing**: Pile bearing capacity at tip depth
- **pressure**: Hammer operating pressure
- **time**: Time of measurement

This standardized property system enables interoperability between different data providers and analysis tools while maintaining ability to expand the allowable properties without schema changes and to provide flexibility for local naming conventions through propertyName.

PDARecord

The PDARecord object captures measurements from Pile Dynamic Analysis (PDA) testing. While structurally like PileDrivingRecord, it includes additional properties specific to PDA analysis (Figure 6; complete online documentation can be found at: https://diggsml.org/docs/latest/Piling_xsd_Element_diggs_ PDARecord.html). These include:

Pile Dimensions and Material Properties:

- **effectiveLength**: The length of the pile below gages (LE
- **crossSectionAreaAtGages**: Cross-sectional area at gage location (AR)
- **elasticModulus**: Pile material elastic modulus (EM)
- **pileUnitWeight**: Pile material unit weight (SP)

Wave Properties:

- **waveSpeed/waveSpeedCalc**: Measured and calculated stress wave speeds
- **dampingConstant**: Case damping factor (Jc)
- **multiplicationFactor**: Capacity multiplication factor for Jc > 0.9
- **distancePileTopToGage**: Distance from pile top to gage location

PDA Instrumentation:

The pdaInfo property contains configuration details through three specialized objects:

- **PDAAccelerometer**
  - **serialNo**: Instrument ID
  - **calibrationConstant**: Raw reading conversion factor

- **PDAStrainTransducer**
  - **serialNo**: Instrument ID
  - **calibrationConstant**: Calibration factor

- **PDAConnectorCable**
  - **serialNo**: Cable identifier

Like PileDrivingRecord, measurement results are stored in PDARecordResultSet using standardized property definitions from the DIGGS dictionary. The dictionary includes PDA-specific measurements like RMX (maximum Case Method capacity), CSX (maximum compression strength), TSX (maximum tension strength), and EMX (maximum observed energy). These can be recorded as individual values or statistical aggregates over depth intervals.

