1st North American Landslide Conference

June 3-8, 2007
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1st North American Landslide Conference

Vail, Colorado - June 2007

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GEOLOGY IN LANDSLIDE ENGINEERING

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Abstract: Geology is a critical component in geotechnical engineering analysis and mitigation of landslides. Specific factors related to the cause of a landslide can be identified in the geology, such as low strength rock or soil, faults or bedding planes, and hydrostatic pressures.

Regional geology is important in the study because it can uncover factors that are most useful in guiding a geotechnical investigation. Regional geologic criteria to be sought in landslide investigations include material types, geomorphic landforms, geologic structures, groundwater conditions and weathering, among other factors. These criteria can be used to estimate the boundaries of a landslide, and to assess the susceptibility and incidence of a landslide. Geomorphic evaluation of geologic patterns and landforms is a key part of the regional study.

Local geology is important in mapping the boundaries and surface features of a landslide to understand the landslide mechanics. Typical local features include: slopes, scarps, cracks, grabens and mounds; vegetation type, extent and condition; surface water conditions; manmade features; etc.

Examples of regional and local geology in a geotechnical engineering investigation of a landslide demonstrate its application. Three examples are presented to: describe its use or misuse in determining the cause of landslide damage, show how it can be used to better understand the relationship of landslide movement to a road and a reservoir, and demonstrate how geology can make sense of chaotic information.

INTRODUCTION AND PURPOSE

This paper and presentation emphasizes and strongly recommends including the study of the regional geologic setting as well as the local geology in the modeling, analysis and mitigation of landslides. This task should be the initial part of an investigation to collect information for geotechnical analysis and design.

The solution to engineering or fixing a landslide is typically found in the subsurface conditions, i.e., the geology. Therefore, a critical understanding of geologic conditions and processes is essential before a geotechnical engineering model is drawn. This is especially important for most medium-sized to larger landslides with plan areas greater than 20,000 square feet. The geologist’s role is to provide insight into the physical boundaries, mechanics, and groundwater system of the landslide. Critical geologic interpretations enable the engineering model to be defined with accuracy, which in turn improves the reliability of the analyses and resulting designs. Misunderstood geology or no consideration of the geology can lead to misinterpretation of failure conditions and incorrect solutions. Geology will help make sound design decisions or, after a failure, help determine causation and errors in design.

The intent of this paper and presentation is to demonstrate how the inclusion of sound geologic principles in geotechnical investigations can help produce better results. Regional and local geologic criteria that should be used in evaluating landslides are reviewed below, and their importance is discussed in three examples. Due to sensitive issues at the example landslides, geographic information and references to previous work were intentionally omitted. For detailed reviews of the methods for observing and mapping landslides, see Keaton and DeGraff (1996), Cruden and Varnes (1996) and Cornforth (2005).

GEOLOGIC CRITERIA

Tables 1 and 2 provide summaries of regional and local geologic criteria that are used in landslide investigations. Some landslides can be characterized from a few key features, while others need extensive assessments of many of the criteria to develop an accurate model for engineering analysis.

A geologic investigation should start at the regional scale. Look for factors that could influence a geotechnical investigation, such as stratigraphy, susceptible rock or soil, evidence of a groundwater system, weathering, tectonic deformation, other landslides, manmade features, etc. Some of these factors may be observable only at a distance from the site and can be overlooked if the regional geologic setting is not studied.

Local criteria should be sought at a site-specific scale to identify the characteristics of an individual landslide. Local geologic factors include the geotechnical parameters of rock and soil, shapes and dimensions of surface features, age of surface features, etc.

Regional and local factors should be used to focus the efforts of the site specific investigation, for instance, locating exploratory drilling to collect critical subsurface data. Exploration and monitoring should target specific causative factors, such as weak rock or soil, hydrostatic pressures and changes to site conditions.

Regional Criteria

Regional criteria for a landslide investigation are summarized in Table 1. The objectives of the regional study are to determine:

- Physical boundaries of a landslide.
- Susceptibility or likelihood of occurrence of a landslide, i.e., which material is more likely to fail and why.
- Incidence or spatial distribution and frequency of landslides, i.e., where and how often do landslide occur in time and area.

