Experiences with Geospatial and Statistical Based Surveys of Subsurface Soil

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Overview

- Most sites undergoing decommissioning have not experienced substantial issues with residual radioactivity in the environment
 - Some common areas of isolated contamination
- Monitoring and record keeping during operations are key to identification of potential areas of concern
 - NEI 07-07 groundwater protection initiative
 - 50.75(g) documentation process
- With the exception of well-known but isolated cases, groundwater monitoring in the current fleet has not identified substantive issues
 - Remediation has been implemented, as warranted
 - For example, in most cases, pump-and-release and monitored natural attenuation techniques have been practiced



Scoping and Characterization Surveys Land Areas

- To support decommissioning, the extent of radiological contamination in site areas needs to be determined
 - Surveys biased based on Historical Site Assessment
 - Information collected during other work included (i.e. soil samples) collected during Groundwater Monitoring well installation)
 - Systematic sampling done when no events have occurred in an area
 - Additional sampling to bound contamination horizontally and vertically, if detected
 - Determines limits of the required remediation
 - Need to evaluate for Hard To Detect Nuclides (HTDN, i.e., Alpha, Pure) Beta nuclides) early in the process
- Information used to inform remediation and Final Status Survey (FSS) design



Case Study: Soil and Groundwater Contamination at Connecticut Yankee (Reference: EPRI Report #1013511, Connecticut Yankee Decommissioning Experience Report, 2006)

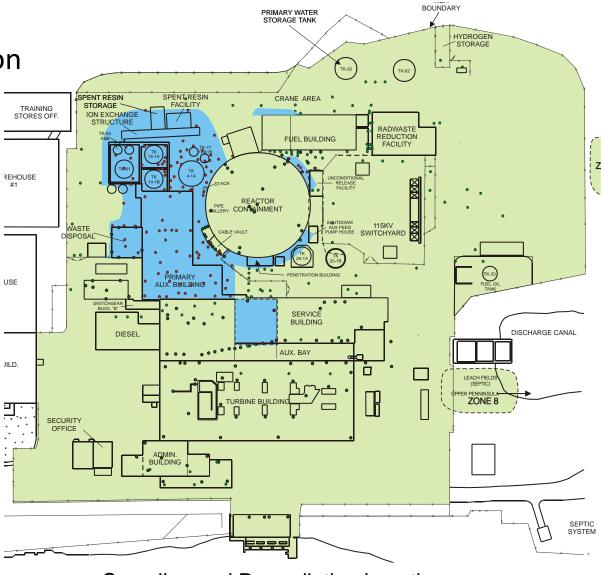
Subsurface Soil Sample Locations - Characterization

Areas in blue required subsurface remediation





Direct Push Sampler

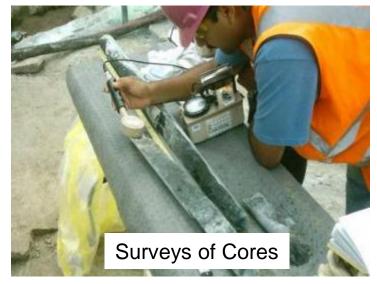


Sampling and Remediation Locations



Techniques used to Assess Contamination in Bedrock





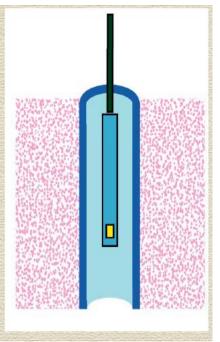




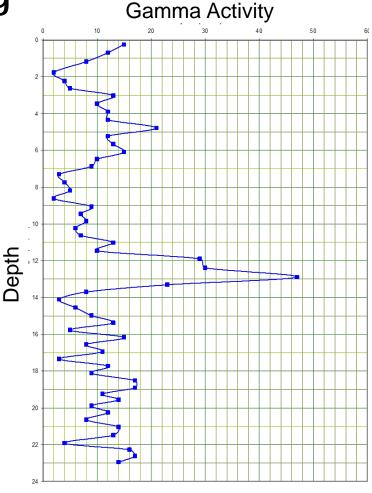
Alternate Technique: Assessing Bedrock/Soil Using

