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Executive Summary

Daniel B. Stephens & Associates, Inc. has prepared this feasibility study (FS) update to address remediation of ongoing land movement in the Portuguese Bend Landslide Complex (PBLC) using the results of past environmental, engineering, and hydrogeologic work completed to address regional slope failure on the greater Palos Verdes Peninsula. This FS is an update to efforts completed primarily in 1997 and 2000 that characterized the hydrogeologic and geotechnical conditions driving landslide activity and proposed a variety of various approaches and technologies to abate slope failure in the PBLC. ~~Remedies appropriately~~

Earlier remedies focused, in part, on the removal of subsurface water (groundwater) and the elimination of continued stormwater loading to groundwater in key areas.

Some proposed recommendations were implemented after the 1997 FS was drafted, including installation of dewatering wells, mass regrading, and surface water infiltration control with an above-grade piping system. However, land movement was largely unabated, and slope failure continues today at rates of up to approximately 8 feet per year. Slope failure is continually managed by a City of Rancho Palos Verdes (City) maintenance program, with significant cost and effort to maintain area utilities and the nearby roadway in a functional state. Additional measures, including a major excavation for a buttress extending nearly half a mile along the coast, were proposed in 2000, but were not implemented.

This FS ~~update~~ focuses on ~~implementable, effective, and~~implementing cost-effective technologies as options for ~~stormwater~~ the City to consider regarding storm water control and groundwater extraction to achieve manageable and sustainable land stability. ~~Traditional~~Other geotechnical engineering solutions, such as buttresses, were also considered with other options, but were screened out due largely to poor overall implementability.

The ~~selected remedy consists of installing a flexible liner system in the upper and lower canyons in the watershed where stormwater directly infiltrates to groundwater in the~~ FS remedies focus on the southern PBLC area ~~and directing flow to a stormwater~~ mainly within the control ~~channel discharging to the ocean. Groundwater extraction is proposed to be completed with several~~

~~subsurface directional gravity drains (horizontal drains or hydraugers). Drains would be installed from the coast extending north under Palos Verdes Drive South into and under the area of greatest~~ of the City that is subject to a relatively high level of land movement~~.~~, where the surface water drainage currently is not functioning properly, and where groundwater extraction is most needed. ~~Once drains take effect and the groundwater surface is lowered in key areas, groundwater extraction with a traditional but expanded extraction well network is also proposed to supplement the horizontal drains where needed. Preliminary three-dimensional slope modeling confirms that a reasonable reduction in the elevation~~An engineering analysis and evaluation of the ~~groundwater surface~~ existing stormwater drainage system of ~~5 to 15 percent would result in a significant reduction in land movement in the PBLC area. Annual~~this area should be completed to assist in the design and construction of an updated system to convey runoff to the ocean and eliminate ponding areas which have been created over the years due to land settlement. At the same time, efforts need to be made for design and installation of groundwater extraction drains (horizontal drains or hydraugers). Hydrauger design and installation can be tested and modified based on results obtained. These horizontal drains could be installed, for example, into the coastal bluff and extend north under PVDS, and directly drain into the ocean.

Further, it is recommended to perform an engineering analysis of the watershed including the northern canyon areas (upper Portuguese, Ishibashi, and Paintbrush Canyons) to identify where, how and to what extent stormwater infiltrates into groundwater in the PBLC. Subsequently, efforts could be made for design and installation of an environmentally friendly flexible liner system in the watershed canyons where the stormwater significantly infiltrates to groundwater in the PBLC in an attempt to minimize this infiltration and allow the stormwater to be discharged to the ocean in a controlled manner.

Further, it is recommended to identify existing surface fractures throughout the PBLC area and install land surface fracture sealing ~~is also a component of the selected remedy. Surface fractures in the PBLC should also be filled in before the rainy season each year to prevent~~with environmentally friendly material to minimize direct~~,~~ uncontrolled stormwater infiltration~~, deep percolation, and groundwater recharge.~~ which currently percolates into groundwater. These sealed surface fractures in the PBLC should be checked and maintained annually prior to the rainy season.

Finally,Sanitary sewer septic systemssystem effluent in the area haveupslope areas has long been recognized as a source of groundwater recharge in the PBLC area that needs to be eliminated. AIn addition to the above options, it is recommended that the City consider working with its neighboring city, Rolling Hills, to construct a centralized sanitary sewer system is proposedand a storm water drainage system for the Portuguese Bendresidential neighborhood andat the uppertop of the watershed above the Portuguese, Ishibashi, and Paintbrush Canyon areas in the adjacent City of Rolling Hills at the top of the watershed, as well as within the City's Portuguese Bend neighborhood.

Importantly, the selected remedy options identified can be implemented in accordance with the Palos Verdes Land ConservancyCity's Natural Communities Conservation Plan./Habitat Conservation Plan (NCCP/HCP). Several stormwater control and groundwater extraction remedy elements, as envisioned, can be designed to be largely integrated into the native habitat.

Estimated order-of-magnitude costs for implementation of the selected remedyrecommended remedies total approximately $31.3 million, with additional operating, maintenance, and monitoring costs totaling $22 million approximately over 30 years. Additional hydrogeologic and geotechnical data are needed, however, before full-scale design can proceed.will be collected as an integral step leading to final design and implementation. In addition, remedy construction is proposed to be completed incrementally and iteratively starting with a pilot test program for directional subsurface drains. Drain pilot testing costs (included in above estimates) are estimated to total approximately $350,000 over about 12 to 18 months.

Stakeholder participation has been identified as a key pathway to project success and community acceptance. It is recommended that public workshops be scheduled at various stages of project implementation which could include the design phase, pre-construction, any pilot testing implementation and post construction phases of the project.

1. Introduction

This report has been prepared by Daniel B. Stephens & Associates, Inc. (DBS&A) to present the methods, results, and conclusions of the Portuguese Bend Landslide Complex (PBLC) feasibility study (FS) update. This FS update has been completed to summarize the physical characteristics of the PBLC and vicinity, and to systematically compile historical PBLC investigation work, related vicinity geologic and hydrologic studies, previous efforts toward achieving land movement stabilization, and regulatory drivers that will impact implementation of PBLC stabilization measures. The currently available information has been presented and analyzed in this FS update in order to identify techniques and technologies that can be implemented to stabilize the PBLC. PBLC stabilization will be considered achieved when a significant reduction in land displacement is recorded, as measured by the land survey monitoring system currently in place or a successor land survey methodology.

The format of this FS broadly follows the U.S. Environmental Protection Agency (U.S. EPA) FS format (U.S. EPA, 1988) developed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). That is, this document is a CERCLA-analogue FS. The time-tested CERCLA FS approach is a systematic, methodical, and thorough concept-level process widely accepted in the engineering industry to develop, analyze, and select cost effective mitigation alternatives that can be accepted by federal, state, and local regulators and community stakeholders.

This introductory section presents site background information, regulatory history, the purpose and objectives of the FS, and a summary of community involvement opportunities.