Table 1. Regional Geologic Criteria in a Landslide Investigation

Material Units	Rock type, soil type, occurrence, variations, facies, basic chemistry, geotechnical properties (assumed or known).
Geomorphology	Landforms and their origin.
Structures	Bedding, joints, faults.
Groundwater	System(s), resource.
Weathering	Climate, rate.
Other	Seismicity, tectonics, uplift/subsidence, base level changes, vegetation, Pleistocene and Holocene geologic history.

Assessment of regional criteria typically begins with researching the availability of information, and then extracting the factors that influence the landslide. Typical sources of information include, but are not limited to:

- Topographic maps (typically USGS 7.5 minute quadrangles)
- Aerial and satellite photography
- GIS databases
- Digital terrain models including Laser Imaging Detection and Ranging (LIDAR)
- Geologic maps, reports and papers
- Geologic field trip guides
- Natural Resource Conservation Service soil reports

With available information in hand, geologic study begins with geomorphic evaluation of patterns in the topography or terrain model, such as shapes or polygons, lineaments, and drainages. Two common examples of geomorphic patterns include differences in slope on a topographic map, or the tree-shaped pattern of a dendritic drainage. The steep slopes of resistant rock and the gentle slopes of weak rock create a pattern on a topographic map that reveals the relative strength and location of the underlying material. The tree-shaped pattern of a dendritic drainage reveals a homogenous underlying material, the pattern of which can be interrupted when one of the tributaries follows the trace of a fault or is diverted by a change in rock or possibly a landslide.

Geomorphic patterns can be grouped to assess the frequency, distribution and relationships of underlying geologic material. A pattern itself or a disruption in the pattern can reveal the presence of a landslide(s). In combination with a simple understanding of the geology, patterns reveal the materials that likely form the physical boundaries of a landslide, such as the presence of low-strength rock/soil, structures (joints, faults), facies within a geologic unit, and three dimensional boundaries.

In some cases landslides may not reveal themselves in regional geologic patterns. They could be masked by the scale or quality of the information source, which makes the assessment of local criteria more relevant.

Local Criteria

The making of a landslide site plan and field-developed cross section (Williamson *et al.*, 1991) uses local criteria. Local criteria are the features of the landslide that are related to the specific site conditions, which control the shape and size of a landslide. Combining observations and measurements can create an accurate prediction of the subsurface geometry.

Examples of local geologic criteria are the shape, dimension and location of a headscarp, backscarp, toe and lateral scarps. These features are an indication of the mechanics and depth of slide movement, for instance, the width of a graben can correlate to the depth of a translational slide. Another example is the relative age of the features, i.e., is the scarp old and from a previous episode of movement or is it related to current movement? The answer of which might indicate that slide conditions have changed.

In addition to geology, local criteria can also be gained from other disciplines such as soil science, botany, forestry, mathematics and, of course, geotechnical engineering. A list of local criteria that can be used in the field is summarized in Table 2.

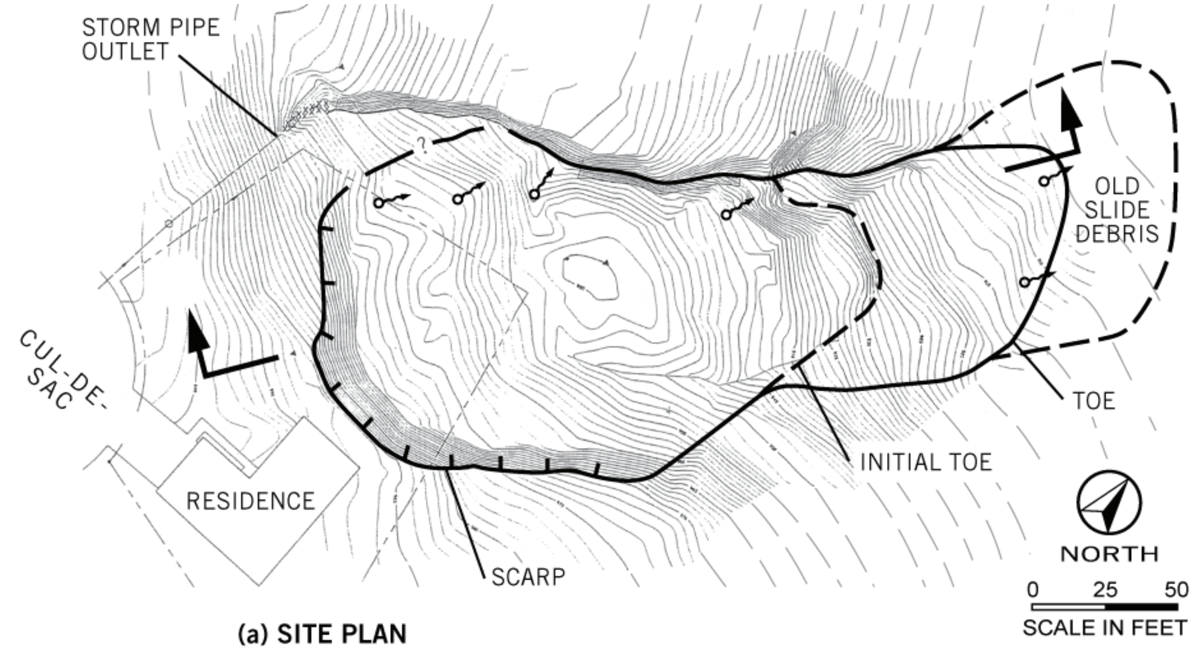
Table 2. Local Geologic Criteria in a Landslide Investigation