Down-Hole Gamma Logging









Sensitivities as low as 1 pCi/g for Fission Products with High Resolution Spectra Gamma Logging



Assessment of Excavations at CY

Surfaces of excavation evaluated by:

Soil sampling where safe to perform

 In-situ gamma spectroscopy of bedrock and steep sidewalls



FSS Approaches used for Subsurface

- Most plants have surveyed soil excavations as if they were surface land areas
- CY needed a more comprehensive FSS approach as there was concern that all subsurface contamination had not been identified during site characterization
- NRC approved a graded subsurface survey protocol summarized below:
 - Table shows the required # of direct push sample locations for various survey areas
 - Gridded plus biased sample locations in Class A areas
 - Random samples were obtained in Class B and Class C areas:
 - In addition, biased samples were obtained based upon characterization data and professional judgment.
 - Samples were obtained to a depth of 3 meters or bedrock
 - These samples were homogenized over the entire depth of the sample obtained and evaluated using MARSSIM based statistical methods.

Classification of Survey Area	Number Sample Locations Required for Each Type of Survey Area (Total for Each Type)
Class A (Highest Potential)	31 Samples (1 sample per 500 m ²)
Class B (Medium Potential)	25 Samples
Class C (Lowest Potential)	15 Samples



Use of Geostatistics to Evaluate Subsurface Contamination (Reference: EPRI Report #3002007554, Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning, 2016)

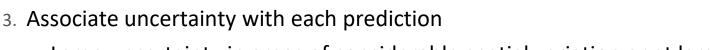
Background

- To date, site characterization and final status survey guidance has focused on surface contamination
 - For example, US approach described in MARSSIM (NUREG-1575)
 - When performed, <u>subsurface</u> characterization has been addressed using non-standard, site-specific approaches
- Although not currently required, regulators desire a standardized approach to subsurface characterization
 - Improves technical basis for site release
 - Allows cost-effective decommissioning planning for utilities
- Goal of this 2016 EPRI project was to educate the industry about the precedents for and potential benefits of geostatistics

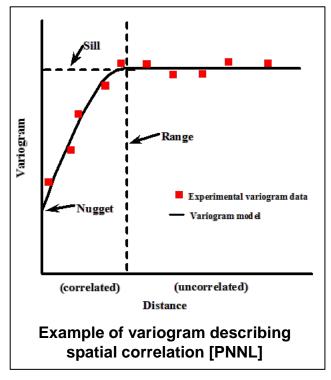
Introduction to Geostatistics

Overview

- Geostatistics is a class of methods to:
 - Infer patterns from spatially structured data:
 - Sparse or large data sets
 - Structured or unstructured grids
 - Multidimensional spaces
 - Make predictions at an arbitrary point (or manifold) in space, crediting spatial correlation
 - Many such predictions can be made to attain a virtually continuous representation of the spatial variable



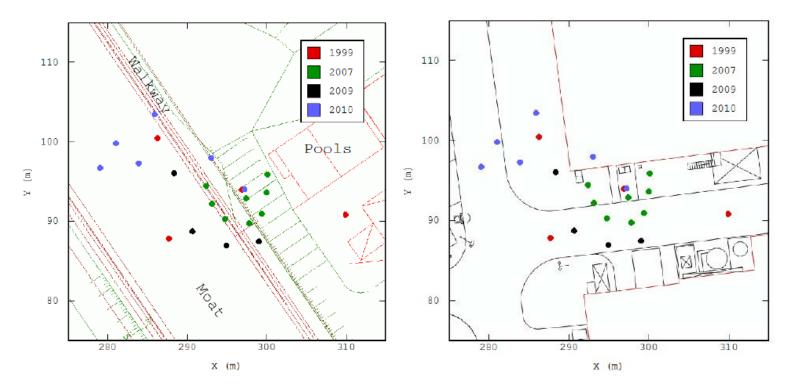
- Large uncertainty in areas of considerable spatial variation or at large distances from measured data points
- Low uncertainty near measured data points
- Prevalent use in many fields, including mining, oil and gas, hydrogeology, environmental monitoring, climate science, and epidemiology