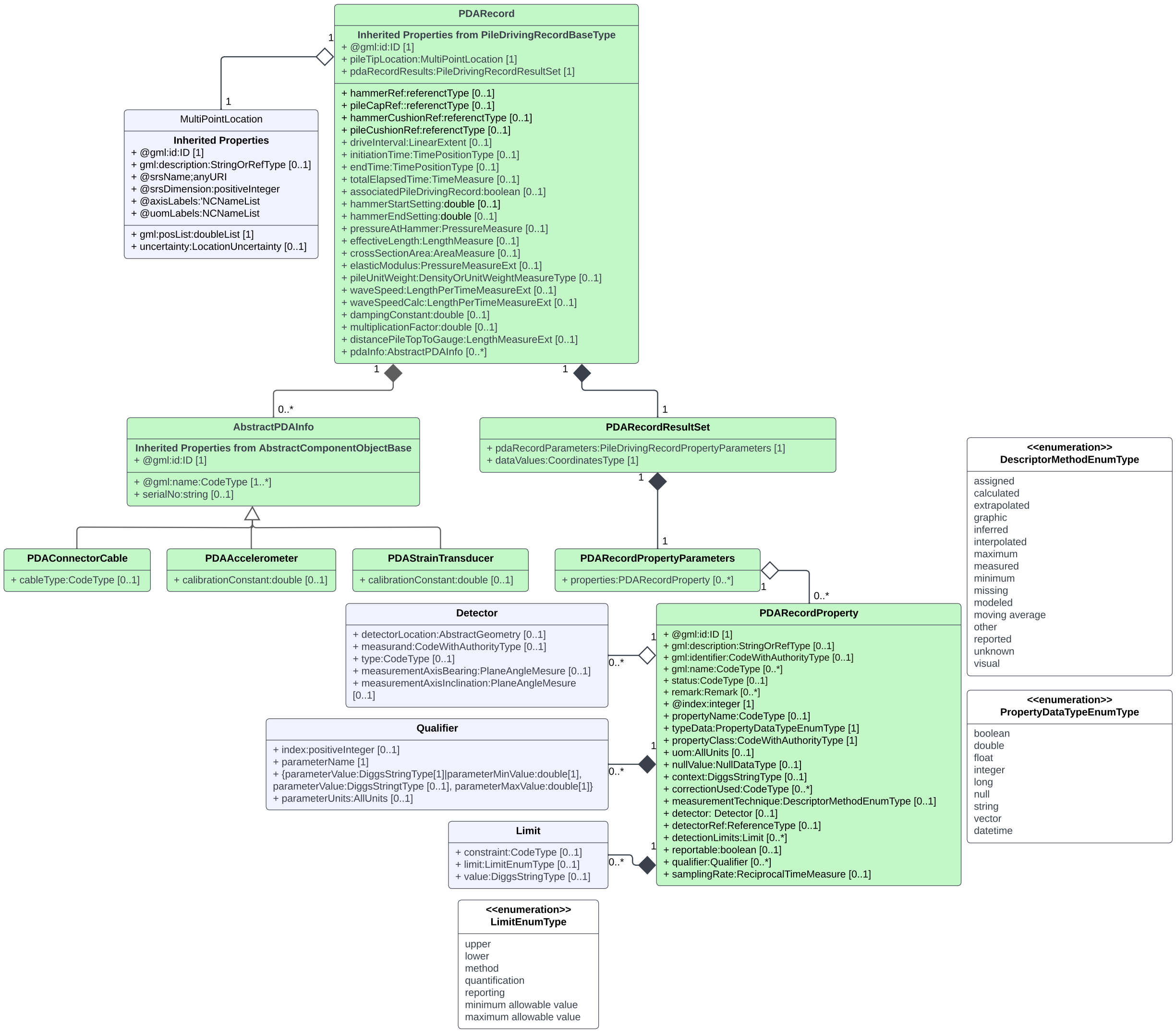
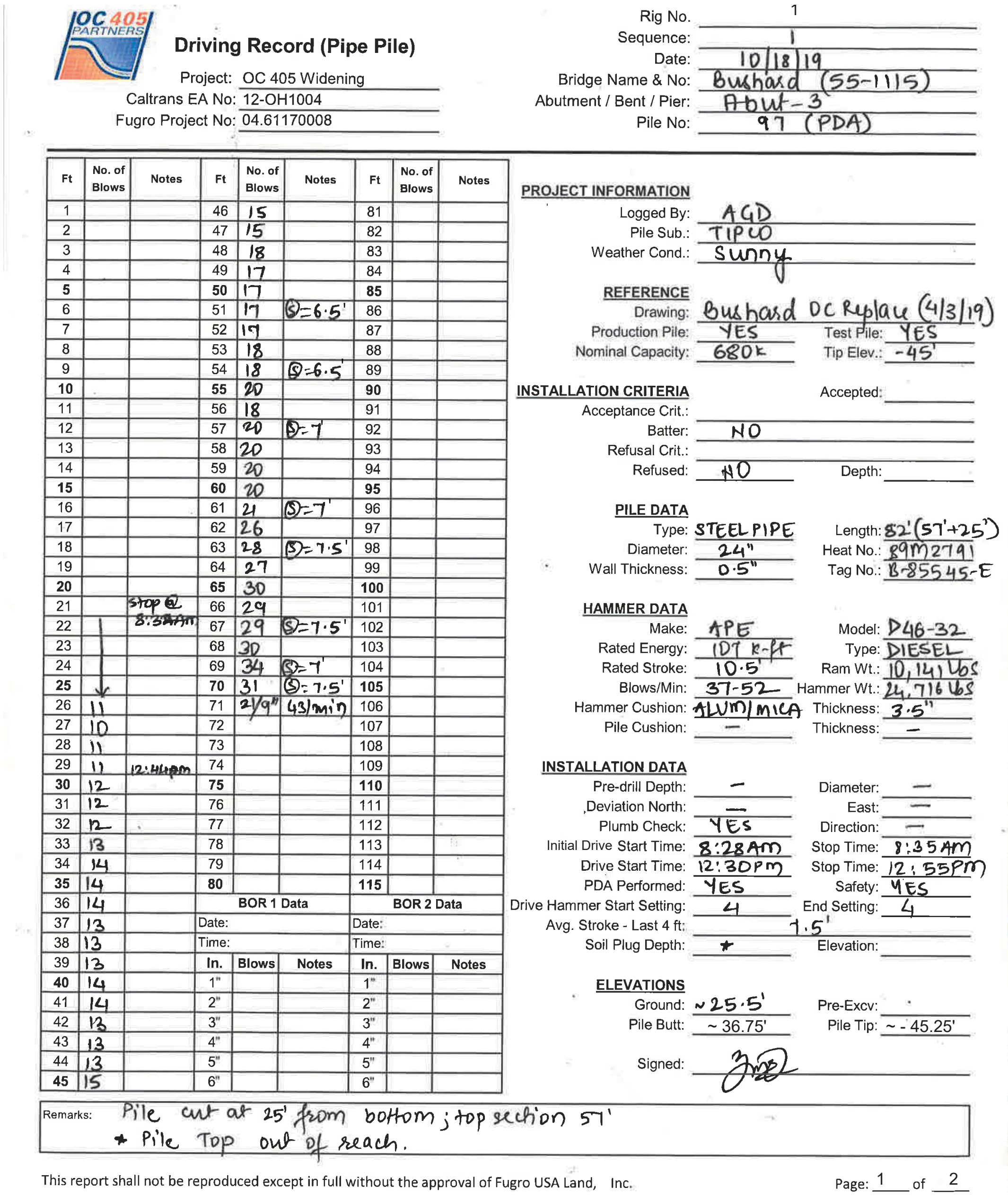


