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PRINCIPLES AND OBJECTIVES OF CONTAINMENT VERIFICATION AND PERFORMANCE MONITORING AND TECHNOLOGY SELECTION

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Abstract

While a number of technologies or methods of subsurface imaging and monitoring exist, most require some adaptation to meet the site-specific objectives of a particular in-situ waste containment/stabilization verification and monitoring program. The selection of methods and their site-specific adaptation must be based on sound, scientific principles. Given this, specific information about the site and the objectives of the containment or remediation are required to design and implement an appropriate and effective verification and monitoring program.

Site and technology information that must be considered and how it affects the selection and adaptation of monitoring technologies is presented. In general, this information includes the objectives of the containment or remediation, the verification and monitoring systems, and the physical properties of the site and the waste containment/stabilization system. The objectives of the containment or remediation and the verification and monitoring system must be defined to provide a goal for the technology developer's design. The physical properties of the site and the waste containment/stabilization system are required to ensure the proper technology is selected. A conceptual framework and examples are given to demonstrate the impacts of these aspects on technology selection.

1.0 INTRODUCTION

Several general site needs or objectives are presented as possible drivers for verification and monitoring systems. These include short-term containment of a waste form, long-term containment of a waste form, and in-situ remediation or treatment. Each of these in-situ remedial alternatives requires different verification and monitoring approaches. These approaches range from imaging the subsurface, monitoring potential[1] distributions, and direct sampling of the subsurface materials. The basic principles of subsurface barrier verification and monitoring are also presented. Which include imaging, mapping potential distributions, and direct sampling.

2.0 SITE CONTAINMENT AND OR REMEDIATION OBJECTIVES

The ultimate driver for determining the verification and monitoring strategy used at a site where some form of in-situ containment option is to be applied is the final objective of the in-situ containment. This may range from short-term isolation of a waste form during a removal activity to long-term isolation of waste from the surrounding environment. Other objectives may include an in-situ remediation such as with the use of reactive or permeable barriers. The verification and monitoring must be designed such that the objectives of the in-situ containment can be shown to be met initially (verification) and maintained over time (monitoring). For example, a containment system designed for short-term use may not require long-term monitoring, yet some form of as built information demonstrating

[1] In this text, *potential* is used to describe a physical quantity, capable of measurement at every point in a flow system, whose properties are such that flow always occurs from regions of higher potential to lower potential regardless of the direction in space (Hubbert, 1940)

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containment continuity and proper placement as specified in the design would be useful; whereas a system designed for long tern isolation of a contaminant would require emphasis on changes in containment performance addressed through monitoring.

With respect to the above, subsurface barriers can be defined by either a specified set of dimensions or by a change in the transport and fate of the contaminants in the subsurface. If the objective of the subsurface barrier emplacement is to install a feature with some specified set of dimensions and continuity, then ideally, the verification process will produce some form of image of the structure. (The concept of imaging is discussed in Section 3.1) If the objective is to alter the fate and transport of the contaminants, initial verification may be difficult, but monitoring over time will indicate if the fate and transport processes have been altered as planned. Imaging may aid in the assessment of the changes in fate and transport by defining the changes in the physical system for modeling purposes.

For both verification and monitoring, some measurable characteristics of the containment and or remediation system must be defined to assess the effectiveness of the system. For the different general objectives given in this paper, some possible measurable characteristics will be discussed.

2.1 Short-term Containment of a Waste Form

Short-term containment types of subsurface barriers may be employed during retrieval and or treatment of waste in the subsurface. The purpose for such structures is often to prevent contamination of additional soils by the accidental spillage of waste during removal. For example, if drums of waste are being excavated, a barrier system may prevent contamination of additional soil in the event a drum is accidentally ruptured. Other short-term containment systems may be designed to provide excavation shoring, without which over excavation may be required for slope stability.

For these types of applications, verification of the continuity and dimensions of a barrier may be adequate. Additionally, some data demonstrating the effectiveness of the barrier system upon completion of the removal activity may be required.

2.2 Long-term Containment of a Waste Form

Long-term containment systems are often proposed for sites where no removal action is planned for the foreseeable future either because the risk involved with exposure to workers is much greater than the risk of leaving the waste in the ground or the cost of removing the waste is greater than the potential cost of the risk of leaving it in place. The purpose of these types of structures is often to prevent further release of contaminants from a source term into the subsurface. Long-term containment of a waste form may require initial verification that the containment system has been installed as planned; however, demonstration that it is continuing to perform as planned requires monitoring the changes in the system over time.

Long-term monitoring may demonstrate that the barrier is sufficiently slowing the release of contaminants from a source term such that the natural attenuation processes which act upon the contaminant are maintaining the concentration at an acceptable level or actually decreasing the concentration of contamination in the subsurface

Other indicators that long-term containment is functioning as planned may be a change in the subsurface movement of contaminants in such a manner that will lessen the impact of the contaminants on human health and the environment. This is similar to the above goal of a subsurface barrier to result in a net decrease in the contamination through natural attenuation; however, in this respect, the contaminants are prevented from migrating to new areas. Long-term monitoring in this instance would demonstrate that sufficient and planned changes in the local flow regime for the contaminants have been imposed and maintained by the barrier system.

