Geotechnical Engineering: The Observational Method Applied to Monitoring of Slopes during Operational Activities for Heap Leach Pad Facilities

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Abstract

The soil and rock materials within heap leach facilities (HLF) are heterogeneous, and precise assignment of their engineering geotechnical material properties is challenging during the design phase prior to operations. As such, it is critical to develop a comprehensive, robust "Observational Method" program using various methods to monitor the continually changing conditions of the HLF during operation activities. Prior to significant movements, there are typically measurable deformations, pore pressure changes, or other observable phenomena that provide indications of potential slope instability or HLF damage. Therefore, ongoing routine engineering oversight and investigations are incorporated into an Observational Method program to enable engineers to detect these continually changing conditions due to changes to the engineering geotechnical material properties (i.e., permeability, shear strength, material behaviour) during operations that may lead to slope instability.

To minimize this risk of slope instability, the Observational Method is used to verify that the construction and operation of the HLF is continually managed as discussed with the Engineer of Record (EOR) and/or within the intent of the engineering parameters from the design criteria. The design criteria are determined based on completing a thorough geotechnical investigation with surface and subsurface collection sampling, as well as laboratory testing programs, during the initial design stage and construction phases.

In addition, as part of this management, the geotechnical and operational teams in conjunction with the EOR use a series of overlapping collection methods for data sources, which generally consist of, but are not limited to, geotechnical investigations (sample collection and laboratory tests), visual inspections, pore pressure monitoring, and deformation monitoring. Monitoring should be performed on a regular schedule (i.e., hourly, daily, weekly, monthly, etc.) dependent on the data collection method, even if slope instability is not indicated, so that baseline data are collected and early slope instability data are detected.

Methods for sources of data include regular visual inspections by the geotechnical and operational teams, pore pressure measurements from piezometers, and deformation measurements using equipment such as, but not limited to, Global Positioning System (GPS) units or survey prisms, inclinometers, or shape arrays, and/or Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), or radar.

The geotechnical and operational teams, in conjunction with the EOR, utilize these data to develop critical slope stability models regularly spaced around the perimeter of the HLF, or critical locations as discovered during the Observational Method. Afterwards, slope stability model results are used to identify data gaps along each critical section, which are then circulated back into the Observational Method monitoring program. In addition, there may be a need to collect in-situ data via cone penetration tests (CPT) or drilling to collect samples for laboratory testing and/or install additional instrumentation, such as piezometers or GPS units, to provide more information to incorporate within the slope stability models and evaluation of the results.

Furthermore, slope stability model results and field observations are used to establish trigger levels to allow for proactive slope stability observational monitoring and provide for timely responses to changes measured by instrumentation (i.e., piezometers and deformation devices). Lastly, this interactive system is utilized to develop mitigation measures (i.e., changes with irrigation areas, irrigation rates, drainage systems, buttresses, etc.) to maintain the local, intermediate, and global slope stability of the HLF.

Introduction

The Observational Method was best described in the 1969 Rankine Lecture presented by Ralph Peck (Peck, 1969), regarding its use for the stability evaluation of a facility during construction where reliable factors of safety may not be readily quantified due to changing conditions in the field. A permanent HLF is under continual construction during the facility life as new ore is loaded onto the top of the pad, and irrigation rates as well as areas under irrigation vary and continually change across each lift. It is unlikely that a detailed design and engineering program will be able to accurately predict the engineering geotechnical material properties of the entire ore body prior to the start of mining, or estimate the conditions under which the facility will be operated during the life of mine. A comprehensive, robust observational monitoring program is required to provide sufficiently reliable data to evaluate the performance of the HLF during the life of mine with stacking and irrigation processes.

During the life of the HLF, these visual inspections and collected data (i.e., laboratory, instruments, etc.) as part of the Observational Method are utilized to adjust and reset the acceptance criteria originally determined during the design, and reassessed as necessary through the continual use of the Observational Method. As the amount of data collected from the monitoring program increases, the acceptance criteria for HLF performance may become more critical to the operation of the facility than the factor of safety for slope stability. Controlling seeps, erosion, and/or preventing large rates of deformation become the main focus of the Observational Method, using trigger levels as the focus for proper and safe operation of the HLF on a daily basis.