Location	Location and vicinity map. General comments with ballpark directions and distances. Photographer positions.
Type of slide	Translational, slump, debris flow, rockfall/ravelling, soil creep, other. General description.
Slide scarp	(Head, lateral, toe). Slope angle, height, soil/rock type, vegetative state, width and length of graben if any.
Ground cracks	Location, characteristics (size, pattern, shape, relative movement, etc.), freshness, age, etc.
Terrain	Overall slope angle (compare to angle of undisturbed slope), patterns, orientations, and slopes of surface features.
Soil	Characterize (density/consistency, color, classification), type, age, thickness.
Rock	Characterize (hardness, weathering, color, fracturing/jointing, mineralization, distinguishing features), Formation name (if known).
Sag pond	Location, size, degree of siltation or infill.
Springs, seeps	Location, surrounding soil and rock type, rate of flow, chemistry.
Creeks	Location, channel morphology, bed load characteristics.
Vegetation	Type, age, degree and shape of tilted/bent trees.
Erosion	Location, extent, cause and level of activity.
Roads, utilities	Deformation, displacement, cuts/fills (height, thickness, volume).
Measure and sketch	Plan map, field developed cross section, balanced geometry (area and volume), measurement methods.

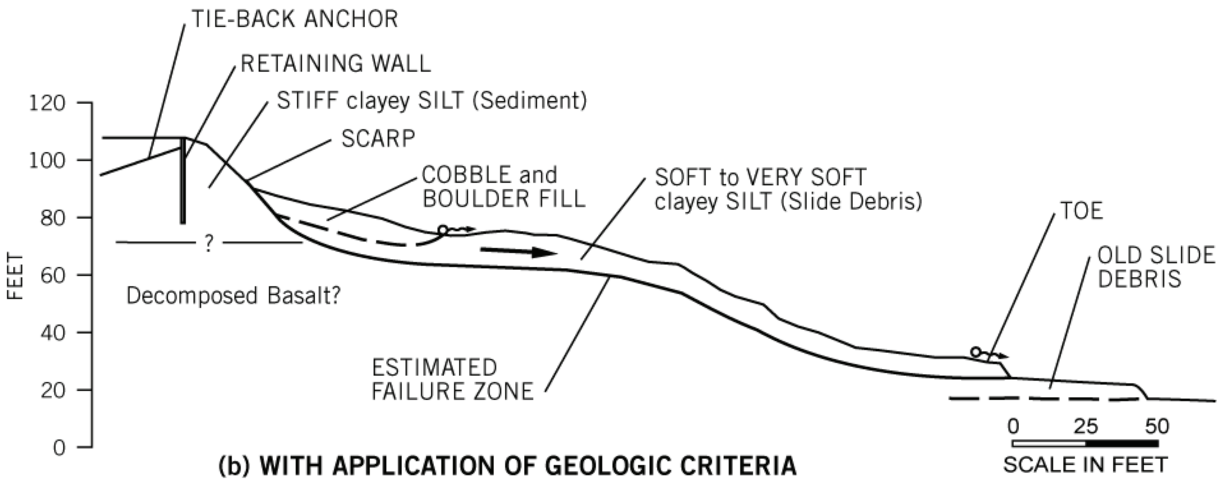
EXAMPLE 1

A home owner built a tied-back soldier pile retaining wall to protect property at the top of a half-acre landslide. Initially, it was believed that the slide was caused by erosion below a storm pipe outlet. Subsequent to construction of the wall, the slide was investigated as part of an evaluation into measures to control erosion on the slope. Figure 1 provides a site plan and cross section interpretations of the landslide.

