ROCK GROUTING EXTENSIONS TO DIGGS

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ABSTRACT

DIGGS is an emerging XML-based data transfer standard designed to facilitate exchange of data within the geo-profession. DIGGS' development initially focused on geotechnical exploration (boring, cone sounding and test pit data, in-situ and laboratorytests) and is now being enhanced with foundation and ground improvement technology data sets.

As owners become more sophisticated, their expectations for data delivery in a timely fashion is ever increasing. Establishing industry standards for data exchange helps everyone in the deep foundation industry to meet these needs from the point of acquisition through storage. This common structure further allows experts at each step of the process to maximize their skills in handling and using this data for the betterment of the project and all team members involved, rather than spending time converting data sets into usable formats.

DFI Special Project fund supported a pilot effort to develop the extension of this data transfer format for rock grouting procedures as a model and educational tool. Currently, many of the steps required paper capture, downloading of data from loggers, translation in spreadsheets or CSV file formats, and manipulation from one software package to another to achieve the proper interpretation and visualization. The DIGGS schema for rock grouting is now a baseline upon which many other technologies can be readily built into the system. With the schema, every step of the construction process can be documented, and data handling expedited. From the drilling of the hole where monitoring while drilling data capture is already in place on many drills, to packer setting and water testing data, to grout injection and mix properties, to closure tests, the data can flow efficiently if every step of the process uses a common format. With this common structure, the data is entered once and never touched again, saving time and eliminating opportunities for error.

INTRODUCTION

The DIGGS schema development has sofar focused exclusively on the storage and transfer of geotechnical data that are obtained from ground investigations. This includes the development of objects that describe construction of exploratory boreholes, soundings and other features, sampling activities and samples obtained from such features, laboratory tests performed on field samples, as well as in-situ tests and monitoring activities. Although the current production version of DIGGS (v2.5.a) is limited to this subset of geotechnical activities, the schema structure is designed in a modular fashion and with extensible object base types that facilitate expanding the schema to accommodate other types of activities within the geotechnical and geoenvironmental disciplines, while maintaining the current DIGGS structure and minimizing schema bloat.

With support from the Deep Foundations Institute, (DFI), the DIGGS development team has completed a pilot project to extend DIGGS to accommodate grouting activities, thus expanding DIGGS' domain beyond exploratory efforts to include geotechnical construction activities. The current effort is limited to rock grouting within boreholes but plans are currently underway through ASCE's GeoInstitute to cover additional grouting processes, such as compaction grouting, consolidation grouting, tunnel grouting, deep soil mixing, jet grouting, etc. We expect these efforts to serve as a foundation for extending DIGGS to capture other types of construction activities in the future

Rock grouting is a process of drilling, insitu testing, material mix design and production, and delivery of the material controlled by pressure, flow rates and volume. The location and orientation of every grout hole is critical. Data is captured from diverse locations such as the drill, the grout plant, and the injection point which must all be combined. The capture and interpretation of the data in real time is critical to the injection process. The need for data and report transmission in near real time is demanded. The interpretation and visualization of the data and results is expected in 2D and 3D tools. All of these steps collect critical data for the contractor, engineer and owner to understand the site and effectiveness of the grouting effort. Often this grouting is performed on critical structures where reporting and long-term storage of the data and interpretation is mandatory and today's construction and contract documents present a variety of expectations on projects where engineers and contractors are challenged to meet these requirements as they continue to evolve. The DIGGS schema is not the interpretation, presentation and storage tool, but it is a common structure so efficient tools for each of these steps can speak to one another without human intervention where time is expended and potential for error is introduced.

The new DIGGS schema additions, including example XML files and other resources, are part of DIGGS development version 2.6; the latest snapshots of which can be found on GitHub at https://github.com/DIGGSml/diggs-schema/tree/2.6. This version is meant for testing purposes in advance of including these new extensions in a future DIGGS production release.