Figure 6. UML diagram illustrating the proposed PDARecord object and associated objects (green). Light-blue colored objects have been previously developed. The PDARecord object is structurally similar to other measurement objects, like a Test, where properties observed during pile driving are defined in the PDARecordProperty object and the actual results recorded in the dataValues property of the PDARecordResultSet object. See text for further discussion.

Implementation Example

In this section, we demonstrate how reported pile driving data would be mapped into DIGGS objects to produce a DIGGS instance document that encodes the pile driving data in a standardized way. Here we focus only on data relevant to the sampling feature objects and the pile driving activity. The full instance example (and others as they are developed) can be found at: https://github.com/DIGGSml/diggs-examples in the Piling Development folder.



Driving Record (Pipe Pile)

OC 405 PARTNERS

Project: OC 405 Widening
Caltrans EA No: 12-OH1004
Fugro Project No: 04.61170008

Rig No. 1
Sequence: 1
Date: 10/18/19
Bridge Name & No: Bushard (55-1115)
Abutment / Bent / Pier: Abut-3
Pile No: 97 (PDA)

Ft	No. of Blows	Notes	Ft	No. of Blows	Notes	Ft	No. of Blows	Notes
1			46	15		81		
2			47	15		82		
3			48	18		83		
4			49	17		84		
5			**50**	17		**85**		
6			51	17	S=6.5'	86		
7			52	19		87		
8			53	18		88		
9			54	18	S=6.5'	89		
10			**55**	20		**90**		
11			56	18		91		
12			57	20	S=7	92		
13			58	20		93		
14			59	20		94		
15			**60**	20		**95**		
16			61	21	S=7'	96		
17			62	26		97		
18			63	28	S=7.5'	98		
19			64	27		99		
20			**65**	30		**100**		
21		Stop @	66	29		101		
22		8:35AM	67	29	S=7.5'	102		
23			68	30		103		
24			69	34	S=7'	104		
25			**70**	31	S=7.5'	**105**		
26	11		71	21/9"	43/min	106		
27	10		72			107		
28	11		73			108		
29	11	12:44pm	74			109		
30	12		**75**			**110**		
31	12		76			111		
32	12		77			112		
33	13		78			113		
34	14		79			114		
35	14		**80**			**115**		
36	14							
37	13							
38	13							
39	13							
40	14							
41	14							
42	13							
43	13							
44	13							
45	15							

BOR 1 Data			BOR 2 Data		
Date:			Date:		
Time:			Time:		
In.	Blows	Notes	In.	Blows	Notes
1"			1"		
2"			2"		
3"			3"		
4"			4"		
5"			5"		
6"			6"		

PROJECT INFORMATION
Logged By: AGD
Pile Sub.: TIPCO
Weather Cond.: Sunny

REFERENCE
Drawing: Bushard OC Replace (4/3/19)
Production Pile: YES Test Pile: YES
Nominal Capacity: 680K Tip Elev.: -45'

INSTALLATION CRITERIA
Accepted:
Acceptance Crit.:
Batter: NO
Refusal Crit.:
Refused: NO Depth:

PILE DATA
Type: STEEL PIPE Length: 82' (57'+25')
Diameter: 24" Heat No.: 89M2791
Wall Thickness: 0.5" Tag No.: B-85545-E

HAMMER DATA
Make: APE Model: D46-32
Rated Energy: 107 k-ft Type: DIESEL
Rated Stroke: 10.5' Ram Wt.: 10,141 lbs
Blows/Min: 37-52 Hammer Wt.: 24,716 lbs
Hammer Cushion: ALUM/MICA Thickness: 3.5"
Pile Cushion: — Thickness: —

INSTALLATION DATA
Pre-drill Depth: — Diameter: —
Deviation North: — East: —
Plumb Check: YES Direction: —
Initial Drive Start Time: 8:28AM Stop Time: 8:35AM
Drive Start Time: 12:30PM Stop Time: 12:55PM
PDA Performed: YES Safety: YES
Drive Hammer Start Setting: 4 End Setting: 4
Avg. Stroke - Last 4 ft: 7.5'
Soil Plug Depth: * Elevation:

ELEVATIONS
Ground: ~25.5' Pre-Excv:
Pile Butt: ~ 36.75' Pile Tip: ~ - 45.25'

Signed:

Remarks: Pile cut at 25' from bottom; top section 57'
* Pile Top out of reach.