Geotechnical investigations

Initial geotechnical investigations during the design stage focus primarily on evaluating the geotechnical foundation conditions of the HLF and the geomembrane liner system. It is unusual to obtain fully representative samples of the ore material at this stage, and these are primarily sourced from core samples or metallurgical column test samples. This limited number of samples, which also tend to be limited spatially within the ore body, likely does not reflect the full variability of the engineering geotechnical material properties of the ore as stacked and irrigated during the life of the facility.

Periodic geotechnical field and laboratory investigations should be completed during the operational life of the HLF to allow for the collection and evaluation for the potential range of engineering geotechnical material properties for the ore. The investigation should include the collection of relatively undisturbed samples representative of ore materials stacked within the heap, as well as identify any areas of the facility that may be saturated, or nearly saturated.

In addition, the investigation should include laboratory tests that generally consist of, but are not limited to, particle size distribution, Atterberg Limits, triaxial, direct shear, etc. The collection and laboratory tests of these representative samples are particularly important as engineering geotechnical material properties will change over time due to the process of decrepitation, which is the mechanical and geochemical breakdown of ore during ore processing and leaching. Decrepitation is of particular concern when acid solutions are used as part of the leaching process where there is a high degree of geochemical breakdown of the ore.

An additional tool that can be used to develop engineering geotechnical material properties is the cone penetration tests (CPTs), if the HLF has a crush size to allow for pushing of the cone. CPTs can provide data on material behaviour types (Robertson, 2016), shear strength, pore pressure conditions, and other index properties of the ore. Periodic CPTs can also allow a geotechnical engineer to track if material behaviour changes over time (i.e., soils change from contractive to dilative, or sand-like to clay-like behaviour).

These behaviour types, as shown in Figure 1, are also useful to identify zones of the HLF that should be sampled over time, installation of piezometers, and identify potential areas of concern for further slope stability analyses.

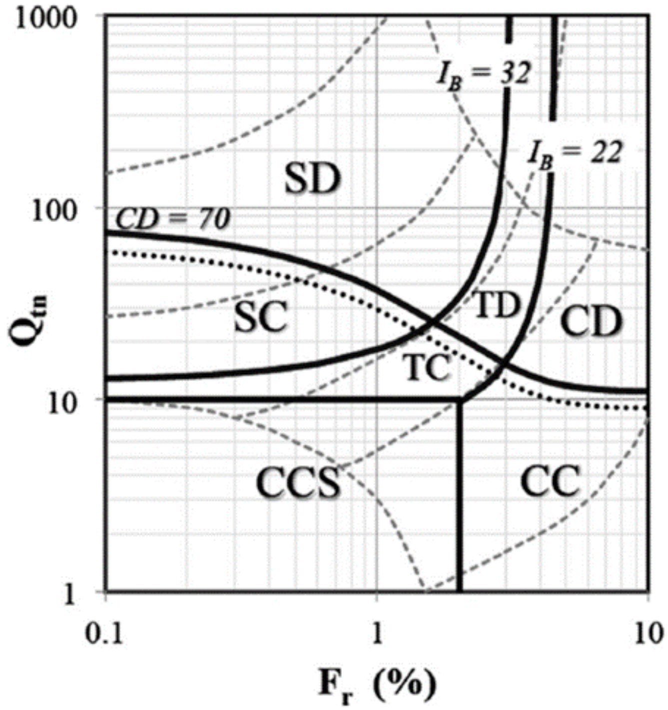

Figure 1: Robertson (2016) normalized CPT behaviour type (SBTn) chart

Visual monitoring

Visual monitoring provides direct observations of the HLF performance and allows operators to evaluate whether conditions have changed as compared to the expected conditions defined per the initial design criteria. For example, seepage reporting to the slope face could be a direct indication for the buildup of pore pressure within the HLF. A majority of designs for HLFs assume a free draining ore, and any pore pressure within the heap would constitute an abnormal condition. In addition, identification of cracking, bulging, or scarp development could be an early indication of slope movement.

The operation teams of the HLF should make periodic (i.e., weekly) visual inspections of the HLF to evaluate if any unusual or abnormal conditions exist. Unusual or abnormal observations include, but are not limited to the following:

- surface erosion
- gullies
- cracking
- scarps
- displacement
- bulging

- settlement/subsidence
- sinkholes and depressions
- piping (internal erosion)
- sloughing and slumping
- ponding on benches or near perimeter crest
- ore outside of the footprint of the pad
- seepage exiting the pad face
- vandalism or wildlife damage
- other abnormal conditions.