DEVELOPMENT PROCESS FOR THE ROCK GROUTING SCHEMA

The Deep Foundation Institute Committee Project Fund approved this project to gather representatives from across the industry to become educated about the Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) data structure and adapt this to fit rock permeation grouting needs as a demonstration for applicability to other DFI committee needs. To accomplish this, representatives from the Geo-Institute of ASCE DIGGS committee gathered with representatives from academia, construction, design and owners involved in the grouting industry. Four virtual workshops were held over a 4-month period. The first two workshops provided significant background and training on the structure of the DIGGS schema. Example data sets and data capture forms were collected from participants and a preliminary list of data fields was developed for review and discussion. Over the next two workshops the data structure was reviewed and clarified to resolve the needed structure within the schema. The final workshop reviewed the status and provided demonstration of a quick tool developed by one of the participants to read a grout data file and graph the results.

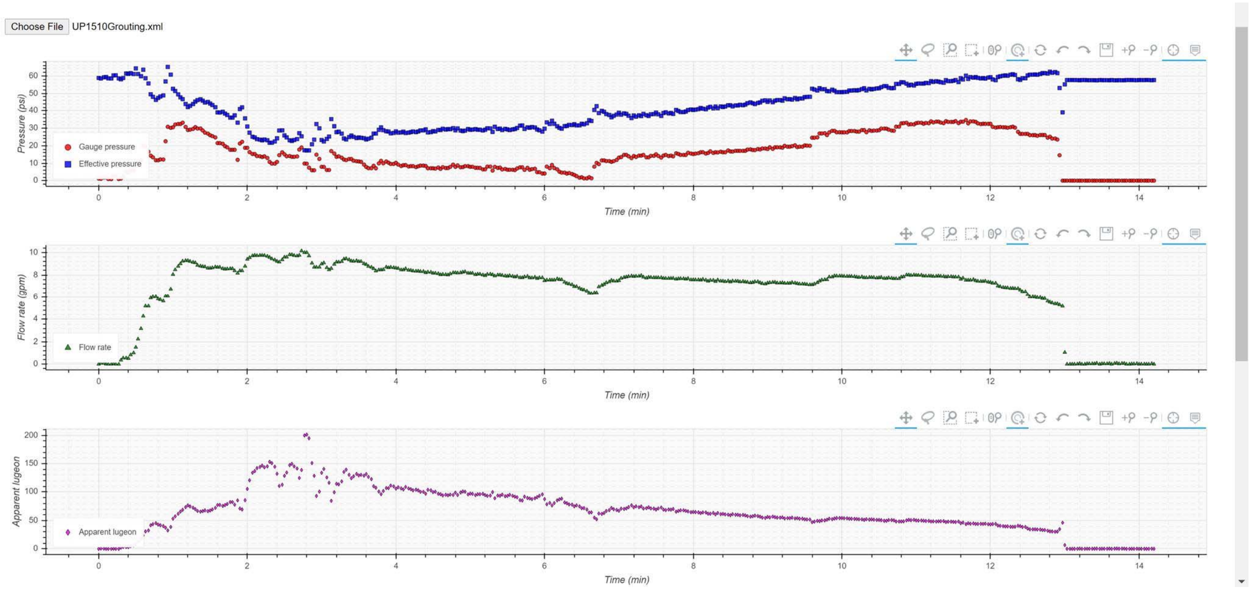

Figure 1 Simple rock grouting plots developed from new DIGGS Instance.

HOW ROCK GROUTING FITS INTO DIGGS

DIGGS defines a structure that describes real-world objects and activities and their relations within the geotechnical discipline. Data are stored as ASCII text in eXtensible Markup Language (XML) format that:

a. conforms to Geographic Markup Language (GML) standards for defining objects, properties and geometries for location-based geotechnical data, and
b. defines data structure, objects and properties.

As defined by the DIGGS schema, DIGGS XML instance documents consist of a collection of XML elements that capture data that fall within one of the following top-level classes:

a. **Projects** - business activities that encompass a collection of sampling features, activities, samples, measurements and observations. A project may occur at a physical location, in which case it can optionally contain geometries.
b. **Sampling Features** – physical objects or locations through which we observe or measure properties of an investigation target or perform some type of activity. Investigation targets can be real world objects, such as natural ground, ground water, a pipeline - or the reason for an activity, such as ground improvement. Current DIGGS sampling features include boreholes, soundings, transects, wells, trial pits, trench walls, and stations. All sampling features have properties that define their geographic location and geometries such that observations and measurements obtained from them can be precisely located.
c. **Sampling Activities** - the action taken to obtain or produce a physical sample. This activity typically occurs at some location within a sampling feature, or could occur elsewhere, such as in a laboratory.
d. **Samples** – a specimen of earth material, fluid, or gas that is obtained as a result of a sampling activity, for the purpose of observation and/or testing.
e. **Observations** - qualitative descriptions or interpretations obtained within the context of a sampling feature or a sample. Common observations are soil descriptions and field classifications as would be reported on a boring log, descriptions of the character and geometry of fractures or geologic structures, or interpretations that derive from such descriptions, such as stratigraphic units or geologic facies.

f. **Measurements** – Acts or events whose results are quantitative estimates of the values of properties of the target of investigation (eg. natural ground, earthworks, etc). DIGGS has two classes of measurements, 1) tests, which are measurements made over a spatial domain, such as laboratory or in-situ tests and 2) monitoring activities, which are measurements made over a temporal domain. Water level measurements or inclinometer readings are examples of monitoring activities.

DIGGS objects are XML elements of complex type – meaning that they have other elements that contain data nested under an element tag. These nested elements can be either properties (XML elements of simple type – eg. tags that surround a simple text string), or other objects. Top level DIGGS objects are called features and derive from base objects that fall under one of the classes defined above. This inheritance architecture allows objects of similar class to share a common set of properties and is used to constrain how various objects are organized within a DIGGS instance document.

For example, borehole features occur within a DIGGS instance document surrounded by a <samplingFeature> property tag; schema rules only allow objects of sampling feature type to exist between samplingFeature tags. While each major DIGGS feature stands on its own within a DIGGS instance document, features of different classes are associated with each other through referencing properties. For example, every borehole (a sampling feature) contains a reference property that holds the ID of the project feature that the borehole is associated with. Similarly, sample, observation and measurement features carry properties that reference the sampling feature from which they are obtained; the specific locations of samples, observations and measurements are also defined within the sampling feature's geometric reference system. The modularity of DIGGS' schema design allows for significant flexibility for how various data associations are modeled and allows the same features to be utilized in different contexts. For example, the same Sample feature structure is used to describe a sample whether it is derived from a borehole, a trial pit, or another sample; the context is defined by the values held in the sample's referencing properties.

The introduction of rock grouting into the DIGGS schema constitutes a new class of information – a construction activity. Extending DIGGS to accommodate grouting data therefore requires the addition of a top-level "constructionActivity" property, and a base feature from which all construction activities will derive. Thus, the grouting data will occur within a DIGGS instance document surrounded by the <constructionActivity> tag.

As currently defined, this construction activity base feature in turn derives from a base GML object type and contains standard feature properties: a mandatory id, an optional name (or names) and properties that hold information on data status, comments, roles and personnel associated with the activity and links to external files, such as electronic documents or images. Additional properties carried by all construction activity features include properties to reference an associated project, sampling features, or measurements, properties to describe construction methods and equipment, and a property to define the time interval over which the activity takes place.

These additions are all that is required to extend DIGGS to accommodate not only rock grouting, but any other construction activity that would logically derive from the same base activity feature. As these additional properties and features are optional, their addition to the schema has no effect on other existing DIGGS instance documents.

RockGroutingActivity Feature

All data associated with rock grouting is contained within a single feature, named "RockGroutingActivity". RockGroutingActivity inherits all of the properties of its base construction activity feature plus additional objects and properties that are specific to rock grouting. Additional construction activity features will have to be created to carry data specific to other activities, such as compaction grouting, pile construction, etc. to accommodate those specific activities.

Rock grouting occurs in the context of a borehole; however as DIGGS already has a feature to carry borehole construction data, as well as other features to hold data that might be collected during drilling and sampling of the drilled hole, that information would be stored in those features and the RockGroutingActiviy feature would point to the associated borehole in its samplingFeatureRef referencing property. There are some aspects of borehole construction as part of a rock grouting project that were not accommodated in the borehole feature in v 2.5.a; these include the potential for multiple casing installation and removal events as well as multiple backfill and redrill events during rock grouting. This necessitated some extensions to the v2.5.a borehole feature in v2.6 that are summarized in the next section.