1.1 Site Background

1.1.1 Overview and Problem Statement

The PBLC is located along the south central section of the Palos Verdes Peninsula within the City of Rancho Palos Verdes in Los Angeles County, California ~~(Figure 1).~~. The terminus of the active landslide complex, and generally the southwest boundary of the PBLC, is the Pacific

Ocean. In this location, the shoreline runs in a generally northwest to southeast direction along the coastal coves known as Portuguese Bend on the east and Smuggler's Cove (Sacred Cove) and Abalone Cove on the west. (Figure 1). Two other prominent features on the coastline at the terminus of the PBLC are Inspiration Point and the more westerly Portuguese Point. The eastern border of the PBLC is formed by an approximate line that runs northward from western Yacht Harbor Drive to the confluence of Ishibashi and Paintbrush Canyons. The northern boundary of PBLC is a small distance south and subparallel to Burma Road, a trail that was established along the path of the former proposed Crenshaw Boulevard extension. Construction for the Crenshaw Boulevard extension was begun in the 1950s but was never completed. The western boundary of PBLC is an approximate north-south line located a small distance west of Peppertree Drive in a residential neighborhood. The western boundary terminates south of Palos Verdes Drive South (PVDS) and west of Portuguese Point.

Ehlig (1992) describes PBLC as being divided into two parts. The main part is described as moving towards Portuguese Bend (Figure 2). The western segment is described as moving into Sacred Cove between Inspiration Point and Portuguese Point. The main landslide has an area of about 190 acres and the western segment has an area of about 70 acres. Later, as reported by Douglas (2013), the PBLC was further divided into several subslides: (1) inland, (2) eastern, (3) central, (4) seaward, and (5) western subslides (Figure 3).

Douglas (2013) reports that the PBLC (along with the Abalone Cove landslide to the west of PBLC) is a reactivated part of an approximate 2-square mile ancient landslide mass termed the Altamira Landslide Complex on the overall south flank of the Palos Verdes Peninsula. Douglas (2013) states that the landslide mass is a composite of numerous slides ranging from small slumps to large translational block slides that have occurred over the last approximately 800,000 years. Contrary to this view, Ehlig (1992) states that the slide originated about 120,000 years before present and was a megaslide that started moving as a unit but fragmented as movement progressed. A guide to landslide terminology, such as earthflow or landslide complex, is included as Appendix A for reference.

Regardless of the original movement of the larger landslide mass, in 1955, reactivation of the PBLC was initiated when Los Angeles County was constructing an extension to Crenshaw

Boulevard with the goal of extending the road down the south side of the Palos Verdes Hills to an intersection with PVDS. A relatively small landslide was triggered in 1956 during the road construction, and approximately 160,000 cubic yards of material was removed and placed at the head of the PBLC. MacKintosh and MacKintosh (1957) concluded that the sliding area had a very low factor of safety (FOS) prior to movement in 1955, and that the immediate cause of movement in 1956 and 1957 was the placement of approximately 3 million cubic feet of fill upon which to build the Crenshaw Boulevard extension. Consistent with antecedent instability noted by MacKintosh and MacKintosh (1957), Douglas (2013) reported that evidence of movement in historical aerial photographs had been discovered as early as 1948, and slide damage to the Portuguese Bend Club pier had been noticed as early as 1946. MacKintosh and MacKintosh (1957) observed that the most rapidly moving portion of the slide, on the eastern side of the slide, traveled about 22 feet in the seven months between September 17, 1956 and April 26, 1957.

Douglas (2013) reported at the time of Crenshaw Road extension project that houses in the area were using septic waste systems that recycled household water into the subsurface, and that the neighborhoods did not have storm drains. Both of these factors had been contributing to groundwater recharge in the PBLC area by the time the road construction began. Douglas (2013) also stated that Converse Consultants concluded that increased pore water pressure that resulted from elevated groundwater levels was a significant causal factor.

Since the reactivation in 1956, the slide has moved at various rates. In general, the area of greatest movement has stayed the same and is focused in the eastern and seaward subslide areas as reported by Douglas (2013) and described above. Figure 4 presents a map of the horizontal displacement that occurred between October 8, 2013 and September 19, 2014. Horizontal displacement of over 8.5 feet per year was measured within the eastern and seaward subslides.

Continued land movement in the PBLC area over the last several decades has resulted in significant infrastructure damage to homes, utilities, and roadways. The City of Rancho Palos Verdes has expended nearly 50 million dollars over the years repairing and maintaining the damage and addressing the overall technical and administrative issues associated with managing such a complex problem.

1.1.2 Regulatory Background

Historically, the primary driving force for conducting projects to stabilize the PBLC has not been of regulatory origin. Preservation of infrastructure, preservation of private property, preservation of open lands, preservation of the natural vegetation and recreational attributes of the Palos Verdes Nature Preserve (Preserve), reduction in soil erosion losses, restoring the water clarity in Portuguese Bend Cove, reduction in the cost of operation and maintenance of infrastructure, and health and safety concerns related to maintenance of the integrity of the key road system, the sewer system, and other infrastructure have been the leading drivers that have motivated the City of Rancho Palos Verdes and citizens to strive to achieve stabilization of the PBLC. As a result, there is little in the record that involves regulatory action with respect to the PBLC. Nonetheless, the following is a summary of applicable regulatory based actions taken relative to historical PBLC projects that may influence future work in the PBLC.

In September 1987, the Rancho Palos Verdes Redevelopment Agency (RDA) proposed a grading and drainage project as part of a series of projects designed to contribute to the stabilization of the PBLC. The project was examined on a general basis in previous environmental impact reports (EIRs) prepared by the RDA. This particular EIR provided an analysis of environmental impacts associated with grading, drainage, and relocation of PVDS. The final proposed project incorporated alterations that mitigated non-significant short-term negative impacts.

The Community Development Commission for the County of Los Angeles also completed a National Environmental Policy Act (NEPA) environmental assessment and the project was found to be in compliance with applicable laws and regulations and did not require an environmental impact statement (EIS). A finding of no significant impact (FONSI) was made stating that the project would not significantly affect the quality of the human environment (City of Rancho Palos Verdes, 1987).

In 1988, a general investigation study by the U.S. Army Corps of Engineers (USACE) was authorized by Public Law 99-662, Section 712 of the Water Resources Development Act of 1986, to study the feasibility of constructing shoreline erosion mitigation measures in order to provide additional stabilization for the PBLC and adjacent landslide areas (USACE, 1998). The authorization read that the Army was ". . . authorized to study the feasibility of constructing shoreline erosion mitigation measures along the Rancho Palos Verdes coastline and in the City of Rolling Hills, California for the purpose of providing additional stabilization for the Portuguese Bend landslide area and adjacent landslide areas."

The study focus was on controlling sedimentation and turbidity in the nearshore and offshore zones that result from erosion at the shoreline, which impacts the marine species and habitat of the area. Additional fish and wildlife enhancement studies were authorized in the Water Resources Development Act of 1990, Section 116 which read ". . . investigative measures to conserve fish and wildlife (as specific in Section 704 of the Water Resources Development Act of 1986), including measures to demonstrate the effectiveness of intertidal marine habitat." The reconnaissance study was initiated in October 1988 and completed in 1990, with a recommendation to proceed to a feasibility study based on a plan to help stabilize the landslide. However, a decision by the Assistant Secretary of the Army stated in a letter dated October 28, 1991 that "Landslide stabilization is outside the purview of the Army Civil Works program." The reconnaissance report was revised in 1992 to reflect that decision, and no further study was recommended.