Regular visual inspections are the best way to identify potential slope instability or conditions that could lead to slope instability, as the majority of the surface of the HLF can be inspected. Monitoring using instrumentation can be limited as they are typically a single point in space and may not be currently installed in an area of concern. However, the use of instrumentation may also indicate specific areas that the operational team should investigate as part of the visual inspections. Furthermore, the visual inspections and the monitoring using instrumentation may dictate locations for geotechnical investigations.

Pore pressure monitoring

Piezometers are the primary method for measuring water levels or pore pressure within the HLF. Water levels are typically measured using open standpipe piezometers with a short section of screened casing that is sealed at the top of the screened interval to prevent water higher within the heap from infiltrating along the casing and reporting to the screened interval. Multiple open standpipes can be installed at a single location to provide information on the gradient of solution flow or determine if the water within the HLF is static or perched.

Pore pressure is measured using either vibrating wire piezometers or pressure transducers that are buried within a borehole so that they have direct contact with the ore and pore water. This allows for the immediate measurement of pore pressure changes where water levels measured in open standpipe piezometers will take time to fill up the piezometer casing through time in response to changes in pore pressure.

Figure 2 illustrates a piezometer time history plot where the measured pore pressure (orange line) is nearly at a trigger level (green line) and is actively being managed by pulsing irrigation to maintain an adequate factor of safety with respect to slope stability.

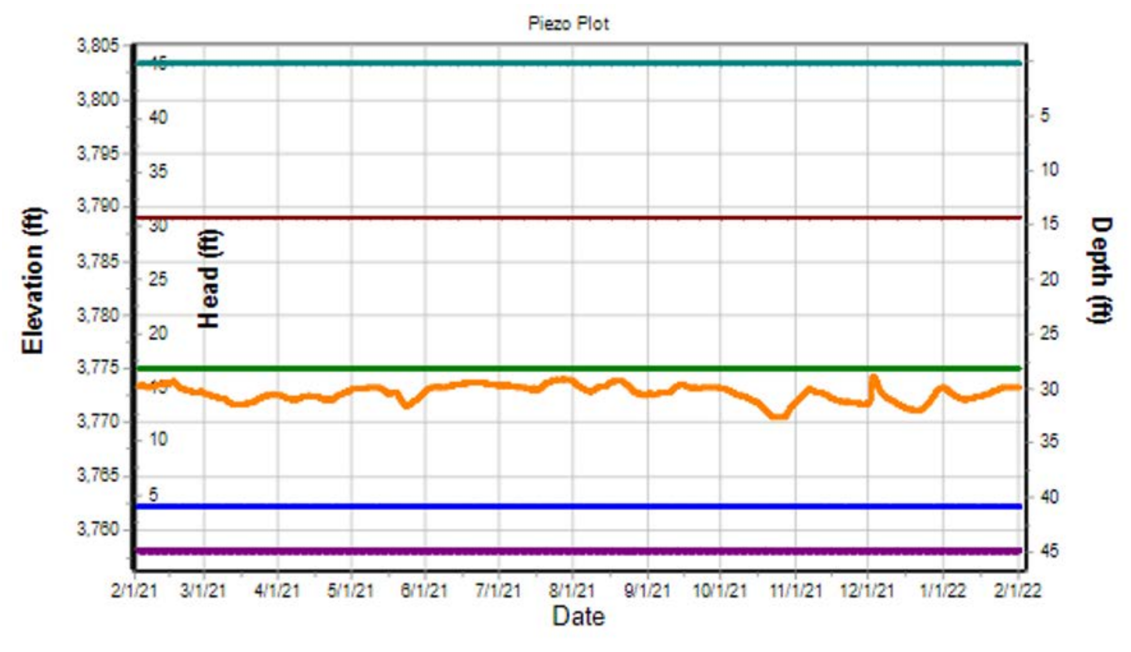

Figure 2: Piezometer time history plot

A companion method for evaluating pore pressure conditions within a HLF is the use of geophysical methods to identify areas of potential saturation using electrical resistivity measurements. This method allows for measurements taken along cross-sections of the HLF that can span across the entire height or length of the heap. Multiple cross-sections can be used to obtain an estimate of saturated areas, which can then be targeted during subsequent geotechnical investigations to confirm the presence of saturated conditions or identify areas for the installation of piezometers to measure the pore pressure.

Deformation monitoring

The intent of deformation monitoring is to observe the HLF and check that the performance and behaviour are as expected with the design intent so that the facility remains safe and operationally efficient. As a benefit, it also provides early warning of slope instability along the HLF. Remote deformation monitoring requires a variety of methods to develop a wholistic view of the response of the HLF to continuous stacking and irrigation of the ore. Each method of measurement provides a different scale of view, accuracy, frequency of measurement, and requirements for interpretation. They can also be used to corroborate the measurements from other instruments.