Regional geologic criteria were limited for this example. Published geologic maps indicated that the area was comprised of a deposit of fine-grained sediments overlying weathered basalt bedrock. Interpretation of available aerial photographs was hindered by dense forest. The feature was too small to be visible on a standard 1:24,000 USGS 7.5 minute quadrangle topographic map. Publicly available LIDAR with 2 meter resolution provided hints at the ground features, but the scale of the slide was again too small.



(a) SITE PLAN



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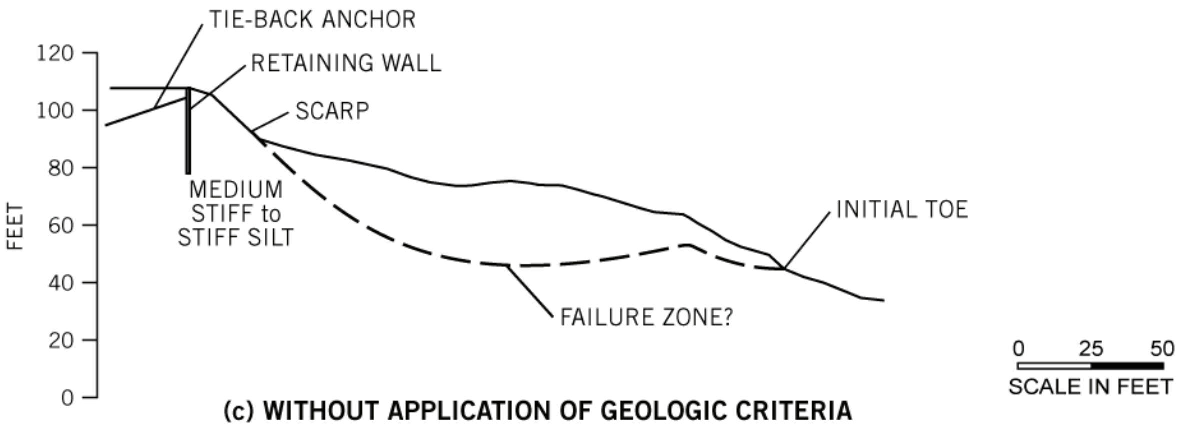

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Figure 1. Example 1 site plan and cross sections

Geologic reconnaissance identified a very slow flowing slide mass. As shown on Figure 1a, the upper slide is bowl-shaped, the middle of the slide narrows as the bowl-shaped mass becomes constricted in a swale, and the lower part of the slide was a flow of very soft and saturated soil creeping downslope.

A number of springs were observed in the slide, some emitting from bouldery fill within the upper slide mass. An eroded gully followed along one side of the slide, which initiated at a storm pipe outlet located a few feet to the side of the upper slide. Downslope of the toe, the drainage had eroded through a small bench and exposed soil that had a texture of flow slide debris. The "bench" appeared to be the toe of an older slide that probably originated at the same location.

From the regional geology, it could be anticipated that the subsurface materials would present a perched groundwater condition. From the local geology, it was determined that a landside had previously occurred at this site. Also, the fill that was within the upper slide would surely have a negative impact on its stability.