In anticipation of another proposed Portuguese Bend Grading Project located within the City of Rancho Palos Verdes Redevelopment Area, an initial study was prepared in September 1994 in accordance with the provisions of the California Environmental Quality Act of 1970 (CEQA) as amended (Public Resources Code Section 21000 et seq.), and the State CEQA Guidelines for Implementation of the California Environmental Quality Act of 1970 as amended (California Code of Regulation Section 15000 et seq.). The project site was comprised of three vacant non-contiguous areas located on the eastern portion of the PBLC.

This report of the initial study complied with the rules, regulations, and procedures for implementation of CEQA adopted by the City of Rancho Palos Verdes (the Local CEQA

Guidelines). The project grading activity, specifically cutting and filling within the PBLC, proposed the removal of approximately 50,000 cubic yards of earth material from a cut area approximately 6.25 acres in size located in the southeastern portion of the PBLC. The project also proposed redistribution of the 50,000 cubic yards of earth material to two previously graded/disturbed fill areas. The reported purpose of the proposed project was to reduce driving forces in an active portion of the PBLC by moving earth from a driving force area to a neutral area of driving force (EDAW, 1994).

In accordance with Section 15050 and 15367 of the State CEQA Guidelines, the City of Rancho Palos Verdes was designated as the lead agency, defined as the public agency that has the principal responsibility for carrying out or approving a project. The project was funded by the RDA and implemented by the City working for the RDA. After implementation of the initial study, it was concluded that although the proposed project could have a significant effect on the environment, there would not be a significant effect in this case because of mitigation measures that were added to the project. As a result, a mitigated negative declaration was prepared. Mitigations required as a component of the approved project included the following:

- Control of construction-generated dust
- Cessation of vehicular traffic when the wind speed exceeds 15 miles per hour (mph)
- Appropriate NO_x emission controls on construction vehicles
- Minimization of footprint for construction vehicle routes
- Identification of optimum construction vehicle routes to avoid areas of sensitive vegetation
- Preparation and review of erosion control plans by the Director of Public Works and a qualified biologist to protect sensitive plant species and minimize disturbance to non-sensitive plant species
- Post-construction re-establishment of vegetation

- Prohibition of grading/construction during the mating/breeding/nesting season for the California gnatcatcher and the coastal cactus wren (mid-February through July)

- Limitation of construction hours to Monday through Saturday, 7:00 a.m. to 5:00 p.m. (noise control)

- Equipment of construction equipment with mufflers (noise control)

An extensive biological assessment of the Rancho Palos Verdes development area was attached to the study that was based on a literature review and field surveys of the study area and, in some cases, surrounding areas. It is noteworthy that the study concluded that the proposed project would not impact the quality of existing recreational opportunities and that the project was not located in an area of existing recreational use, or designated for recreational activity. That conclusion may require re-evaluation to consider current uses of the area.

Another initial study to evaluate a proposed erosion control project was conducted in 1994 (EDAW, 1994). The proposed project consisted of the placement of three drainage inlets and a 48-inch corrugated metal pipe (CMP) at the bottom of Portuguese Canyon, from PVDS to a point in the canyon approximately 1,600 feet north of PVDS. Approximately 350 linear feet of 1211 CMP was to be placed on the surface and staked down at each joint or at intervals not to exceed 15 feet.

The proposed project also involved minor grading and brush removal at the bottom of the canyon, as necessary for installation of the drainage pipe and inlets. A finding was issued that, although the proposed project could have a significant effect on the environment, there would not be a significant effect because the mitigation measures described on an attached sheet have been added to the project. Preparation of a negative declaration was recommended (EDAW, 1994).

Subsequent to the Secretary of the Army declining to participate in a landslide study, Congress added funds for a feasibility study to develop a shore protection project that would provide for restoration of the natural marine habitat at Rancho Palos Verdes. An agreement between the City of Rancho Palos Verdes and the USACE to perform the study was signed in December

1994. The alternative selected as the proposed recommended plan in the feasibility study was to construct a dike 400 feet offshore with natural removal of sediment deposits in the restoration area by wave action.

1.1.3 Recent Community Involvement

The Landslide Subcommittee of the Rancho Palos Verdes City Council organized and held a series of public meetings on June 1, June 20, June 29, and July 6, 2017. The purpose of the meetings was to invite the community to participate in creating and identifying goals for the PBLC and to discuss the path forward in addressing the challenges faced by the community with respect to the PBLC.

At the first public meeting, held on June 1, 2017, goals were identified that included the following:

- Control of the PBLC and attendant costs
- Stabilize residences
- Retain use of PVDS
- Protect the integrity of the Preserve and preserve the marine ecology
- Restore the ecology of the ocean and land resources
- Explore the possible of a geological hazard abatement district (GHAD)
- Identify plausible potential solutions
- Provide the basis of a design-build proposal to solicit federal funding

The June 20, 2017 public meeting focused on potential solutions and/or actions for intercepting water on the PBLC. The meeting discussions were wide-ranging, and emphasized (1) the need to fully understand the hydrology of the watershed in which the PBLC is located, (2) the need to re-establish and maintain an effective stormwater control system, (3) the importance of capturing and controlling water before it gets into the PBLC, and (4) to minimize impacts to Preserve land.

The June 29, 2017 public meeting addressed the effects of the PBLC on the surf zone. Consensus of the participating public focused on (1) hiring competent engineers to implement recommendations, (2) early communication with relevant regulatory agencies (e.g., Coastal Commission) regarding any planned PBLC projects, (3) use of road maintenance funds to underwrite the necessary technical work needed to slow the PBLC movement, and (4) assessment of the environmental impacts to the Preserve land and ocean ecology plus restoration of potentially damaged habitat to its original condition.

The July 6, 2017 meeting focused on major actions that could be considered as a means of addressing the PBLC problem. As with a previous meeting, the public consensus focused on understanding the hydrology of the PBLC, understanding the occurrence of groundwater as it relates to the movement of the PBLC, and understanding and completing previous work on surface drainage.

On October 17, 2017, a meeting was held between representatives of the City, DBS&A, the PVPLC, and the ~~PVPLC~~Wildlife Agencies to discuss potential impacts of PBLC solutions within the context of the City's draft Natural Community Conservation Plan~~ and ~~/Habitat Conservation Plan (NCCP/HCP~~) (URS, Undated). The purpose of the meeting was to discuss potential impacts of PBLC solutions within the context of the NCCP/HCP.~~). The City's goal for the meeting was to develop a programmatic policy ~~that ensured~~ensuring that, while the probability for successfully resolving the PBLC problem was maximized, all appropriate measures were being considered to minimize potential impacts to biological resources within the Preserve.