Any of the below methods have limitations with respect to accuracy of measurement that are often site-dependent, and it is critical that more than one method of deformation monitoring is used to verify measurements. For instance, InSAR can provide deformation measurements with sub-inch accuracy across areas of several square miles as long as the viewing direction of the satellite is oriented correctly with the

HLF. Furthermore, it may not always be obvious that the measurements are accurate and another method such as survey prism or GPS units should be used to confirm measurements in areas of abnormal deformations.

GPS units

Deformation measurements are collected by placing a GPS unit at a single fixed location, similar to a survey prism, and can be placed on a survey rod that can be moved to take measurements at multiple locations as required. The GPS unit simultaneously communicates with a nearby base station that corrects for any induced error by the satellite system providing the signal.

Stationary GPS units are permanent installations at a single location that continuously take measurements of the given location. Each unit takes numerous readings every few minutes and averages those readings every few minutes or hours to provide a more accurate location of the GPS unit. Readings can be automatically uploaded to a network server for review by the operation teams.

Survey prisms

Prisms are reflective mirrors attached to a frame that is anchored to the ground to allow for measurement of surface movement of the HLF. A total station instrument uses a laser that reflects off the prism's mirror and measures the distance between the total station and the prism. Measurements taken over time allow for estimates of the direction and rate of deformation. The total station requires relocation to different parts of the facility to obtain line-of-sight for each prism due to the size and shape of each facility.

Typically, a site uses a permanent total station location to provide more consistent measurements, reduce the error between measurements, and reduce the time required to collect measurements. However, this arrangement may require installation of several permanent total stations to monitor an HLF.

LiDAR

Fixed LiDAR stations are similar to total stations except they do not require a prism as a reflector. The energy projected by the LiDAR instrument is sufficient to obtain readings from a wide range of surfaces. LiDAR is also used on mobile equipment, typically truck mounted or unmanned aerial vehicle (UAV)/ drone mounted.

This allows for rapid measurements across a large area, provided there is adequate line-of-site between the mobile equipment and the area under survey. UAVs provide the greatest opportunity for making large LiDAR surveys.

InSAR

InSAR satellite imagery is used to evaluate the deformation of HLFs across large areas. Data is collected as a satellite passes over the mine site in either a descending or ascending flight path. Each flight path has a different orientation with respect to each facility and takes measurements. The accuracy varies per facility due to the relative orientation of the facility to the flight path. Each mine has areas without any measurements taken when the relative position of the area does not have a direct line-of-site to the satellite flight path.

Radar

Radar measurements are made in the same fashion as InSAR except from a land-based position, which allows for greater accuracy and frequency of measurements. Fix monuments are not required as readings are taken from any point on the ground within the line-of-site of the radar instrument. The rapid measurements taken can provide highly detailed maps of deformation across large areas and typically are used for monitoring active slope failures within open-pit mines. This allows for the rapid identification of movement and quick response to those movements.

The evaluation of the movement rate is primarily dependent on the time required to receive the data from the instrument and processing time for the quantity of data collected. Radar is significantly limited to measuring small incremental movements. However, the number of measurements taken often offsets this limitation by comparing snapshots of measurements through time to develop total displacement measurements and an average displacement rate as well as an inverse velocity.

Inclinometers

Inclinometers are used to measure the tilt of a structure and the occurrence of shear planes, typically below ground surface, using a casing with aligned grooves and a probe installed within the grooves. Subsequent measurements allow for a calculation of the differential tilt as well as an estimate of the rate and direction of deformation.

Measurements can be taken manually with a probe being lowered and raised in each pair of grooves, a permanent installation using a string of probes locked to the grooves, or a shape array installed within the casing but not within the set of grooves. The manual probe and fixed probe in the grooves are limited to measuring deformation in the orientation of the grooves, which requires an interpretation of the data to estimate the direction of movement.

The shape array allows for measurement of deformation in any direction. Figure 3 provides an example inclinometer plot with measured displacement indicating the potential development of one or more shear planes.