Case Study in the Use of Geostatistics

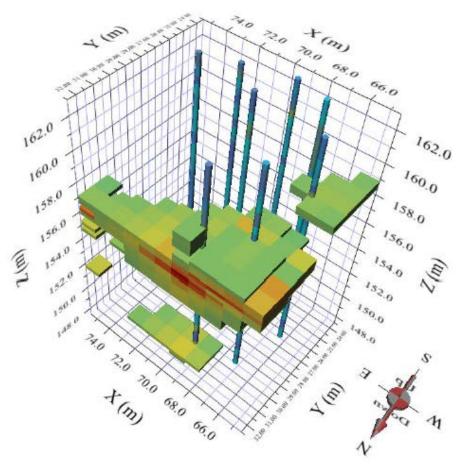
Subsurface Characterization at Fontenay-aux-Roses (1/4)

- Fontenay-aux-Roses is a CEA research facility in France
- A series of drill hole campaigns were conducted to characterize Cs-137 concentration in the soil where buildings and structures were previously located at the facility.



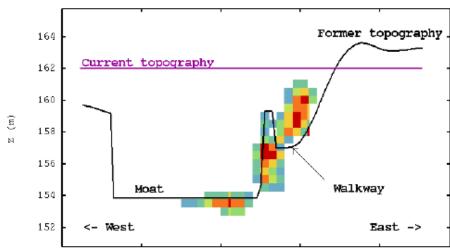
Subsurface Characterization at Fontenay-aux-Roses (2/4)

- 3D kriging map was developed using measurements from the 2007 campaign
- This kriging map informed the placement of the 2009 and 2010 sampling campaign locations



Subsurface Characterization at Fontenay-aux-Roses (3/4)

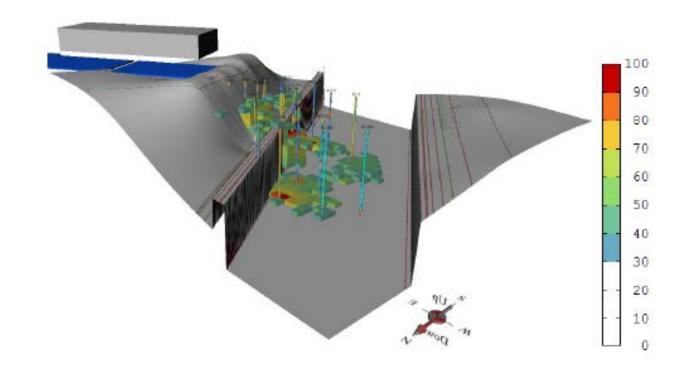
- Analysis of the 2007 and 2009 campaigns revealed a thin contaminated layer along a vertical gradient
- The gradient was consistent with topology of the first generation site configuration, lying along the bank of a former moat



 Agreement between the contamination pattern and the former topology led the investigators to conjecture that the source of the contamination was an accidental spillage from the storage pools or contaminated media used to fill the moat

Subsurface Characterization at Fontenay-aux-Roses (4/4)

Enabled by geostatistical maps, the area was successfully remediated in 2013 producing $2,000 \text{ m}^3 \text{ of very}$ low level waste and 2,000 m³ of conventional waste



Software Review (1/2)

- A large set of geostatistical software products was reviewed as part of the EPRI project
- Factors considered when appraising geostatistical software products included:
 - Cost
 - User interface
 - Flexibility
 - Algorithm availability
 - Visualization capabilities
- The review extended to contemporary standalone software, contemporary libraries deployed by common programming languages, and software with historical precedent



Software Review (2/2)