1.2 Project Area Definition

This FS focuses on significantly reducing land movement in the defined Red Zone area (project area) of the PBLC, where land movement has consistently been measured at the greatest rates. As shown in Figure 2, in addition to PBLC, landslides in the southern Palos Verdes Peninsula include the Abalone Cove, Portuguese Bend, Flying Triangle, Klondike Canyon, and most of the Ancient Altamira Landslide. All of these landslides are located within the City of Rancho Palos Verdes except for the majority of the Flying Triangle Landslide, which is in Rolling Hills.

As described by Douglas (2013), two of the landslides, Portuguese Bend and Abalone Cove, are reactivated parts of a much larger and older slide mass that covers over 2 square miles and extends from the crest of the peninsula, near Crest Road, to the shoreline. Douglas (2013) named this ancient landslide mass the "Ancient Altamira Landslide Complex."

Douglas (2013) reported that the Abalone landslide and surrounding area, including portions of the ancient landslide complex, has been largely stabilized through the use of groundwater dewatering using vertical wells. The Klondike and Flying Triangle Landslides are closely related in space and time to the PBLC and Abalone Landslides, and are also part of the Ancient Altamira Landslide Complex, but they are commonly considered separate failures (Douglas, 2013).

The PBLC project area within which land movement is being addressed by this FS is the area of greatest movement within the PBLC. As shown in Figure 4, the area in which measured horizontal movement has ranged from 1 foot, 10 inches to 8 feet, 7 inches is the area of greatest PBLC movement (the Red Zone). As mapped, the Red Zone is approximately 86 acres in area. This Red Zone area comprises what Douglas (2013) delineated as the eastern, central, and seaward landslide subareas of the PBLC, along with a small portion of the western PBLC landslide subarea, south of PVDS to the ocean.

The total PBLC area is approximately 250 acres (101 hectares) in area. However, the area of land on which conditions that contribute to landslide instability exist is much greater. Numerous hydrologic, geologic, and engineering reports of the PBLC have concluded that controlling the water that enters into and is stored in the PBLC subsurface is critical to achieving landslide stabilization. Therefore, this FS considers that the selected landslide stabilization solution will be implemented over an area larger than the PBLC or the Red Zone itself. Water can move into the PBLC subsurface, where it contributes to instability, via three pathways.

The first pathway is via rainfall and stormwater that runs off and subsequently infiltrates and percolates into the subsurface. Water is also introduced into the subsurface through residential use and disposal via onsite wastewater treatment systems (e.g., septic systems), a second pathway. The third pathway is via groundwater underflow. Groundwater underflow occurs when groundwater that has percolated to the water table in one location migrates laterally to another location. In the PBLC location, previous contouring of groundwater levels indicates that groundwater is moving in the subsurface from upslope areas to the north of PBLC toward the south.

As a result, the larger area that is being considered when targeting a PBLC landslide stabilization solution is the watershed. A watershed is defined as the area of land bounded peripherally by a divide and draining ultimately to a particular watercourse or body of water. For example, in Portuguese Canyon, the watershed is defined as the land area from which all water that drains will ultimately drain into Portuguese Canyon. Based on review of topographic and drainage maps along with the use of field observations and aerial photographs, subsurface water in the PBLC is being impacted by water from Portuguese, Ishibashi, and Paintbrush Canyons. Figure 5 depicts the combined watershed boundary of the three canyons.

1.3 Purpose and Overview

This FS report has been prepared consistent with methodologies that have been developed pursuant to CERCLA, also known as Superfund. Specifically, this FS was prepared using methodologies presented in the *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (U.S. EPA, 1988). The CERCLA FS process is typically used to abate the risk of exposure to toxic environmental contaminants. In this project, toxic contamination is not an issue, and the criterion related to reduction of contaminant toxicity is removed from consideration.

The resulting FS process represents a systematic methodology established for characterizing the nature and extent of complex problems, evaluating potential remedial options, and selecting the optimum remedial solution~~.~~ options for the City's consideration. The overall goal of the FS process is to gather sufficient information to make an informed management decision regarding potential remedial actions, and to develop a comprehensive, reliable, restoration strategy that satisfies community and regulatory requirements. The specific purpose of this FS is to identify ~~and select a~~viable conceptual solution options that will accomplish the following project goals:

- Provide the geotechnical conditions that significantly reduce the risk of damage to public and private property and would allow for the significant improvement of roadway infrastructure, safety, and stability.

- Significantly reduce human health risk and improve safety in the City of Rancho Palos Verdes.

- Significantly reduce sediment dispersal and deposition into the Pacific Ocean that is causing unacceptable turbidity in the coastal and marine environment.

- ~~Make all reasonable efforts to identify a~~Select remedy options that will be consistent with the Natural Communities ~~Conservation Plan (~~NCCP~~) and the Habitat Conservation Plan (~~/HCP, specifically Section 4.1.2~~)~~.

1.4 Document Organization

This FS document generally follows the methodology and organizational format of the CERCLA feasibility study process (U.S. EPA, 1988). Section 1 presents an introduction that includes project background, history, project purpose, projection area definition, and a description of community involvement with the project. Section 2 provides a summary of the relevant previous work related to the PBLC and vicinity that forms a foundation for moving forward toward remedy selection and implementation options. Section 3 present a description of the physical characteristics of the project area including topography, watershed hydrology, soils, geology, groundwater, and landslide characteristics. Taken together, Sections 1 through 3 represent a characterization of the current information and data available to use in defining the PBLC setting and problem.

Using the information and data presented in Sections 1 through 3 as the basis, Section 4 presents the remedial FS section of the report. Sections 4.1 and 4.2 present the introduction and purpose of the FS and the summary of infrastructure concerns related to the PBLC, respectively. Section 4.3 presents the applicable or relevant and appropriate requirements (ARARs) potentially governing remedy implementation. Section 4.4 establishes the remedial action objectives (RAOs). Section 4.5 establishes general response actions (broad classes of available technologies) to control movement of the PBLC. Section 4.6 identifies and screens the identified technologies appropriate to achieve the RAOs. Section 4.7 provides a more detailed discussion and analysis, presenting the pros and cons, of the technologies most suitable to achieve RAOs. Finally, the preferred alternative~~(s) is selected and~~ options are identified in Section 4.8 as the most appropriate technology and methodology to address RAOs. An analysis of remaining data gaps, the need for pilot testing, and an estimate of the cost of implementation of the selected remedy are also presented.

2. Summary of Previous Work

As noted by Douglas (2013), numerous geologic, hydrogeologic, environmental, and engineering studies have been completed and numerous reports have been produced by several authors over the years since the PBLC was first recognized. Not all of the documents have been digitally archived and some information has likely been permanently lost over the years. However, some key documents are available that describe past efforts and designs for land stabilization that are useful to review and form a foundation for moving forward toward a solution. These documents, supplemental to those described in Section 1.1.2, are summarized below.