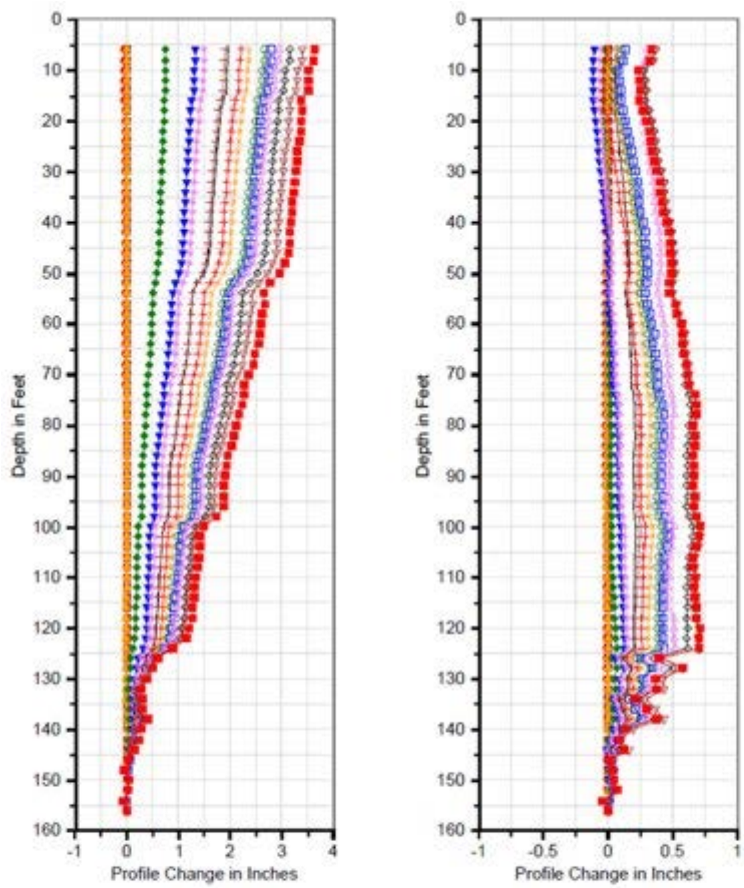

Figure 3: Example inclinometer plot indicating potential shear plane development

Inclinometers are typically installed into a layer of soil or rock that is estimated not to move as part of the general deformation for the HLF monitored to allow for valuations of total deformation. However, this is problematic for geomembrane-lined HLFs where the inclinometer cannot anchor unless anchored through the geomembrane liner. These instruments can still be useful to evaluate mid-slope deformation, but cannot be used for total deformation estimates if there is any movement along the geomembrane liner surface.

Slope stability modeling

The data collected from the Observational Method monitoring program should be used to develop, and over time, refine slope stability models along critical sections to define factors of safety under existing conditions and evaluate pore pressure conditions for maintaining acceptable factors of safety. The slope stability models should include ore material characterization developed from the geotechnical investigation (including laboratory tests and CPT results), pore pressure conditions, and slope geometry of the existing HLF as well as expected geometry during the near future. Potential failure modes can be evaluated with the model utilizing data obtained from the various methods. Deformation monitoring might indicate zones of high deformation or the development of a failure plane within the HLF. Trigger levels for pore pressure monitoring should be developed for pore pressure conditions to allow the operating team to evaluate whether changes of pore pressure will lead to unsafe slope stability factors of safety.

Figure 4 provides an example slope stability model with material behaviour types developed from CPT and a network of piezometers used for development of pore pressure conditions.