Software (Developer)	Cost	Dimensionality	Directed Workflow?	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Krgiing	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
ASCEM (U.S. DOE)	Proprietary	3D	n	n	n	n	n	n	n	n	n	n	n	n	n	у	у	n	n	model assimilation with flow and transport predictions
Earth Volumetric Studio (C Tech)	High	3D	n	у	у	у	у	у	n	n	n	у	n	n	n	n	n	n	у	block diagram interface, treatment of geological lithofication, borehole optimization
geoR and RGeostats (R Software)	Free	3D	n	у	n	у	у	у	у	у	у	у	n	у	у	у	n	n	n	exemplary combination of breadth and depth
Geostatistical Analyst (ESRI)	High	2D	у	у	n	у	у	у	n	у	у	у	n	n	у	у	n	n	у	high degree of user control, user-friendliness
GS+ (Gamma Design Software)	Low	2D	n	у	n	у	у	у	у	у	у	у	n	у	у	у	n	n	n	abundance of autocorrelation measures
GsTL (C++)	Free	3D	n	n	n	n	n	у	n	у	у	у	n	n	у	n	n	n	n	generic programming paradigm
HPGL (Python)	Free	3D	n	n	n	у	у	у	n	у	у	у	n	n	у	n	n	n	n	efficient and parallelized algorithms
HydroGeoAnalyst (Schlumberger)	High	3D	n	n	n	n	n	у	у	у	n	n	n	n	n	n	n	n	у	integrated data management utilities
Isatis (Geovariances)	High	3D	у	у	n	у	у	у	у	у	у	у	n	у	у	у	n	n	у	journal file, principal component analysis, abundance of variogram model forms, block kriging in complex subregions, suppored by active R&D
Kartotrak (Geovariances)	High	3D	у	у	у	у	n	у	n	n	у	n	n	n	n	n	n	n	у	real-time data streaming, highly structured workflow, MARSSIM and ISO 8550 sampling protocols
mGstat (MATLAB)	Free	3D	n	n	n	у	у	у	n	у	n	n	у	n	у	n	n	n	n	interfaces for gstat and SGeMS
Native command set (SAS)	Free	2D	n	у	n	у	у	у	n	у	n	n	n	n	у	n	n	n	n	automated exploration of many variograms
SADA (University of Tennessee)	Free	3D	у	у	у	у	у	у	n	n	у	у	n	n	у	у	n	у	у	area of concern maps, map arithmetic, sampling optimization, remediation cost-benefit analysis
SGeMS (Stanford)	Free	3D	n	у	n	у	у	у	у	у	у	у	n	n	у	n	n	n	n	optional command line interface, downscaling predictions, multiple-point geostatistics
Surfer (Golden Software)	Low	2D	n	у	n	у	у	у	у	у	n	n	n	у	n	у	n	n	у	native scripting language
T-Progs (Lawrence Livermore)	Free	3D	n	n	n	у	у	n	n	n	n	у	n	у	у	n	n	n	n	transition probability / Markov chain geostatistics
VSP (Pacific Northwest NL)	Free	2D	у	у	у	у	n	у	у	n	n	у	у	n	n	n	n	n	n	Walsh's outlier test, data quality objective (DQO) based sampling planning, economic analysis



Challenges for Demonstrating Subsurface Compliance (1/2)

- Surface compliance frameworks often rely on surface scanning technologies to characterize the spatial variation of contamination. There is no analogous option viable for the subsurface
 - Places emphasis on other methods for spatial characterization
- The extension from the surface to the subsurface increases the number of dimensions, resulting in generally sparser data sets
 - A framework is required that may make compliance possible in spite of spatial uncertainty
- The subsurface environment can present heterogeneity and complex processes
 - Places new emphasis on integrating data-driven analysis with a conceptual or physical understanding of the environment
 - Compounds the risk of hot spots in the subsurface environment



Challenges for Demonstrating Subsurface Compliance (2/2)

- The subsurface sample design requires vertical characterization in addition to lateral characterization of contamination
 - Compliance framework may need to accommodate different subsurface measurements, including from core boring, laboratory samples collected at well locations, or borehole gamma logging
 - Differences in the spatial variation in lateral directions versus the vertical direction need to be accounted for
 - Sample costs increase, which places a premium on the empirical science used to derive information from samples
- The exposure pathways for subsurface contamination are distinct from the surface, including groundwater migration and excavation scenarios



Roadmap for Applying Geostatistics

General

- EPRI report provides a roadmap identifying:
 - Major phases of geostatistical analysis
 - Steps within each phase
 - Key questions associated with each step