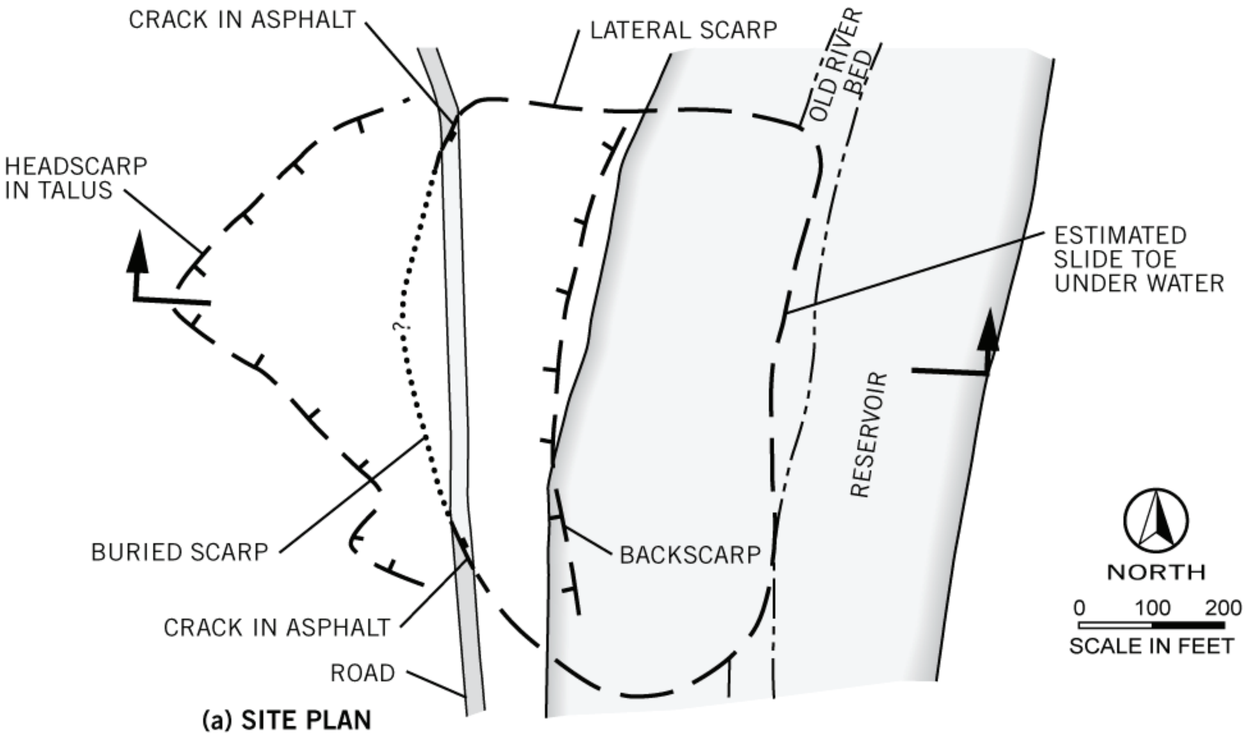
Due to the landslide damage, the homeowner claimed (without application of geologic criteria) that the land agency was liable due to the erosion caused by concentrated runoff at the storm drain outlet. If a complete geologic understanding was included in the litigation, the results may have been different. In addition, assumptions of the subsurface conditions were made in the design of the retaining wall. Based on the location of the fill and the buried spring, additional investigation of subsurface conditions should probably have been performed. Currently, the agency has the responsibility to mitigate erosion at an unstable landslide. Also, potential poor foundation conditions and future slide movement may threaten the integrity of the retaining wall.

EXAMPLE 2

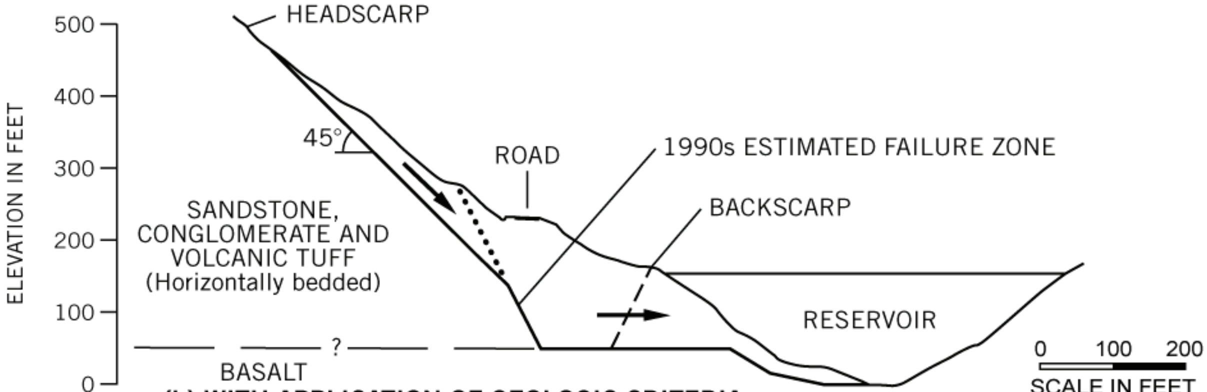
In the early 1960s, a landslide impacted a road shortly after construction of a reservoir, a state park, and an access road. Maintenance repairs to the roadway were performed during the 1960s and 1970s. More disruptive movement occurred in the 1980s. As a result of geotechnical studies in the late 1980s, the road was lowered 20 feet and 25,000 cubic yards of material were removed to unload the slide. However, the slide continued to move and annual maintenance was needed to keep the road and park open. Figure 2 provides a site plan and cross section interpretations of the landslide.