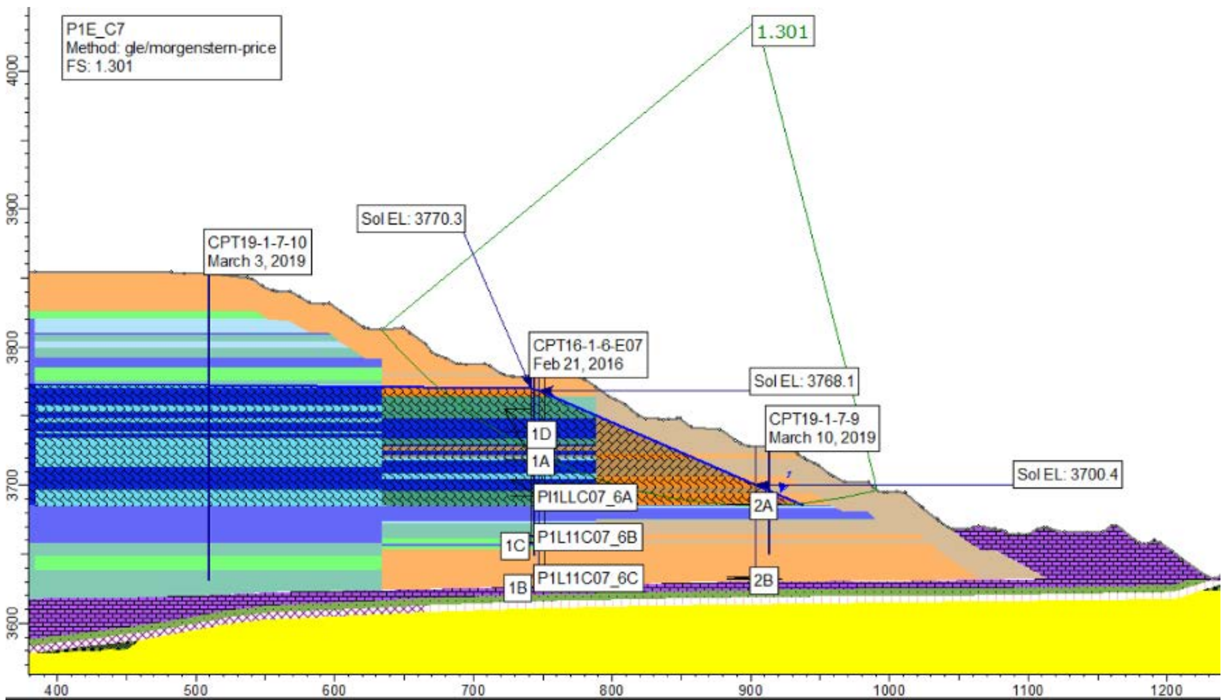

Figure 4: Example slope stability model

During the model development, each critical section should be evaluated to determine if there is sufficient data to accurately represent the subsurface conditions for both material behaviour types and for pore pressure conditions. This evaluation can be used to identify future geotechnical investigation locations for collecting samples to perform laboratory tests or CPTs, as well as where piezometers should be installed to provide additional detail about the pore pressure conditions.

The results of the slope stability models can also be used to evaluate and design mitigation measures if minimum factors of safety are not reached. If piezometers rapidly react to changes in irrigation, then irrigation rates could be reduced to decrease pore pressures (refer to Figure 1) along a critical stability section. If seepage at the slope face is identified as the critical condition for failure, then drainage systems (i.e., French drains, horizontal drains, wells, collection pipes, etc.) could be installed to control the seepage. If conditions continue to deteriorate, then a buttress could be designed to improve factors of safety for current conditions and anticipated future conditions to maintain slope stability during the remaining life of the HLF.

Acceptance criteria

The results of slope stability models, data collected from instrumentation (i.e., piezometers, deformation, etc.), InSAR, and visual monitoring are used to generate acceptance criteria (identified through key performance indicators) that are likely to govern daily performance and maintenance of the HLF facility more than by factors of safety alone. For example, seepage flow rates, erosion, and height of saturated ore within the slope face will dictate local slope stability that might not be captured by assumed critical stability cross-section locations.

As another example, deformation rates that exceed previously measured rates may indicate a zone of instability. These changes may occur during time frames that do not allow for updating slope stability cross-sections or locations with insufficient data that factors of safety cannot reliably be calculated.

Conclusions

Operational variability among ore engineering geotechnical material properties and operating conditions (i.e. stacking rates, irrigation rates and timing, rates of decrepitation, etc.) over time will likely require re-evaluations of design assumptions through the life of a HLF. The Observational Method provides a framework for the geotechnical investigation associated with the collection of data that can be used to verify initial design criteria or develop new design criteria based on actual field performance of a HLF.

The key to the Observational Method is having sufficient data to justify a need to change the initial design criteria that was used for the design of the HLF. The Observational Method is utilized to possibly adjust and reset these acceptance criteria originally determined during the design and reassessed as necessary through the continual use of the Observational Method. The data also needs to be verifiable from different sources as there are always inherent errors in measurements and observations.

Therefore, a comprehensive, robust Observational Method program having more than one method and source for evaluating pore pressure conditions (seepage mapping from visual monitoring, piezometers for direct pore pressure measurements, geophysical methods for area of extent measurements and pore pressure distribution based on CPT) and/or deformation (visual monitoring for unusual cracking, GPS units for displacement measurement, and InSAR for area of extent measurement) is critical to verifying field conditions, performance and slope stability models for the continual monitoring of the HLF to maintain slope stability.

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