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Figure 7. Pile driving record report for Pile No. 97 at Abutment 3 for the Bushard Street overcrossing in southern California (OC 405 Partner JV Design Build Team, 2019). This data sheet records manually counted hammer blows at 1 ft depth intervals, along with metadata associated with the pile driving activity.

Figure 7 is a pile driving record for a steel pipe pile (Pile No. 97) installed at Abutment 3 of the Bushard Street overcrossing in southern California (OC 405 Partner JV Design Build Team, 2019). This record provides hammer blow data collected when the pile was being installed along with metadata about the pile and equipment used. These data will be the basis for our example instance.

Encoding the sounding and pile objects

First, we create a Sounding object, which represents the space through which the pile was driven, with its reference point at ground surface and extending to the final pile tip elevation. We start first with the basic information:

```
<samplingFeature>
   <Sounding gml:id="s97">
      <gml:name>97</gml:name>
      <investigationTarget>Deep Foundation</investigationTarget>
      <projectRef xlink:href="#CT_12-OH1004"/>
```

Sounding, as with many other objects in DIGGS, requires an id attribute whose value must be unique within the XML instance. In this case it is created from the pile name, and for convenience, we give the sounding the same name as the pile. The <projectRef> element points to a Project object that provides additional information about the project that installed the pile. A fully encoded Project object is included in the example instance file referenced above.

Next, we define the referencePoint and centerLine spatial reference information:

```
<referencePoint>
   <PointLocation gml:id="rps97" srsName="https://www.opengis.net/def/crs-
compound?1=http://www.opengis.net/def/crs/EPSG/0/26911%262=http://www.opengis.net/def/crs/EPSG/0/6360”
srsDimension="3">
      <gml:pos>380000 3750000 25.5</gml:pos>
   </PointLocation>
</referencePoint>

<centerLine>
   <LinearExtent gml:id="cls97" srsName=" https://www.opengis.net/def/crs-
compound?1=http://www.opengis.net/def/crs/EPSG/0/26911%262=http://www.opengis.net/def/crs/EPSG/0/6360”
srsDimension="3">
      <gml:posList>380000 3750000 25.5 380000 3750000 -45.75</gml:posList>
   </LinearExtent>
</LinearExtent>
</centerLine>
```

The referencePoint and centerLine properties are defined in a 3D coordinate system and the values of gml:pos and gml:PosList are tuples that represent the x, y, and z coordinates. The long URL value of the srsName attribute in PointLocation and LinearExtent calls a web service that returns a GML definition for a compound coordinate reference system where the horizontal coordinates are in NAD83 / UTM zone 11N (EPSG:26911) and the vertical coordinate is NAVD88 height (ftUS) (EPSG:6360), thus readily providing receiving applications a standardized CRS definition and coordinate units.

Once the coordinates of the Sounding are reported, we finish the Sounding by defining a linear referencing system, that defines how are depths are measured:

```
<linearReferencing>
  <LinearSpatialReferenceSystem gml:id="lsrs97">
    <gml:identifier codeSpace="CT">CT-lsrs97</gml:identifier>
    <glr:linearElement xlink:href="#cls97"/>
    <glr:lrm>
      <glr:LinearReferencingMethod gml:id="lrm-s97">
        <glr:name>chainage</glr:name>
        <glr:type>absolute</glr:type>
        <glr:units>ft</glr:units>
      </glr:LinearReferencingMethod>
    </glr:lrm>
  </LinearSpatialReferenceSystem>
</linearReferencing>
<totalMeasuredDepth uom="ft">70.75</totalMeasuredDepth>
```

This code defines the Sounding's centerline in the glr:linearElement property as the line that our depth measurements are tied to. The LinearReferencingMethod object's values indicate that coordinates on that line represent absolute distances from the centerline's origin and are in ft units.