In the 1990s, renewed geotechnical investigation included evaluation of geologic criteria including three critical factors. The regional geology consisted of near horizontal-bedded conglomerate, sandstone and volcanic tuff overlying a sequence of basalt. In adjacent drainages that were eroded through the same geologic material large groundwater springs were known to occur at the base of the sediments. In addition, ancient or paleo-landslides were also recognized in the drainages. The toes of the paleo-slides were apparently at a low elevation on the valley slopes, possibly near the base of the sediments.

The road traverses the lower portion of a 500-foot high talus slope, and the talus is toeing on a sloped bench along the shoreline of the reservoir (Figure 2). A complex pattern of ground features was observed during field mapping. The major features, shown on Figure 2, include a headscarp that crosscut the middle of the talus slope, a set of cracks crossing the road inside of the headscarp, and a prominent backscarp near the shoreline. Based on the relative position of these three features, it became apparent that a deep translational slide block was being pushed into the reservoir by the down-dropping graben, which in turn was being loaded by the failing



(a) SITE PLAN



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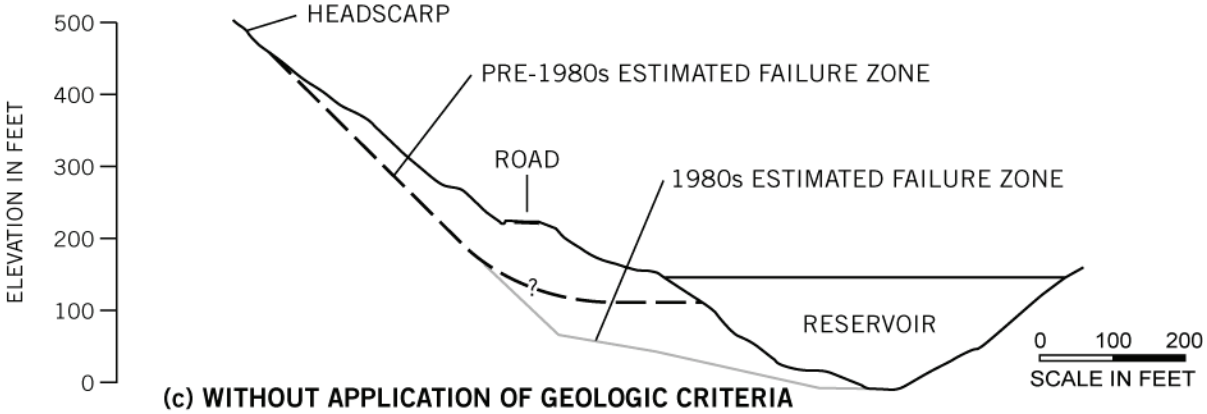


(c) WITHOUT APPLICATION OF GEOLOGIC CRITERIA

Figure 2. Example 2 site plan and cross section

talus slope (Figure 2b). Based on the width of the graben, the thickness of the sliding block could have been as deep as or deeper than the reservoir; however, with the anticipated depth of basalt rock, the depth of the slide was probably above the old river bed.

Based on the geology, a single drilling location at the shoreline was recommended to measure the depth and rate of ground movement and groundwater pressures beneath the slide mass. However, the proposed location was in an environmentally sensitive area. With negotiation that included discussion of the geologic model and the importance of the location to the results of engineering analysis a drilling permit was awarded for this difficult site. One inclinometer and two vibrating wire piezometers were installed at the shoreline, with results that confirmed the geologic model and demonstrated the relationship of the reservoir level to the slide movement.