2.1 Historical Documents, 1957-1997

In 1957, a report was written that described the ground movement of an approximately 200-acre area of land extending from above a major body of fill on Crenshaw Boulevard southward to the Pacific Ocean (MacKintosh, 1957). The report recommended that immediate emergency action be undertaken ". . . to protect the large investment in homes, streets, sewers, communication lines, and other utilities and improvements." As of 1989, over 140 homes have been destroyed. Of the residents that remain, home utilities and foundation structures must be maintained continuously. It was also reported that over 10 million tons of mud and rock were deposited in the ocean. Disruption of vital community transportation and utility transmission lines is continuously threatened and millions of dollars have been spent to maintain community safety and services.

Between March and August 1957, the County of Los Angeles and Palos Verdes Properties installed a group of 22 reinforced concrete caisson "shear pins" across the active failure surface in an effort to stabilize the PBLC. Each of these caissons was 4 feet in diameter, 20 feet in length, and embedded 10 feet into the material underlying the "failure surface" as it was understood at that time. The landslide reportedly slowed by approximately 65 percent (from 0.8 to 0.25 inch per day) following the installation of these shear pins. This reduced rate of movement was only maintained for approximately five months. In early 1958, the landslide abruptly returned to its pre-shear pin displacement rate of nearly 0.8 inch per day. Several intact shear pins have since been displaced to, and deposited on, the shoreline by subsequent landslide movement and wave action (Ehlig and Yen, 1997).

From the late 1950s through the mid-1980s a series of geologic and engineering studies were conducted to understand and characterize various aspects of the PBLC and related landslide complexes in the vicinity.

In 1972, Palos Verdes Properties provided financial support for a dissertation that analyzed the reasons for the movement of the PBLC (Vonder Linden, 1972). The report stated that "If movement were halted by eliminating infiltration of water, lowering the existing water table, and regrading parts of the slide surface, the factor of safety thereby would be raised to a value of at least unity."

The City of Rancho Palos Verdes was incorporated in 1973, and at that time the City took over the maintenance of roads and utilities in the PBLC area within the City limits. It was reported that approximately 20 percent of the City budget for street maintenance was spent for the 0.8± mile of PVDS through the landslide (Ehlig and Yen, 1997).

In September 1978, the Rancho Palos Verdes City Council adopted Urgency Ordinance No. 108U, which established the Landslide Moratorium Area in and around the PBLC. In February 1981, the City Council adopted Ordinance No. 139U, which added the area known as Klondike Canyon to the Landslide Moratorium Area.

In 1984, the City put a landslide stabilization plan of control (POC) into operation. In 1984, it was reported that the PBLC was moving over 40 feet per year. The stabilization plan consisted of installation of dewatering wells, major surface drainage, and regrading redistribution of earthen mass. This initial effort has since been called Phase I (Ehlig and Yen, 1997). It was reported that 5 years after initiation of the POC, the PBLC was moving less than 1 foot per year.

The RDA proposed a grading and drainage project in September 1987, as Phase II of the POC intended to stabilize the PBLC (Ehlig and Yen, 1997). The grading portion performed in January and March 1988 involved redistribution of 500,000 cubic yards of earth from areas where the slide plane was steep to areas where the slide plane was relatively level so that the weight of the landslide material acted as a resisting force rather than a driving force. Generally speaking, the rate of slide movement responded positively to dewatering, regrading, and surface drainage improvements in Phase I and II, but these were not ultimately able to stop the slow movement. In fact, the rate of movement increased in subsequent years as earlier work deteriorated.

Following a period of severe wave erosion and shoreline regression in early 1988, rock-filled wire baskets (gabions) were installed along the western shoreline of the landslide in 1988 in an attempt to reduce the rate of wave erosion. Although this temporarily abated the erosion, the gabions were essentially destroyed within an 18- to 24-month period by the combination of wave action, corrosion of the wire baskets, and landslide deformation (Ehlig and Yen, 1997).

In January 1989, the USACE held a public information workshop to present to the community a study it was beginning in order to identify the federal interest in solutions to problems associated with shoreline erosion mitigation measures and storm damage along the coast of Rancho Palos Verdes, including consideration of how such a solution would contribute to landslide stabilization. In June 1993, the Assistant City Manager of Rancho Palos Verdes wrote a memorandum describing an upcoming workshop on the RDA's interaction with the USACE on a feasibility study for shoreline protection and marine environmental restoration. The discussions centered on the need for shoreline protection, not landslide abatement.

~~Grading (~~Phase III~~)~~ grading was completed during August and September 1990. This phase of grading involved the relocation of approximately 60,000 cubic yards of soil from the central uphill margin of the landslide to the eastern portion of the failure immediately upslope of PVDS. Following this unloading, perceptible movement of the Landward Zone appears to have stopped until the heavy rainfall of January 1995. Between the completion of the 1990 Phase III grading and 1995, the rate of landslide movement gradually increased to approximately 0.25 inch per day (Ehlig and Yen, 1997).

In 1991, Rancho Palos Verdes staff gave a presentation to the City Council on the progress of the stabilization plan. The progress reported included the performance of extensive geologic investigations using the services of 25 experts in the fields of geology and engineering. In addition, $1.5 million had been spent to implement grading, dewatering wells had been installed, and drainage structures had been constructed to control and convey water through the PBLC.

In September 1994, a consultant proposed a grading project to the City of Rancho Palos Verdes in which several areas of the PBLC slide area were identified as “cut” zones where 50,000 cubic yards was to be removed, and other areas of lower elevation were identified as “fill” zones. As with the earlier proposed grading project of 1987, the purpose was to reduce driving forces in an active portion of the PBLC by moving earth from a driving force area to a neutral area of driving force.

In 1997, the City of Rancho Palos Verdes and the USACE commissioned a study to determine the impact of the PBLC on the ocean environment (Abbott Associates, 1997) that concluded that 3,589,000 cubic yards of earth had entered into the ocean as a result of landsliding.

2.2 1997 Ehlig and Yen Feasibility Study

A preliminary geologic and geotechnical engineering report was jointly prepared by Perry Ehlig (Ehlig) and Bing Yen & Associates, Inc. (BYA) which was presented to the City Council of Rancho Palos Verdes in 1997. The report evaluated the feasibility of a POC developed in 1995 by Ehlig and BYA and amended it for the 1997 report. The POC was intended to minimize or arrest the movement of the more rapidly moving portion (East-Central Subslide) of the PBLC and if successful, would provide valuable insight on the feasibility of stabilizing the western portion of the PBLC.

The scope of work of the study incorporated compilation and evaluation of the historical surface and subsurface data to determine where additional exploration was needed to develop a preliminary geotechnical model for analysis. The study also consisted of installation of 13 additional monitoring wells to characterize groundwater, drilling of 18 large-diameter, 8 rotary-wash, and 4 rotary-core boreholes for subsurface mapping of the slide plane(s), and collection of slide plane samples for additional laboratory testing. Back calculation of the slide behavior was performed on the slide model to calibrate the soil parameters and confirm the validity of the model. Assessment of the proposed POC in mitigating the slide movement was done using the model to identify primary and supplemental mitigation techniques and their effectiveness. Based on the results of the POC assessment, conclusions and recommendations were presented in a formal report.