Next we create a SteelPipePile object to represent the physical pile. Because a pile is a sampling feature in DIGGS, just like a Sounding, the XML structure of the basic information, spatial reference and linear referencing elements are the same as in Sounding (with different values of course). Looking at the basic information:

```
<samplingFeature>
  <SteelPipePile gml:id="p97">
    <gml:name>97</gml:name>
    <gml:name codeSpace="Heat No.">89M2791</gml:name>
    <gml:name codeSpace="Tag No.">B-85545-E</gml:name>
    <investigationTarget>Deep Foundation</investigationTarget>
    <projectRef xlink:href="#CT_12-OH1004"/>
```

we see that DIGGS allows for multiple names for an object. Thus, the Heat No. and Tag Name can also be encoded with the plan identifier for the pile (97).

Following encoding of the spatial reference and linear referencing information for the pile, in exactly the same way as the Sounding, we add the pile specifications from the "PILE DATA" section of the report:

```
<pileSizeDesignation>PP24X0.5"</pileSizeDesignation>
<wallThickness uom="in">0.5</wallThickness>
<openEnded>true</openEnded>
```

Following that, we encode the elevation and length data:

```
<groundSurfaceElevation uom="ft">25.5</groundSurfaceElevation>
<cutoffElevation uom="ft">6.75</cutoffElevation>
<totalPileLength uom="ft">82</totalPileLength>
<lengthAboveGroundSurface uom="ft">11.25</lengthAboveGroundSurface>
<lengthBelowGroundSurface uom="ft">70.75</lengthBelowGroundSurface>
<finalTipElevation uom="ft">-45.25</finalTipElevation>
```

For the pile's constant cross-section, we define a single taper interval:

```
<taperInterval>
  <Taper>
    <intervalLocation>
      <LinearExtent gml:id="p79-int1" srsName="#lsrp97" srsDimension="1">
        <gml:posList>0 82</gml:posList>
      </LinearExtent>
    </intervalLocation>
    <widthAtTop uom="in">24</widthAtTop>
    <widthAtBottom uom="in">24</widthAtBottom>
  </Taper>
```

Note that the coordinates for the extent of the taper interval (0 82) are 1D coordinates representing the interval from 0 to 82 ft and that the srsName attribute points to the id of the linear spatial reference system that we defined for the the pile (lsr97.

Finally, we add the structural information and splice data:

```
<productionPile>true</productionPile>
<testPile>true</testPile>
<nominalCapacity uom="klbf">680</nominalCapacity>
<allowableDrivingStress uom="kpsi">45</allowableDrivingStress>
<splices>
  <Splice>
    <spliceLocation>
      <PointLocation gml:id="sp1" srsName="#lsrp97" srsDimension="1">
        <gml:pos>57</gml:pos>
      </PointLocation>
    </spliceLocation>
  </Splice>
</splices>
```

This completes the encoding of the physical pile object in compliance with the schema structure. The next sections cover the PileDrivingActivity and associated records.

Encoding the PileDrivingActivity object

The PileDrivingActivity object contains all information about the pile installation process, including equipment used and measurements taken. We start with the basic structure and references:

```
<constructionActivity>
  <PileDrivingActivity gml:id="pip97">
    <investigationTarget>Deep Foundation</investigationTarget>
    <projectRef xlink:href="#CT_12-OH1004"/>
    <samplingFeatureRef xlink:href="#p97"/>
```

Note that the samplingFeatureRef property points to the id of the SteelPipePile. This ties the PileDrivingActivity to that specific pile object.

Next we record the environmental conditions, timing. And total length of the activity:

```
<constructionEnvironment>
  <Environment gml:id="coe">
    <weather>sunny</weather>
  </Environment>
</constructionEnvironment>
<activityDateTime>
  <TimeInterval gml:id="act">
    <start>2019-10-18T12:30:00</start>
    <end>2019-10-18T12:55:00</end>
  </TimeInterval>
</activityDateTime>
<totalDrivenLength uom="ft">70.75</totalDrivenLength>
```

Next, we define the hammer equipment used for driving:

```
<hammer>
  <PileDriveHammer gml:id="APE_D46-32">
    <make>APE</make>
    <modelNumber>D46-32</modelNumber>
    <hammerType>diesel</hammerType>
    <ramRatedEnergyMax uom="1000 lbf.ft">107</ramRatedEnergyMax>
    <ramWeight uom="lbf">10141</ramWeight>
    <ratedStroke uom="ft">10.5</ratedStroke>
    <totalHammerWeight uom="lbf">24716</totalHammerWeight>
    <hammerCushion>
      <Cushion gml:id="Cushion1">
        <cushionElement>
          <CushionElement>
```

```xml
                <material>Aluminum/Mica</material>
                <thickness uom="in">3.5</thickness>
              </CushionElement>
            </cushionElement>
          </Cushion>
        </hammerCushion>
        <blowsPerMinuteMin>37</blowsPerMinuteMin>
        <blowsPerMinuteMax>52</blowsPerMinuteMax>
    </PileDriveHammer>
</hammer>
```