The inclusion of geology in the study provided the information necessary to diagnose the condition of the landslide and to determine the geotechnical drilling that was needed. Based on the results of the geotechnical analyses, the road agency and the reservoir owner were able to understand how the road maintenance practices and annual lowering of the reservoir were causing movements of the landslide.

EXAMPLE 3

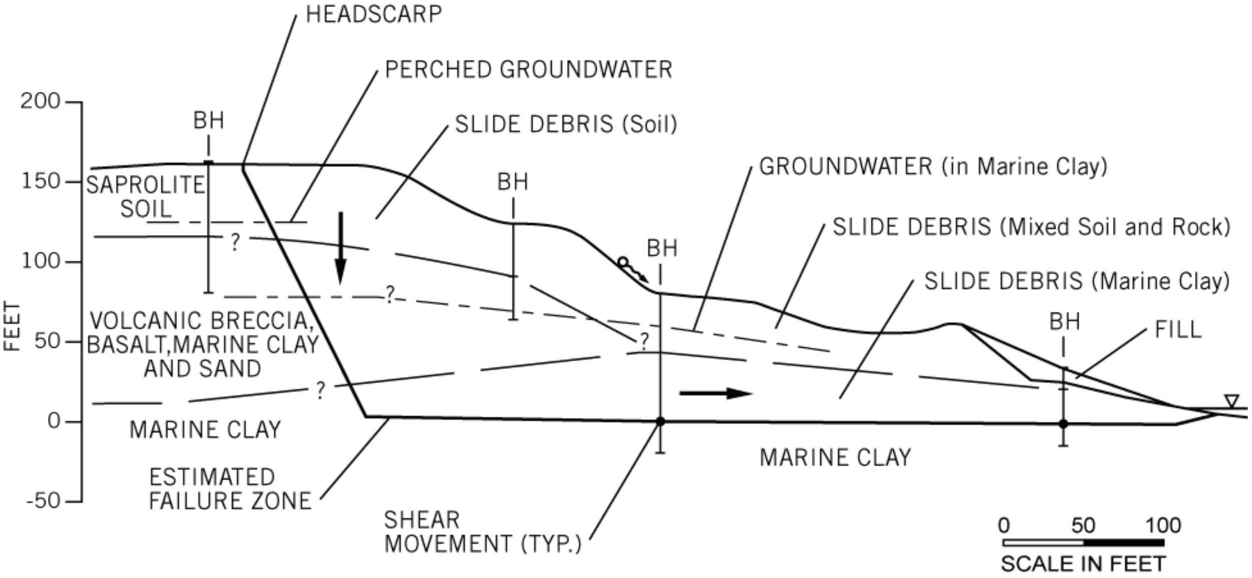
Construction was progressing on a multi-million dollar facility when a large section of a 100-foot high marine bluff started to slide, threatening to delay the project. In the emergency, geotechnical drillers from an adjacent foundation investigation were quickly diverted to the landslide. Rapid drilling and limited samples were taken to quickly investigate the landslide and install slope inclinometers and piezometers. Figure 3 provides interpretive cross section of the landslide.

Geotechnical drill holes encountered thick saprolite soil of soft to medium stiff clayey silt and medium dense fine sand overlying marine sediments and fresh to decomposed rock (Figure 3b). The underlying material varied widely, and included a chaotic mix of fresh vesicular basalt, medium stiff to stiff clayey silt, loose to dense marine sand, hard marine clay, silt with gravel, and boulders. Two inclinometers measured shear movement at a depth below sea level, which was much deeper than the previously suspected top of the underlying marine clay. Groundwater was measured at depths of about 20 to 30 feet. Geotechnical data of the landslide was obtained; however, the mechanics of the landslide were not understood.