In general, only one RockGroutingActivity feature need be created to carry all activities within a hole as the feature can handle multiple grout stages and grout mixes. However, multiple rock grouting activity features can be associated with a single hole where it may make logical sense to do so, as in the case where subsequent grouting occurs after some period of time using a different project manager, personnel, or equipment, or if physical conditions change, such as a change in static water level.

At the top level of the grouting feature are a number of "static" properties and objects that pertain to the overall grouting activity, These include the position of the water table, target geologic units, total depth interval over which grouting takes place, length of the overburden casing sleeve pipe (OCSP), overburden thickness and maximum design pressures. Data obtained on grout mixes used during grout injection in various grouting stages are carried in groutMix and groutStage properties, respectively. Each property contains a nested object that holds information on one grout mix batch (GroutMix object) and one grout stage (GroutStage object), respectively. A RockGroutingActivity feature can hold as many groutStage or groutMix properties as necessary to define the activity.

Figure 2 shows the general structure of the schema which will be described in further detail below.

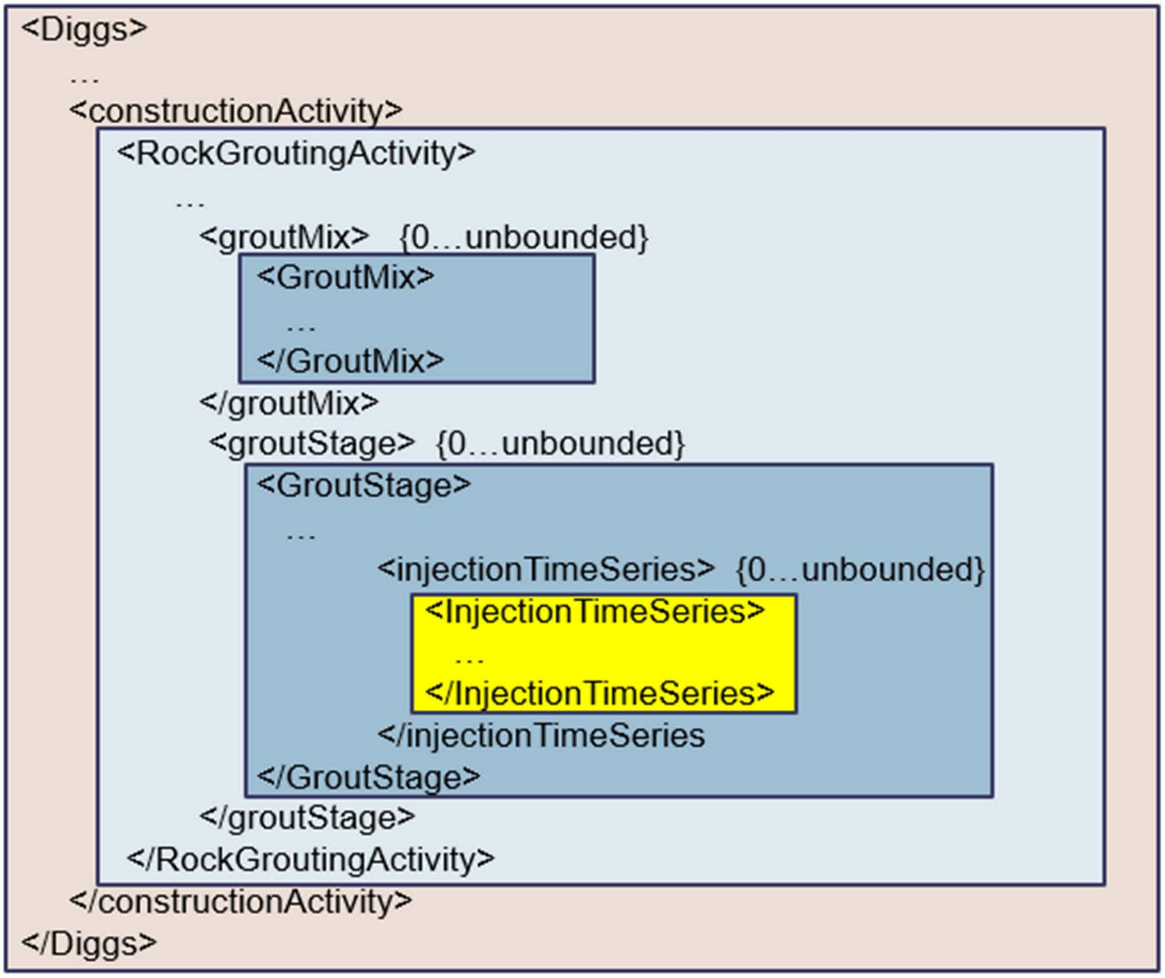

Figure 2. General structure of rock grouting within DIGGS schema

GroutMix Object

This object carries information about each of the grout mixes used in the grouting activity, including:

- mix id and mix number
- type, weight, specific gravity and volume of the admixture, binder, and cement components used in the mix, as well as type, target specific gravity, water volume, theoretical yield and total yield of the grout mix itself,
- physical properties of the grout as derived from bleed, flow cone, marsh cone and pressure filtration tests,
- line loss regression coefficients and line loss test parameters such as maximum header pressure at zero flow and hydraulic column pressure.

GroutStage Object

Most of the information that is used to evaluate the effectiveness of the grouting activity is contained in the GroutStage object. Properties include

- depth interval of the stage
- fill time initiation, pressurization time initiation and time at end of stage filling
- type of stage (ascending or descending)

- delivery type (eg. manchette, tube, etc.)
- target volume, target Grouting Intensity Number, total volume take, total cement, volume injection per unit length