We record data from the final set of blows:

```xml
<lastBlowsData>
    <LastBlowsData>
        <lastBlowsDistance uom="ft">4</lastBlowsDistance>
        <averageStrokeLength uom="ft">7.5</averageStrokeLength>
    </LastBlowsData>
</lastBlowsData>
```

And finally, we include the detailed driving records:

```xml
<pileDrivingRecord>
    <!-- PileDrivingRecord object detailed in next section -->
</pileDrivingRecord>
<pdaRecord>
    <!-- PDARecord object detailed in next section -->
</pdaRecord>
```

The PileDrivingActivity object acts as a container for all data related to the pile installation, linking together the physical pile object, equipment specifications, and measurement records that will be detailed in the following sections.

PileDrivingRecord

Now we'll encode the pile driving record data shown in Figure 7. The PileDrivingRecord object captures the manual blow counts as well as timing and hammer settings during installation. We begin with the measurement data:

```xml
<pileDrivingRecord>
    <PileDrivingRecord gml:id="dr1">
        <pileTipLocation>
            <MultiPointLocation gml:id="dr1-l">
                <gml:posList srsName="#lsrs97" srsDimension="1">
                    22 23 24 25 26 27 28 29 30 31 32 33...70 70.75
                </gml:posList>
            </MultiPointLocation>
        </pileTipLocation>
        <pileDrivingRecordResults>
            <PileDrivingRecordResultSet>
                <pileDrivingRecordParameters>
                    <PileDrivingRecordPropertyParameters gml:id="dr1p">
                        <properties>
                            <DriveRecordProperty index="1" gml:id="p1">
                                <typeData>integer</typeData>
                                <propertyClass codeSpace="https://diggsml.org/def/codes/DIGGS/0.1/pil_properties.xml">
                                    blow_count
                                </propertyClass>
                            </DriveRecordProperty>
                            <DriveRecordProperty index="2" gml:id="p2">
                                <typeData>double</typeData>
                                <propertyClass codeSpace="https://diggsml.org/def/codes/DIGGS/0.1/pil_properties.xml">
                                    pen_increment
                                </propertyClass>
                                <uom>ft</uom>
                            </DriveRecordProperty>
                        </properties>
```

```
        </PileDrivingRecordPropertyParameters>
      </pileDrivingRecordParameters>
      <dataValues>
        8,1,
        9,1,
        9,1,
        ...
        21,0.75,
      </dataValues>
    </PileDrivingRecordResultSet>
  </pileDrivingRecordResults>
```

The MultiPointLocation element defines the depths at which measurements were taken (22 ft to 70.75 ft), using the linear reference system defined in the Sounding object (lsrs97) rather than the SteelPipePile object, because that reference system has its origin at the ground surface. The pileDrivingRecordParameters element defines the structure of the recorded data through DriveRecordProperty objects. Here we have:

1. **blow_count**: Number of hammer blows (integer)
2. **pen_increment**: Distance driven for those blows (double, in feet)

The actual measurements appear in the dataValues element as comma-separated pairs with the values matching the DriveRecordProperty order, and each line associated with one depth value from MultiPointLocation, in depth order.

Finally, we record metadata about the driving process:

```
<recordType>manual</recordType>
<hammerRef xlink:href="#APE_D46-32"/>
<hammerCushionRef xlink:href="#Cushion1"/>
<driveInterval>
  <LinearExtent gml:id="di-97">
    <gml:posList srsName="#lsrs97" srsDimension="1">22 70.75</gml:posList>
  </LinearExtent>
</driveInterval>
<initiationTime>2019-10-18T12:30:00</initiationTime>
<endTime>2019-10-18T12:55:00</endTime>
<hammerStartSetting>4</hammerStartSetting>
<hammerEndSetting>4</hammerEndSetting>
```

The schema structure allows for a PileDrivingActivity to have more than one PileDrivingRecord to accommodate situations where pile driving might cease for a time to change hammer cushions or alter other drive procedures.