Based on movement patterns, geologic, and/or geomorphic features, the PBLC was subdivided into subslides. The subslides were classified on increasing displacement rates which include, from the lowest to greatest rate of movement, the Landward, the West-Central, the East-Central, and the Seaward subslides. The study estimates that for the period from 1956 to 1996, rates of displacement range of the subslides range from 0.2 to more than 1.5 inches per day, and that the higher rates are associated with periods of above-average rainfall.

The Ehlig/BYA POC recommended removal of approximately 450,000 cubic yards of slide plane clay from the upper portions of the Landward and East-Central subslides of the PBLC. This plan requires the excavation and removal of approximately 2.65 million cubic yards of landslide materials. They estimate that roughly 100,000 cubic yards of the landslide materials would consist of bentonitic (slide plane) clay, which could be used as a blanket fill to retard surface water infiltration. The remainder of the removed materials would be exported off-site and replaced with compacted fill.

The POC also included installation of subdrain systems in the removal areas, construction of impervious drainage channels in selected canyons, installation of dewatering wells, and re-establishment of surface drainage within the developed portion of Portuguese Canyon. The study evaluated three scenarios where no reduction in groundwater levels occurred, lowering of the groundwater level of 25 feet, and lowering of groundwater level of up to 35 feet south of the regraded area. The increase in the factor of safety was estimated to range from 7 percent to 16 percent.

After discussing the benefits of dewatering and its positive effect on increasing the factor of safety, the report stated:

> However, engineering analysis also revealed that the Seaward subslide, exacerbated by its steep and dilated bluff and erosion at its toe, will have a lower factor of safety than the regraded northeast PBL. Hence, the Seaward subslide may move first and, consequently, pose the risk that the EastCentral subslide may lose its lateral support towards the ocean. Engineering analysis shows further that the reduction of lateral support will reduce the factor of safety of the East-Central subslide to 1.04. This means that, while it appears to be theoretically feasible that the proposed POC [plan of control] can improve the current state of stability in eastern PBL, the margin of safety for the East-Central subslide (at a factor of safety of 1.04) is too small and the East-Central subslide will have an intermittent slow movement and periodic acceleration following heavy precipitation.

Thus, the authors indicate their opinion that the avoidance of the addition of water to the subsurface in this area is critical. However, the authors stated that even in the best case, the proposed POC would only be capable of improving the stability marginally and that the landslide may still creep intermittently and be susceptible to reactivation. Conditions cited which could contribute to reactivation of the landslide included shoreline erosion, successive years of above average rainfall, lapses in the de-watering or surface drainage maintenance programs, and continued movement of the Seaward and/or West-Central subslides. Thus the authors evaluated supplemental stabilization measures that included (1) slide plane clay strength enhancement, (2) the construction of a revetment along the shore line, and (3) a more extensive dewatering program.

The evaluation indicated that the tests conducted for this report regarding slide plane clay strength enhancement via lime injection were promising but not extensive, nor was the method of field implementation proven. A pilot test was recommended. The construction of a revetment along the shore line was assumed to be implemented in combination with strength reduction due to slow movement. In this scenario, the revetment was deemed a successful approach, but it was recognized that any construction in the vicinity of the existing shoreline would require permits from federal and state regulating agencies, and that obtaining these permits might be a long and costly process with uncertain outcome. Regarding supplemental dewatering, the authors stated that the benefits of lowering the groundwater elevation would be theoretically significant, particularly in the eastern portion of the landslide. However, to lower the water table an average of more than 20 feet may not be feasible because of the high cost associated with lowering groundwater within the low permeability material. At the time, the authors believed that one could not practically expect to lower the water table an additional 20 feet below the October 1996 level across the PBLC as a whole (Ehlig and Yen, 1997).

Ehlig and Yen (1997) also reported on a global positioning system (GPS) satellite survey network that the City of Rancho Palos Verdes established that showed that the eastern portion of the slide moving about twice as fast as the western portion. The report stated that the rate accelerates when groundwater rises and/or when the landward (northern) portion of the slide exerts additional driving forces due to local slope failures or debris accumulations. Erosion of the toe of the slide along the shore exacerbates the instability of the seaward portion of the slide.

2.3 2000 Leighton Feasibility Study

In a report prepared for the Palos Verdes Portuguese Bend Company, Leighton and Associates (Leighton) (2000) reviewed the 1997 POC (Ehlig and Yen, 1997) and recommended revisions. The report was prepared for the proposed construction of an 18-hole golf course and related facilities. The report presented a revised POC termed the Palos Verdes Portuguese Bend (PVPB) POC. The PVPB POC included all but the lime injection aspects of the 1997 POC, supplemented with a more extensive removal and capping of the landslide area, and extensive shear keys, as well as additional subdrains, monitoring wells, and dewatering wells. Grading for the property, including Peacock Hill and the active PBLC, was presented in a proposed grading plan. The PVPB POC was planned in phases, sequenced to limit the probability of major accelerations in the rate of landslide movement.

The scope of work for the study included determination of the subsurface geologic structure, the ancient and active rupture surfaces, the gross stability of the site, and a groundwater analysis. The work performed included review of past geological, geotechnical, and hydrogeological reports and maps, aerial photograph analysis, and geologic mapping of the field area. Analyses of GPS survey and monitoring well data were also completed for the study. Subsurface exploration included drilling of 9 large-diameter and 11 continuous-core borings with downhole wireline geophysical logging, in addition to logging of 3 exploratory trenches. All of the core borings were converted to monitoring wells, and 4 additional monitoring wells were constructed with nests of piezometers. Laboratory testing of slide plane materials was conducted to establish chemical and physical properties for utilization in the slope stability analyses. Slope stability analysis was performed of the present stability and to determine the impacts of the proposed development, and the implementation of the proposed POC was also included.

Other remedial measures proposed by Leighton include construction of two additional large shear keys to support buttresses of recompacted fill with subdrainage. The largest of the shear keys was proposed to be constructed near the toe of the PBLC and a toe protection system consisting of a riprap revetment was also recommended. An elaborate system of subdrainage of horizontal wells would intercept subsurface flow below Paintbrush and Ishibashi Canyons and direct flow to the ocean. Also, permeable drainage membranes, remedial grading, and construction of a drainage culvert would reduce surface water infiltration and facilitate gravity flow for the subdrainage system. Other remedial measures include more extensive capping of the landslide area, a short sheet pile wall at the western Klondike Canyon landslide boundary adjacent to the Beach Club, and construction of a dewatering pit to permit the development of a system of hydroaugers.

The slope analysis conducted by Leighton estimates that the factor of safety for the most active portions of the PBLC would increase by approximately 50 percent. The factor of safety for the less active portions would increase by approximately 20 percent. They also conclude that the slide movement of the active portions of the PBLC located east of Inspiration Point would be arrested.

3. Physical Characteristics of the PBLC Vicinity

This section provides information describing PBLC area topography, hydrology, soils, geology, and hydrogeology, as well as landslide characteristics.