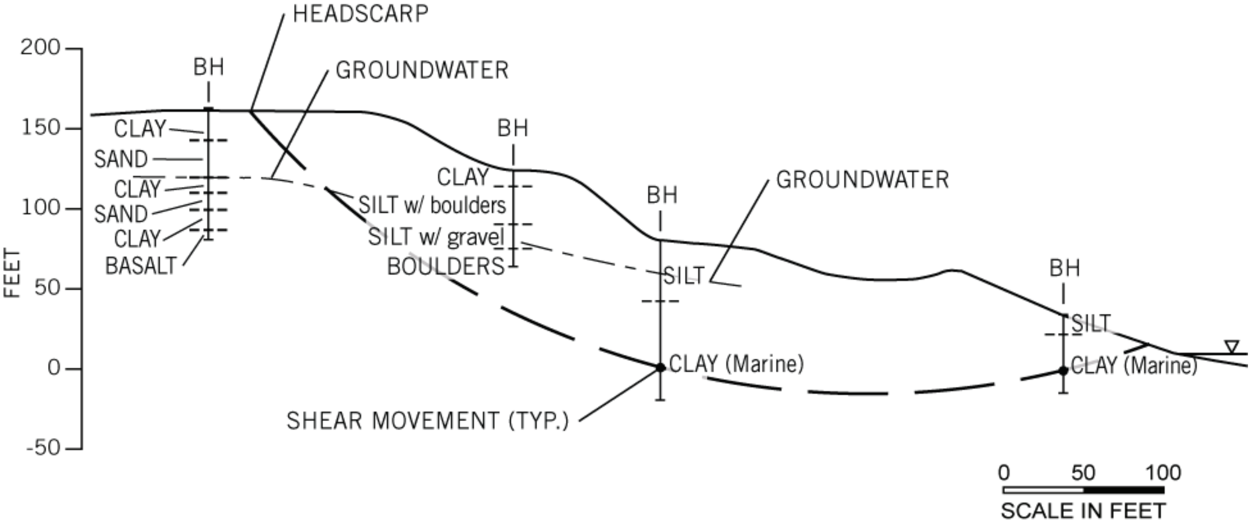
Regionally, the location was on the shore of a volcanic island, downslope of a deeply eroded section of the mountain. Therefore, the site geology was anticipated to be comprised of lava flows and volcanic sediments interfingering with marine sediments. Also, because the site was located in a region of high precipitation, weathering was expected to be significant with volcanic materials decomposing to low strength clayey soil.

Local mapping identified a complex assemblage of volcanic and marine deposits. The volcanic materials included basalt flow breccia, lahar and tuffaceous debris flow breccias, and mega-breccias with clasts on the order of 20- to 100-foot size. Intermixed within the volcanics were deformed and injected lenses of marine clay, silt and sand along with apparently normally stratified deposits of marine sediments. It appeared that the volcanics were emplaced into a marine environment, in part, as rapid or catastrophic deposition of debris flows and lahars. In addition, groundwater springs were observed at locations that did not correlate well with the measured groundwater levels.

The data that had been obtained created a confusing picture, which challenged the geotechnical engineering modeling of the landslide. To simplify the information, subsurface materials were divided into three units: overburden, volcanic material and underlying marine sediments (Figure 3a). Also, groundwater was determined to consist of two systems: shallow perched groundwater within the mixed material and deeper underlying groundwater with hydrostatic pressure at the failure zone. The geologic evaluation produced a relatively simple model of a translational block landslide on over-consolidated marine clay. The deep groundwater level also correlated well with the calculated landslide stability. Ultimately, results of the geologic evaluation improved confidence in the geotechnical model, engineering analyses and various mitigation options. In turn, construction management obtained the confidence of the owner to disperse emergency funds and keep the construction project on track.



(a) WITH APPLICATION OF GEOLOGIC CRITERIA



(b) WITHOUT APPLICATION OF GEOLOGIC CRITERIA

Figure 3. Example 3 cross sections

CONCLUSION

Geology is an important component in landslide modeling, stability analysis and design of landslide mitigation. Regional geology is important in the study because it can uncover factors that are useful in guiding a geotechnical investigation. Geomorphology is critical for identifying geologic patterns and shapes that reflect the underlying geologic conditions.

Local geologic information is important for mapping the boundaries and surface features of a landslide, which reveal the depth and mechanics of landslide movement. Specific factors related to the cause of a landslide can be identified in the geology, such as weak rock or soil, hydrostatic pressures and changes to site conditions. Such factors are important in geotechnical exploration, monitoring and analysis.

Based on experience, landslide investigations that use geology to their advantage are more likely to identify the specific cause of a landslide and, therefore, target their investigation and analysis to design the most appropriate mitigation. Geology in landslide investigations can increase confidence in engineering analysis and help to avoid failures and their consequences.

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