In addition, the GroutStage object contains an InjectionTimeSeries object to capture the grout injection time series recorded during each injection interval. A GroutStage can accommodate any number of InjectionTimeSeries objects depending on the number of injection intervals that occur during the stage. The injection time series incorporates compact encoding, with data reported in two text strings – one for the recorded time instances and one that reports the parameters recorded at each time instant, plus an associated parameter block that defines each recorded parameter along with metadata such as sampling rate, unit of measure, whether the parameter is a raw reading, calculated from other parameters, derived from a moving average, etc. Allowable parameters that can be recorded for each time instant are:

- apparent Lugeon value,
- column pressure
- effective pressure
- elapsed time
- flow rate
- gauge pressure
- grout specific gravity
- grout temperature
- header pressure
- injection pressure
- line loss
- mix ID
- packer pressure
- grout take

Modifications to Existing Diggs Objects

As mentioned above, rock grouting activities commonly involve borehole construction activities that aren't typically done in an exploratory borehole. These include backfilling into an interval of a borehole as part of a grout stage, and then redrilling the borehole with subsequent grout/backfill emplacement. The DIGGS v. 2.5.a Borehole feature accommodates only a single Backfill object that records the materials and backfill layers or lifts that would typically represent backfill in a completed hole. DIGGS v. 2.6 allows for multiple Backfill objects to accommodate multiple backfill events. Additional properties were also added to the Backfill object to record whether backfilling occurred in an open hole, within casing, or in the annular space only, and reference properties to point to the RockGroutingActivity feature and the GroutMix ID associated with a backfill layer that results from a grouting activity. These changes do not affect the validity of DIGGS instances created under v. 2.5.a so older instances will still be valid DIGGS documents if validated to the v. 2.6 schema.

A second modification was made to the Casing object contained within the Borehole feature. The v. 2.5.a Casing object could accommodate sets of casing that was permanently installed. Properties have been added to the Casing object to provide for recording when a casing section was both emplaced and removed as well as to record the number of grout ports within a section of casing installed for the purpose of supporting a RockGroutingActivity.

LugeonTest Procedure

Several tests are typically conducted in association with a rock grouting activity. These typically include in-situ hydraulic conductivity tests (Lugeon test) in the borehole prior to and after grouting, and various material property tests on grout mixes (eg. mud balance, pressure filtration, etc). DIGGS currently has a structure (Test feature) to report results from all types of in-situ and laboratory tests. Additional test procedure objects, however, are constructed in order to record metadata that is specific to each new test procedure or family of test procedures.