3.1 Topography

The regional topography of the ancient Altamira Landslide Complex is mapped in the U.S. Geological Survey (USGS) Redondo Beach, Torrance, and San Pedro quadrangles (USGS, 1963 and 1964). More recently, the Los Angeles Region Imagery Acquisition Consortium (LAR-IAC) developed a digital terrain model (DTM) using LiDAR and generated 2-foot and 5-foot digital contour elevation for Los Angeles urban project areas and Catalina Island, which includes the City of Rancho Palos Verdes (circa 2015) (Figure 6). The PBLC is located in the southeast portion of the larger and older Altamira Landslide Complex, is completely mapped within the San Pedro, California quadrangle (USGS, 1964), and is part of the LAR-IAC DTM.

The Altamira landslide covers over 2 square miles extending from the crest of Palos Verdes peninsula near Crest Road at elevations of approximately 1,200 feet above mean sea level (feet msl) to the shoreline (Douglas 2013, Vonder Linden 1972). The perimeter of the Altamira Landslide Complex is generally bounded by an unnamed canyon adjacent to Barkentine Canyon to the west and the Klondike Canyon to the east and has the overall shape of a rotational landslide. The Altamira Landslide Complex is characterized by rolling hills with numerous gullies and canyons oriented generally perpendicular to the shoreline. Landward, the head of the ancient landslide is the prominent Valley View Graben, which sharply declines in elevation by 145 feet into a relatively flat surface of approximately 400 feet in width.

The extension zone of the Altamira Landslide covers over 50 percent of the area and has a stepwise series of scarps and platforms with the major scarp dropping from 1,200 feet msl to the first head at 900 feet msl. The head scarp of the landslide contains some of the steepest slopes, with between 150 percent and 280 percent gradient. The last "platforms" are at approximately 500 feet msl, where there begins a relatively flat surface in the central portion of the ancient landslide, south of Narcissa Drive, that extends to the head of the Abalone Cove Landslide.

The area of relatively flat terrain covers half a square mile in the central portion of the Altamira Landslide Complex. This area is characterized by rolling hills with slope gradients generally less than 60 percent. The Altamira Canyon cuts through this relatively gentle sloping surface with elevations falling from 400 feet msl to approximately 250 feet msl over a distance of 100 feet. The Altamira Canyon is the longest canyon (8,800 feet) that extends from the crest of the slide to the shoreline, just west of Inspiration Point.

Throughout the Altamira landslide there are a series of canyons that run parallel to each other and range between 800 to 8,800 feet in length. From west to east ~~these are~~there is the unnamed canyon that bounds the landslide, as well as Vanderlip, Altamira, Kelvin, Portuguese, Ishibashi, Paint Brush, and Klondike Canyons, with slope gradients that range between 100 percent and 280 percent.

Abalone Cove Landslide and the PBLC are generally within the compression zone or toe of Altamira Canyon and are characterized by a hummocky topography with rounded hills and some smooth valleys with a maximum elevation of 500 feet msl. On average, there is about 7 degrees dip in topography from the crest to the shoreline (Ehlig and Yen, 1997; Mackintosh, 1957). The crest of the PBLC is approximately 500 feet msl and the toe of the slide extends to the shoreline. In this compression zone, PVDS runs generally east to west, parallel to the shoreline. The elevation of PVDS ranges from approximately 160 to 220 feet msl and is about 800 feet from the shoreline.

Pronounced sea cliffs and narrow beaches are present at the shoreline. The most noticeable features along the shoreline include two promontories that are present in the Western and western Seaward subslide areas of the PBLC (Figure 3), the westerly Inspiration Point and the easterly Portuguese Point with elevations up to 135 feet msl.

3.2 Watershed Hydrology

A watershed is defined as a region or area bound peripherally by a divide and draining ultimately to a particular watercourse or body of water. In this case, the bodies of water of interest are the canyons that convey surface water, to one degree or another, through the area of the PBLC. It is also of interest to characterize the areas from which stormwater drains ~~that~~and ultimately runs off into the PBLC canyons. Water from those areas ultimately flows into the PBLC canyons and, in turn, into the PBLC.

The PBLC receives water (both surface water and groundwater) from the watersheds of Portuguese Canyon, Ishibashi Canyon, and Paintbrush Canyon. These canyons are generally ephemeral, meaning that surface water does not flow through them throughout the year. Rather, these canyons generally have flowing water when and after it rains and they convey stormwater from the high ground in the watershed toward the Pacific Ocean. Collectively, they are referred to herein as the PBLC Canyons. Klondike Canyon is considered herein separate from the PBLC but, as described below, water from Klondike Canyon likely flows as underflow across the watershed divide at the lower southwest end of the Klondike Canyon watershed. Klondike Canyon is also an exception in that perennial water is observed flowing in the lower reaches of Klondike Canyon. The PBLC Canyons are shown in Figure 5 with their collective watershed boundaries.

The PBLC Canyons are located in what is identified as the "Ocean South South" (*sic*) drainage area in the Master Plan of Drainage (MPD) (RBF Consulting, 2015), a part of the Santa Monica Bay Watershed defined by the County of Los Angeles Department of Public Works. The PBLC Canyons are directly tributary to the Pacific Ocean. The PBLC Canyons have storm drain systems located in their upper reaches that discharge into the canyons that, in turn, drain ultimately into the ocean. The area of the Portuguese Bend watershed that drains into the PBLC Canyons is approximately 627 acres.

Over significant reaches of these canyons, notably the portions which direct water to and through the PBLC, the drainage systems consist mostly of canyon bottoms that are unimproved open channels. The surface of the ground within much of the PBLC is generally hummocky, irregular, and locally fissured due to the landslide activity. Previous drainage structures constructed to control and convey stormwater runoff have failed. The MPD (RBF Consulting, 2015) found that the CMP structures were undersized for the calculated flow they would receive. As a result, surface drainage within the landslide is generally poor and difficult to maintain. Infiltration of the runoff conveyed through these canyons is a source of recharge for the groundwater within the landslide (Ehlig and Yen, 1997).

As described in the MPD (RBF Consulting, 2015), Ocean South South has three major canyons: Altamira Canyon, Portuguese Bend Canyon, and Paint Brush Canyon. While a part of the delineated Ocean South South drainage area, surface water from Altamira Canyon does not drain directly into PBLC like the other adjacent canyons and will not be discussed further herein. Groundwater that originates from Altamira Canyon infiltration may, however, flow into the PBLC area. Portuguese Canyon is located on the westerly side of the PBLC and generally forms the boundary of two subslides termed by Ehlig and Yen (1997) as the West-Central and East-Central slides. This boundary, and Portuguese Canyon, is defined by a near vertical fault that extends in a north-south direction along the general alignment of Portuguese Canyon (Ehlig and Yen, 1997). The upper reaches of Portuguese Canyon are steep and convey stormwater quickly to the lower reaches where water moves more slowly in the low gradient terrain. Smaller in size, Ishibashi Canyon, located east of Portuguese Canyon, drains into Paint Brush Canyon which, in turn, drains into an undeveloped mountain-front alluvial fan area of the PBLC. Paint Brush Canyon includes two debris basins in series upstream of the confluence of Ishibashi and Paint Brush Canyons before discharging to the upper end of the PBLC, where evidence in the field indicates that stormwater readily infiltrates.