2.3 In-situ Treatment of Contamination

Barriers in which the planned purpose is in-situ treatment typically require a flux of contaminated media through the barrier. Ideally, the contaminated media will not flow around the barrier, nor will the barrier significantly impeded the flow of contaminated material. To evaluate the performance of such a system, an understanding of the flow regime prior to the installation of the treatment system is required as well as an analysis of the impacts to the flow regime after installation of the treatment system. Such a system will require verification that the system has been emplaced as designed and that it is functioning properly.

A properly functioning treatment system may be characterized by up- and down-gradient contaminant concentrations and the rate at which these concentrations change over time. In addition to contaminant concentrations, the changes in the hydraulic head over time can give an indication of the performance of such a system.

3.0 VERIFICATION AND MONITORING SYSTEMS

As described to in Section 2, verification and monitoring are primarily defined by the time at which they are conducted although, verification tends to be weighted more towards imaging types of technologies and monitoring tends more towards detecting changes in the system performance. Some of the technologies used for verification and monitoring are briefly discussed in the following sections. These discussions are focused on the principles and not necessarily on specific methods. The principles on which verification and monitoring can be based include analysis of subsurface property distributions, potential distributions, and material distributions. The changes in these distributions can be used to assess the existence and performance of the subsurface containment and or remediation system.

3.1 Property Distributions

The transport of contaminants through the subsurface is governed by a number of material properties which include, but are not limited to intrinsic permeability, soil chemistry, soil structure, and fluid properties (chemistry, density, viscosity, etc.,). The distribution of these properties in the subsurface will control the fate and transport of contaminants in the subsurface. Images of subsurface structures are in reality maps of the property distributions. For example, a subsurface barrier may be defined as soil with 60% grout and 40% soil matrix. A map of the soils with this composition would result in an image of the barrier. The barrier may also be defined in terms of other soil properties such as permeability. A map of the permeability distribution with a permeability defined for a barrier would constitute an image of the barrier. Property distribution maps are valuable tools, yet they require a definition of the relationship between the barrier and the property.

To define the extent of a barrier based on a change in the distribution of the transport and flow parameters of the soil requires insight into how the soils change when a barrier is emplaced (Borns, 1995). When a grout material such as cement bentonite is injected into the subsurface, the boundary between grouted and ungrouted soil cannot be assumed to occur entirely within some small discrete zone. This is due to several factors. The effective radius of the grout injection is not constant over the length of the injection due to changes in soil properties, the injection pressure and grout velocity change with respect to the distance from the injection port (the change will result in a net decrease in both pressure and velocity at the lateral most points), and residual fluids from the grout will permeate the formation (the permeation distance is also variable depending on the soil type). These factors lead to permeability changes in the form of filling of pore space by the grout and the destruction of the soil matrix by the grouting action. Other changes include the introduction of additional fluids into the formation and changes in the pore water chemistry from the introduction of new fluids. The conceptual grout panel and permeability distributions shown in Figure 1 illustrate how the boundary between grouted and ungrouted soil might actually develop.

Property distribution maps or images are often used in the verification stages of a subsurface barrier project. Often the property distribution map is made by geophysical measurements of the subsurface. A variety of geophysical methods exist which can map changes in physical properties such as electrical resistivity, dielectric properties, and seismic velocities. While these properties do not directly relate to properties affecting the flow fields, changes in these properties are a result of changes in the properties affecting the flow fields.

Considerable research has focused on understanding these relationships. Poley, *et al* (1978) presented data on very high frequency dielectric measurements for borehole formation analysis. Sen, *et al* (1981) presented a model for the dielectric constant of sedimentary rocks based on studies of fused glass beads. Feng and Sen (1985) presented a model of conductive and dielectric properties of partially saturated rocks. Olhoeft (1987) studied the electrical properties of soils for a frequency range from 10^{-3} to 10^{+9} Hz. Knight and others (1987,1991) and Endres and Knight (1991) have studied the relationship between dielectric properties, resistivity, and seismic velocity for a series of sandstones in an attempt to develop relationships between these properties and the porosity and percent of pore fluid in the rocks.

These studies have focused primarily on naturally occurring sedimentary rocks. Many of the grout types proposed for use are hydraulic cements (i.e. Portland Cement based) or innovative new chemical grouts (polymers, colloidal silica, paraffin, etc.). Very little data exists for developing relationships between the electrical properties and seismic properties of the grouts and the fate and transport properties. However, the properties of the grouts in relation to the host soils should be determined in order to properly select the geophysical methods used to map the barrier. Without a significant contrast in the physical properties between the grout and host soil, geophysical methods can not be used to develop an image of the subsurface.

The highest resolution property distribution maps are attained when the residual or difference between the property distribution before grouting and after grouting are calculated. This effectively highlights only the change, and all other aspects of the distribution which remain constant are removed from the image. Therefore, it is desirable to collect data before and after injection using the same methods from the same locations. Other factors which affect resolution include control of measurement locations, and the ability of the method to resolve small changes in a property.