For the pilot rock grouting project, a test procedure object was created to record Lugeon test procedure metadata, but no test procedure objects have yet been built to record test metadata for the various physical property tests on the grout, as the results are integral to the grouting activity and are recorded within the GroutMix object. Test procedure objects for these tests can easily be created if needed.

The Lugeon test typically produces two result parameters – the Lugeon value and an estimate of hydraulic conductivity. These results are reported within the result block of the standard DIGGS Test feature. The procedure used to derive these values involves injecting water into an interval of the borehole and recording the elapsed time, flow rate, and flow volume over a set period of time at different pressures. The Lugeon test procedure created for v 2.6 allows for the recording of this information and is structured similarly to the GroutStage object insofar as it contains a time-series object to capture the measured flow rates and pressures at different elapsed times. Both Lugeon test results and associated metadata are carried in the Test feature, not within the RockGrouting feature. As with all feature associations, the Lugeon test is associated with the RockGroutingActivity feature by assigning the ID of the Test feature that contains the Lugeon test results to the measurementRef property of the RockGroutingActivity feature.

The following is a partial example instance for rock grouting. The complete example instance document can be viewed at https://github.com/DIGGSml/diggs-schema/tree/2.6/Examples.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<Diggs xmlns="http://diggsml.org/schemas/2.6" xmlns:diggs="http://diggsml.org/schemas/2.6"
   xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xlink="http://www.w3.org/1999/xlink"
   xmlns:gml="http://www.opengis.net/gml/3.2" xmlns:g3.3="http://www.opengis.net/gml/3.3/ce"
   xmlns:glr="http://www.opengis.net/gml/3.3/lr" xmlns:glrov="http://www.opengis.net/gml/3.3/lrov"
   xmlns:diggs_geo="http://diggsml.org/s dchemas/2.6/geotechnical"
   xmlns:witsml="http://www.witsml.org/schemas/131"
   xsi:schemaLocation="http://diggsml.org/schemas/2.6 ../Diggs.xsd" gml:id="bcd">
….
    <constructionActivity>
      <RockGroutingActivity gml:id="UP1510-C1">
         <investigationTarget>Deep Foundation</investigationTarget>
         <projectRef xlink:href="#center_hill)_dam"/>
         <samplingFeatureRef xlink:href="#UP1510"/>
         <activityDateTime>
            <TimeInterval gml:id="ggdt">
               <start>2009-04-21T19:36:46</start>
               <end>2009-04-22T04:54:13</end>
            </TimeInterval>
         </activityDateTime>
         <groutingInterval>
            <LinearExtent gml:id="ggi" srsName="#UP1510-lsr" srsDimension="1">
               <gml:posList>230 235</gml:posList>
            </LinearExtent>
         </groutingInterval>
         <groutStage>
```

```
<GroutStage gml:id="C1">
  <gml:name>C1</gml:name>
  <remark>
    <Remark>
      <content>Water to surface, 1.1 min 5.8 gal; Grout to surface, 14.2 min 97.6 gal</content>
    </Remark>
  </remark>
  <stageType>descending</stageType>
  <stageInterval>
    <LinearExtent gml:id="s1i" srsName="#UP1510-lsr" srsDimension="1">
      <gml:posList>230 235</gml:posList>
    </LinearExtent>
  </stageInterval>
  <startTimeFilling>
    <gml:TimeInstant gml:id="stfti">
      <gml:timePosition>2009-4-21T19225.47</gml:timePosition>
    </gml:TimeInstant>
  </startTimeFilling>
  <endTime>
    <gml:TimeInstant gml:id="endtp">
      <gml:timePosition>2009-04-22T04:54:13</gml:timePosition>
    </gml:TimeInstant>
  </endTime>
  <injectionTimeSeries>
    <InjectionTimeSeries gml:id="s1td">
      <timeDomain>
        <TimePositionList gml:id="tpl-c">
          <timePositionList> 0.00 0.03 ….. 14.17 14.20
          </timePositionList>
        </TimePositionList>
      </timeDomain>
      <injectionDataResults>
        <InjectionDataResultSet>
          <parameters>
            <PropertyParameters gml:id="tdppms">
              <properties>
                <GroutInjectionProperty index="1" gml:id="tdp1">
                 <typeData>string</typeData>
                 <propertyClass>flow_rate</propertyClass>
                 <uom>gal[US]/min</uom>
                 <measurementTechnique>measured</measurementTechnique>
                </GroutInjectionProperty>
                <GroutInjectionProperty index="2" gml:id="tdp2">
                 <typeData>double</typeData>
                 <propertyClass>gauge_pressure</propertyClass>
                 <uom>psi</uom>
                </GroutInjectionProperty>
                <GroutInjectionProperty index="3" gml:id="tdp3">
                 <typeData>double</typeData>
                 <propertyClass>effective_pressure</propertyClass>
                 <uom>psi</uom>
                </GroutInjectionProperty>
                <GroutInjectionProperty index="4" gml:id="tdp4">
                 <typeData>double</typeData>
                 <propertyClass>apparent_lugeon_value</propertyClass>
                </GroutInjectionProperty>
                <GroutInjectionProperty index="5" gml:id="tdp5">
                 <typeData>string</typeData>
                 <propertyClass>mix</propertyClass>
                </GroutInjectionProperty>
              </properties>
            </PropertyParameters>
          </parameters>
```