PDARecord

In addition to recording a manual PileDrivingRecord, the same pile was also instrumented for Pile Dynamic Analysis testing (Figure 8). The PDARecord object is used to capture the more detailed measurements from this test.:

EarthSpectives — Page 1

Case Method & iCAP® Results — PDIPLOT2 2017.2.58.3 - Printed 01-November-2019

OC405 WIDENING AT BUSHARD - ABUT 3 PILE 97 @ EOID — PP24X0.5", 82 FT, D46-32

OP: US — Date: 18-October-2019

AR: 36.91 in² — SP: 0.492 k/ft³

LE: 78.00 ft — EM: 30,000 ksi

WS: 16,807.9 f/s — JC: 0.70

RMX: Maximum Case Method Capacity (JC) — EMX: Maximum Energy

CSX: Compression Stress Maximum — STK: Hammer Stroke

TSX: Tension Stress Maximum - Full Record Search — BPM: Blows/Minute

BL#	Depth	BLC	TYPE	RMX	CSX	TSX	EMX	STK	BPM
	ft	bl/ft		kips	ksi	ksi	k-ft	ft	bpm
8	22.00	8	AV8	134	20.7	6.6	38.7	6.2	42
			MAX	184	28.9	9.0	70.9	8.8	51
			MIN	113	18.0	3.7	27.0	5.3	2
17	23.00	9	AV9	137	18.5	6.1	28.9	5.4	50
			MAX	147	19.8	7.0	34.0	5.8	51
			MIN	128	17.7	5.6	25.3	5.2	49
26	24.00	9	AV9	163	19.9	6.9	32.7	5.7	49
			MAX	186	20.9	7.6	35.4	5.9	51
			MIN	135	18.4	5.6	28.3	5.3	48
36	25.00	10	AV10	172	21.1	6.4	36.1	5.9	48
			MAX	187	22.7	7.3	39.9	6.4	50
			MIN	149	19.5	5.3	31.1	5.4	46
47	26.00	11	AV11	153	20.4	6.0	34.2	5.6	49
			MAX	168	22.3	7.3	39.3	6.2	52
			MIN	143	18.4	4.6	27.0	5.1	47
57	27.00	10	AV10	169	20.2	5.4	32.9	5.4	50
			MAX	217	22.2	6.8	39.0	6.0	52
			MIN	150	18.5	4.1	27.6	5.0	48
68	28.00	11	AV11	193	20.4	5.1	32.7	5.4	51
			MAX	229	21.8	6.0	35.4	5.7	52
			MIN	172	19.5	4.4	30.7	5.1	49
79	29.00	11	AV11	240	22.3	5.2	36.1	5.8	45
			MAX	278	26.3	6.6	48.1	6.8	51
			MIN	201	20.5	3.3	26.0	5.4	2
91	30.00	12	AV12	243	22.7	4.7	37.1	5.9	48
			MAX	270	24.1	5.6	41.5	6.3	50
			MIN	223	21.8	4.1	34.0	5.6	47
103	31.00	12	AV12	222	21.9	4.8	34.6	5.7	49
			MAX	243	23.6	5.7	38.2	6.1	51
			MIN	207	20.4	3.8	30.0	5.4	47
115	32.00	12	AV12	227	22.0	5.0	35.1	5.8	49
			MAX	253	23.4	6.0	39.3	6.1	50
			MIN	210	20.7	4.4	31.4	5.5	47
128	33.00	13	AV13	240	22.2	4.3	35.3	5.9	49
			MAX	258	25.5	5.9	44.1	6.7	50
			MIN	229	20.9	3.5	31.5	5.5	45

Figure 8. A portion of output from PDA testing on Pile No. 97 at Abutment 3 for the Bushard Street overcrossing in southern California (OC 405 Partner JV Design Build Team, 2019). This page shows computed stress and energy values (defined in the page header), blow count rate, and hammer stroke averaged over 1 ft intervals from pile tip depth of 22 ft to 33 ft, plus additional metadata relevant to the PDA analysis.

The PDARecord structure parallels PileDrivingRecord but includes additional properties specific to PDA analysis. In this case, the data presented is an aggregate of individual measurements averaged over 1 foot intervals. The object begins by recording the depth locations where measurements were recorded:

```
<pdaRecord>
  <PDARecord gml:id="pdar">
    <pileTipLocation>
      <MultiPointLocation gml:id="pda-1">
        <gml:posList srsName="#lsrs97" srsDimension="1">
          22 23 24 25...70 70.75
        </gml:posList>
      </MultiPointLocation>
    </pileTipLocation>
```