3.2 Potential Distributions

The distribution of soil gas and groundwater potential in the subsurface can be used to determine contaminant transport paths within and around a subsurface barrier. Additionally, this information can be used to determine material permeability and/or detect zones of low permeability in the barrier, which could be considered as a leak.

Because a subsurface barrier is a three dimensional (3D) object in a 3D potential field that changes with time, the data must be collected in three dimensions as a function of time. As soils and grouts go through wetting and drying cycles, the intrinsic permeability of each will change (Wilson, 1995). Wetting and drying cycles may be caused by water driven from the grout during curing and by seasonal changes in the water table and soil moisture levels. Nested, or multi-level monitoring systems coupled with automatic data loggers can be used to acquire sufficient data in three dimensions and as a function of time for a proper evaluation of the potential distribution in and around the subsurface barrier.

Potential distribution monitoring systems are particularly well suited for long-term monitoring. They can be passive systems which do not require energy to be put into the system, or as active systems which require some form of energy to be put into the system. The issue of passive verses active monitoring may be important when long-term monitoring costs and logistics are considered.

To effectively design a passive system which monitors changes in potential field, predictive models should be developed to ensure adequate sampling points exist and at the same time ensure that the system is not over sampled. It should be noted that every sampling point may require a borehole, which will provide a potential transport path for contaminants. This is true for many of the geophysical methods if used from boreholes as opposed to the ground surface.

3.3 Material Distributions

Material distributions can be obtained from soil samples, groundwater samples, and soil gas samples. Soil sample data may be used to map the presence of grout material in the soil, which will define the extent of the barrier. Groundwater chemistry data can be used to monitor for contaminant concentrations or liquid tracers, this data may be an indicator of how well the barrier is functioning. Soil gas samples can be used to monitor for vapor phase contaminants or for gaseous tracers, as with the groundwater chemistry data, this data may also be an indicator of barrier performance.

The soil composition data is perhaps the most straight forward data set to use. This data can be used to directly determine the penetration or mixing of the grout with the soil. However, this may require destructive sampling of the barrier, which may not be desirable. Some destructive sampling may be necessary to provide "ground truth" data for correlation to other verification and monitoring methods.

Groundwater chemistry can be collected without compromising the barrier system by planing the placement of sampling points outside of the barrier. Groundwater chemistry can be used to develop fate and transport models. The chemical analysis may include analysis for specific tracers injected into the subsurface to determine if the barrier is leaking, or for contaminant concentrations to monitor for leaks or treatment of groundwater by a permeable or reactive barrier system.

Soil gas monitoring systems can also be used in similar fashions as groundwater monitoring systems. Leaks in a barrier can be detected and located by the presence of gas phase tracers or contaminants.

A limitation of direct sampling as a means of verification and monitoring is in the number of samples required to properly characterize an area. Both the indirect physical property measurements (geophysical methods) and the potential field measurements tend to average the data over an area determined by the sample spacing. The data obtained from direct measurements can be averaged over an area defined by the sampling frequency, but this requires statistical considerations to the representativeness of the data. The development of variograms and the use of krigging are often employed for this purpose.

4.0 DISCUSSION

Several general site containment/remediation needs where presented as possible drivers for different verification and monitoring systems. These include short-term containment of a waste form, long-term containment of a waste form, and in-situ remediation or treatment. Each of these in-situ remedial alternatives will require different verification and monitoring approaches. These approaches range from imaging the subsurface, monitoring potential distributions, and direct sampling of the subsurface materials.

Additionally, some of the basic principles of subsurface barrier verification and monitoring were also presented. These addressed issues of imaging, mapping potential distributions, and sampling. Imaging is best achieved using geophysical principles coupled with the results of direct sampling. Passive potential field monitoring was presented primarily as a means of long-term monitoring of a system; however, it can be used in an active mode (i.e. pump test, etc.,) to verify the initial integrity of a barrier system. Direct sampling was presented as a means of verifying barrier performance.

While a number of technologies exist to addresses each of these issues, a fundamental understanding of when to apply a basic principle to meet the needs of a specific site must be addressed. Each of the verification and monitoring principles presented can be adapted to meet the site specific verification and monitoring needs given an understanding of the needs and principles of the technology. Such an understanding will also aid in the selection of the appropriate technologies for the site.

5.0 CONCLUSION

Verification and monitoring is integrally tied to the objectives of the subsurface containment and or remediation. A clear statement of the objectives is the basis for planning the verification and monitoring. Additionally, the physical system in which the verification and monitoring system is to be deployed must be understood to properly select and adapt the verification and monitoring methods. Therefore, in order to develop a verification and monitoring plan which meets the objectives of the remediation system and functions in the physical system present at the site, the verification and monitoring must be considered in the initial stages of the project development. Subsequently, a site-specific verification and monitoring system can be designed for optimum effectiveness and performance.

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