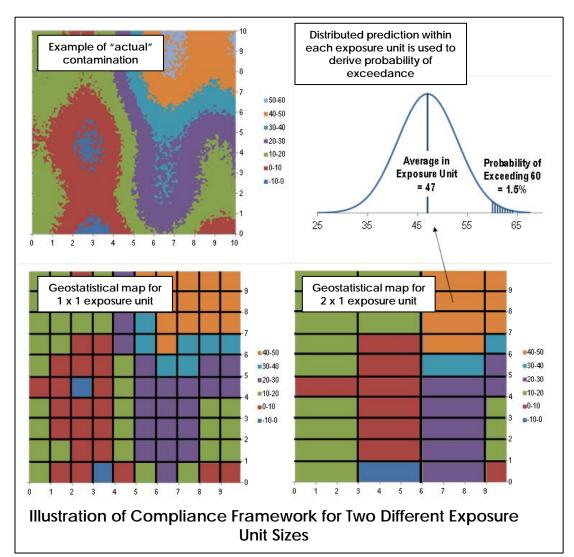
Roadmap Phase	Steps Associated with Phase
Preliminary Steps	 ■ Perform conventional site characterization steps ■ Educate site characterization team on geospatial data characteristics ■ Select software to support geostatistical analysis ■ Develop expertise with selected software
Exploratory Data Analysis	 Define and format data for geostatistical analysis Visualize and consolidate data Perform statistical analysis Assess data for violations of the constraints of geostatistical methods Assess inter-variable correlation Perform data manipulation
Structural Analysis	 Study spatial structure empirically Fit the analytical variogram Assess anisotropy Perform structural analysis for multiple regionalized variables
Geostatistical Interpolation	 Design the prediction grid Select a geostatistical interpolation method Design the search neighborhood Execute geostatistical interpolation
Post- Processing Steps	 Perform inverse transformation Perform cross-validation Perform sensitivity testing Apply geostatistical interpolation results Apply results to demonstrate compliance of subsurface contamination Report the geostatistical analysis



Roadmap for Applying Geostatistics

Example Compliance Framework

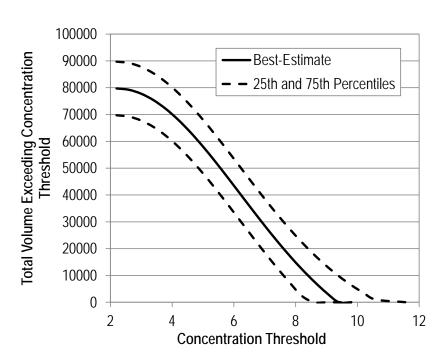
- An exposure unit is defined as the shape, size, and location of the area/volume in which compliance is sought
- DCGL is derived for exposure unit
- Geostatistics is used to calculate average concentration within exposure unit (and its associated uncertainty)
 - Allows for the calculation of probability of exceedance
- Compliance is demonstrated across a range of exposure units





Other Application Capabilities

- Identifying hot spots
 - Statistical methods—without spatial awareness—cannot be used to identify hot spots
 - Less sophisticated interpolation methods can be used, but can be more susceptible to bias for sparse data sets
 - Geostatistical interpolation also allows the analyst to assess contamination maps at different levels of conservatism
- Estimating likelihood of exceeding some concentration threshold
- Visualizing/estimating volume of environment exceeding some concentration threshold
 - Helps investigators identify areas of concern, e.g., requiring remediation
 - Can calculate remediation area as a function of threshold (see right) or as a function of confidence





Key Findings of EPRI Report

- The use of geostatistics addresses numerous challenges associated with subsurface compliance demonstration and provides additional insight to augment existing procedures for surface characterization
- Various nuclear regulators have acknowledged the use of geostatistics as a valid response to challenges associated with subsurface characterization
 - In 2012, the U.S. NRC published NUREG-7021, which endorses the use of geostatistics for decommissioning applications
 - In 2016, the CEA published an ISO standard articulating a set of principles, including geostatistical analysis, for sampling strategy and characterization of soils, buildings, and infrastructures
- Geostatistics has been deployed for decommissioning nuclear plants, laboratories and research facilities in France, Spain, and Belgium, among other countries, leading to tangible cost savings.
 - At the Brennilis and Chooz A NPP decommissioning sites, for instance,
 geostatistics has been used to optimize remediation and excavation activities