We then record the measurements in a similar structure to PileDrivingRecord, but with PDA-specific properties:

```
<pdaRecordResults>
  <PDARecordResultSet>
    <pdaRecordParameters>
      <PDARecordPropertyParameters gml:id="pda1p">
        <properties>
          <PDARecordProperty index="1">
            <typeData>integer</typeData>
            <propertyClass codeSpace="https://diggsml.org/def/codes/DIGGS/0.1/pil_properties.xml">
              bl_no
            </propertyClass>
          </PDARecordProperty>
          <!-- Additional properties for RMX, CSX, TSX, EMX, etc. -->
        </properties>
      </PDARecordPropertyParameters>
    </pdaRecordParameters>
    <dataValues>
      8,8,1,6.2,42,134,184,113,20.7,28.9,18,6.6,9,3.7,38.7,70.9,27,TRUE,
      17,9,1,5.4,50,137,147,128,18.5,19.8,17.7,6.1,7,5.6,28.9,34,25.3,TRUE,
      ...
    </dataValues>
  </PDARecordResultSet>
</pdaRecordResults>
```

The data values represent measurements including:

1. Blow number and count
2. Penetration per blow
3. Maximum Case Method capacity (RMX)
4. Compression stress (CSX)
5. Tension stress (TSX)
6. Observed energy (EMX)
7. Hammer stroke length
8. Blows per minute

Following the measurements, we report metadata including additional material and wave propagation properties used in PDA:

```
<effectiveLength uom="ft">78</effectiveLength>
<crossSectionAreaAtGages uom="in2">36.91</crossSectionAreaAtGages>
<elasticModulus uom="kpsi">30000</elasticModulus>
<pileUnitWeight uom="klbf/ft3">492</pileUnitWeight>
<waveSpeed uom="ft/s">16807.9</waveSpeed>
<dampingConstant>0.7</dampingConstant>
<distancePileTopToGage uom="ft">4</distancePileTopToGage>
```

Finally we specify the PDA instrumentation configuration:


```xml
<pdaInfo>
  <PDAAccelerometer>
    <gml:name>A3 (green)</gml:name>
    <serialNo>K11281</serialNo>
    <calibrationConstant>420</calibrationConstant>
  </PDAAccelerometer>
  <PDAAccelerometer>
    <gml:name>A4 (white)</gml:name>
    <serialNo>K11285</serialNo>
    <calibrationConstant>363</calibrationConstant>
  </PDAAccelerometer>
  <PDAStrainTransducer>
    <gml:name>F3 (green)</gml:name>
    <serialNo>S492</serialNo>
    <calibrationConstant>142</calibrationConstant>
  </PDAStrainTransducer>
  <PDAStrainTransducer>
    <gml:name>F4 (white)</gml:name>
    <serialNo>S493</serialNo>
    <calibrationConstant>143</calibrationConstant>
  </PDAStrainTransducer>
</pdaInfo>
```


Summary

This report presents the proposed extensions to the DIGGS standard to support driven pile installation data. The extensions were developed by the ASCE G-I Deep Foundation Special Project Working Group based on analysis of pile driving records from 18 State Departments of Transportation and data from a major southern California infrastructure project.

The schema extensions are currently included in DIGGS development schema repository at: https://github.com/DIGGSml/schema-dev/blob/main/Piling.xsd. It is now available for beta testing and is targeted for inclusion in the next formal version release. Schema documentation that includes these new extensions is located at: https://diggsml.org/docs/latest.

These schema extensions provide a comprehensive framework for encoding driven pile data through:

1. Installation objects for four pile types (concrete, steel-H, steel pipe, and timber), inheriting from a common AbstractPile base class that provides essential properties like geometry, spatial referencing, and metadata
2. Equipment objects describing pile driving tools including hammers, caps, cushions and striker plates, with detailed specifications for calibration, configuration and operation
3. Construction activity objects that capture both manual/Saximeter pile driving records and PDA (Pile Dynamic Analysis) data in a standardized format, linking physical pile objects, equipment specifications, and measurement data

The example implementation demonstrates how these schema extensions enable encoding of real-world pile driving data, including complex spatial referencing and equipment configurations. The standardized property system, that mirrors other measurement structures in DIGGS, ensures interoperability between different data providers while maintaining flexibility for local naming conventions.

These proposed extensions significantly enhance the DIGGS standard's capabilities for driven pile data exchange. By providing a complete and validated schema for pile installation data, they enable improved data management and analysis workflows across the geotechnical engineering community. Future proposed work includes pre-installation design specifications, cast-in-place piles, vibratory installations, composite piles, and post-installation testing.

References

OC 405 Partner JV Design Build Team, 2019, Bushard Abutments Driven Pile Plan, Rev 001: I-405 Improvement Project (Contract C-5-3843, 62 p.