```
<dataValues cs="," decimal="." ts=" ">
      0.00,1.18,58.80,0.0,C-25 0.08,1.05,58.51,0.5,C-25
       …..
      0.05,0.00,57.52,0.3,C-25 0.00,0.00,57.62,0.0
     </dataValues>
    </InjectionDataResultSet>
   </injectionDataResults>
   <totalElapsedTime uom="min">14.2</totalElapsedTime>
   <totalGroutTake uom="gal[US]">97.57</totalGroutTake>
   <waterLugeonValue uom="Lu">100.0 </waterLugeonValue>
  </InjectionTimeSeries>
 </injectionTimeSeries>
 <targetVolume uom="gal[US]">5.7</targetVolume>
 <totalCement uom="lbf">116.6</totalCement>
 <totalVolumeTake uom="gal[US]">25.9</totalVolumeTake>
 <volumeInjection uom="gal[US]/ft">1.3</volumeInjection>
</GroutStage>
</groutStage>
</RockGroutingActivity>
</constructionActivity>
</Diggs>
```


NEXT STEPS

This project served to bring owners, engineers and contractors together to learn more about DIGGS and how we can transfer data to expedite services and reduce waste and potential error. We further brought the experiences of the grouting community together with the subsurface exploration community to understand needs, expand the schema and realize a new expanded DIGGS that accommodates rock permeation grouting and is readily expandable further for other grouting construction techniques such as jet grouting, soil mixing, compaction grouting, etc. The use of temporal measurement objects accommodates tests and grouting processes. The new top level constructionActivity property has been established to distinguish these filed activities from exploration efforts.

Of greater opportunity is the ability to extend the schema further to accommodate additional site exploration tools fully, earthworks, foundation construction, load testing, and monitoring data from instrumentation. With advent of larger and more robust data sets being collected with electronic tools, expectations for computer visualization and augmented reality presentations, statistical analysis of data sets, archival for asset management, and expectation for more cost effective use and reuse of available data we must have a common language for transferring and documenting the data we collect and share.

SUMMARY

With support from DFI, a pilot project was completed to extend the DIGGS schema to record and transfer data obtained as part of grouting construction activities. The extension was easily made by adding a new top-level property (constructionActivity) and a construction activity base feature from which other construction activity features must be derived. The pilot was limited to rock permeation grouting, but the top-level extension will accommodate other construction activity features.

Data obtained and recorded during a rock grouting activity is carried within a single RockGroutingActivity feature. The feature holds information on grout mix properties, and summary results from each stage of the grouting activity, as well as injection time series data recorded during each interval of grout injection.

The new RockGroutingActivity schema extension is incorporated as part of DIGGS' current development version (2.6) and is available for review and testing, along with example xml instances and other resources at https://github.com/DIGGSml/diggs-schema/tree/2.6. Following appropriate vetting and review, these new objects will be incorporated in a future production release of the schema. Plans are in place, supported by ASCE's GeoInstitute to extend DIGGS further to accommodate additional grouting processes.

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