Klondike Canyon is located east of Paintbrush Canyon and the PBLC. The area of the Klondike Canyon Watershed is 680 acres and a smaller portion of that area drains into Klondike Canyon itself. The southwest margin of the Klondike Canyon Watershed, where Klondike Canyon stormwater empties into the Pacific Ocean, is within the mapped boundary of the PBLC. Though it appears likely, based on its location relative to the PBLC boundary and the generally low-lying surface terrain, it is unknown whether groundwater is moving from the lower Klondike Canyon Watershed into the PBLC Watershed. This is a complicated area where the Klondike

Canyon Watershed abuts the PBLC Watershed and the Klondike Canyon Landslide abuts the PBLC in an area of maximum PBLC movement.

As mentioned above, there are several swales and storm drains that drain the upper reaches of the watershed into the PBLC Canyons and Klondike Canyon where the water is then conveyed to the Pacific Ocean (Figure 7). The upper watershed areas contributing to water flow into the PBLC and Klondike Canyon landslides are located within the City of Rolling Hills. This may represent legal and/or jurisdictional access challenges with respect to the implementation of landslide abatement solutions that involve stormwater control and conveyance. Of the combined approximately 1,300-acre area of the PBLC and Klondike watersheds, approximately 360 acres (28 percent) lies within Rolling Hills. The balance of the watershed areas (940 acres, or 72 percent) lies within the City of Rancho Palos Verdes.

There are currently no known stream gage data based on monitoring of either dry weather or storm water flow in the canyons that convey water into the PBLC and the Klondike Canyon Landslide. These canyons have a bottom generally 10 to 20 feet wide and fall 15 to 20 feet in a 100-foot run. A hydrologic study for this area is not within the scope of this study. Based on information in the MPD, it is estimated that the 100-year storm runoff for each of the above canyons would be approximately 200 cubic feet per second (cfs). This is not a rigorously derived design value, but rather an estimate to provide a basis to establish the rough sizing and feasibility of improvements being considered as part of a conceptual landslide stabilization solution.

3.3 Soils

The U.S. Department of Agriculture (USDA) SSURGO database (USDA, 2015) was used to access information about the surficial soils at the PBLC (Appendix ~~A~~B). The SSURGO database contains information about soil as collected by the Natural Resources Conservation Service (NRCS) over the course of a century. The information is typically displayed in tables or as maps and is available for most areas in the U.S. The information was gathered by walking over the land and observing the soil. In many cases, soil samples were analyzed in laboratories. The maps outline areas called map units. The map units describe soils and other components that have unique properties, interpretations, and productivity. The information was collected at scales ranging from 1:12,000 to 1:63,360. More details were gathered at a scale of 1:12,000 than at a scale of 1:63,360. The mapping is intended for natural resource planning and management by landowners, townships, and counties.

The soil survey information came from the Soil Survey of Los Angeles County, California, Southeastern Part (CA 696), mapped at a scale of 1:24000, using aerial images dated May 25, 2010 to November 24, 2014.

The predominant soil unit symbol in the PBLC is 1168 with a mapping unit name of Haploxerepts, 10 to 35 percent slopes. Rather than a typical association of soil series, the name Haploxerepts refers to the soil taxonomic classification of surficial soils that predominantly occur in the PBLC. Haploxerept soils typically occur at an elevation of 0 to 1,210 feet msl in an annual precipitation zone that typically ranges from 13 to 17 inches. Mean annual temperature typically ranges from 62 to 63 degrees Fahrenheit (°F). In this mapping unit, Haploxerept soils make up about 90 percent of the landscape, with the minor component of 10 percent composed of the Lunada soil that typically occurs on hillslopes.

Haploxerepts generally occur on landslides in mixed slide deposits derived mostly from calcareous shale. The typical soil profile of a Haploxerept is as follows: 0 to 7 inches, loam; 7 to 20 inches loam with the incipient development of soil structure; 37 to 79 inches, channery loam. A channery soil is a soil that is, by volume, more than 15 percent thin, flat fragments of sandstone, shale, slate, limestone, or schist as much as 6 inches along the longest axis. A loam is soil composed mostly of sand (particle size > 63 micrometers [µm]), silt (particle size > 2 µm), and a smaller amount of clay (particle size < 2 µm). By weight, its mineral composition is about 40/40/20 percent concentration of sand/silt/clay, respectively. These proportions can vary to a degree, however, and result in different types of loam soils: sandy loam, silty loam, clay loam, sandy clay loam, silty clay loam, and loam, depending on which particle size predominates.

Haploxerepts typically occur on slopes that range from 10 to 35 percent, are well drained (internally), and have moderately high to high capacity to transmit water. Typical saturated hydraulic conductivities (K_{sat}) of Haploxerepts range from 0.60 to 2 inches per hour. Depth to first water is typically greater than 80 inches.

Soils are also typically classified as lying within a hydrologic soil group that, when considered with land use, management practices, and hydrologic conditions, determine a soil's associated runoff curve number. Runoff curve numbers are used to estimate direct runoff from rainfall (NRCS, 2007). Soils were originally assigned to hydrologic soil groups based on measured rainfall, runoff, and infiltrometer data. As the initial work was done to establish these groupings, assignment of soils to hydrologic soil groups has been based on the judgment of soil scientists. Assignments are made based on comparison of the characteristics of unclassified soil profiles with profiles of soils already placed into hydrologic soil groups. Most of the groupings are based on the premise that soils found within a climatic region that are similar in depth to a restrictive layer or water table, transmission rate of water, texture, structure, and degree of swelling when saturated, will have similar runoff responses.

The Haploxerepts mapped at the PBLC are classified as falling within the characteristic of Hydrologic Group B (NRCS, 2017). Soils in this group have moderately low runoff potential when saturated, and water transmission through the soil is not impeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures (USDA, 2015).

Douglas (2013) also characterized PBLC area soils as commonly comprising soils that are "expansive" in character. Douglas states that weathering and erosion of the Altamira bedrock produced a soil that is rich in clay minerals with distinctive properties. These clays have the ability to absorb and expel water so that they can swell (expand) or shrink (contract). When it rains, the clays in the soil absorb water, expand and become sticky. In the summer, they dry out and the clays lose water and contract. In the dry months, the soils in the area develop cracks, sometimes more than an inch across and up to a foot deep. In the rainy months, the cracks disappear as the clays absorb water. In the process of wetting and drying, expansion and contraction, the soils on the slopes respond to gravity and slowly migrate downslope. This is called soil creep. Expansive soils can also be a problem for slabs or foundations or anything that is placed in or on the ground without proper footing. Expansive soil movement is related to rainfall patterns and can amount to tenths of an inch to inches per year (Douglas, 2013). Douglas (2013) pointed out that in locations where GPS measurements indicate that land displacement is minimal, there is the possibility that the slow movement is due to slope creep from expansive soils.

In summary, surficial soils on the PBLC are generally loamy in texture with a proportion of sand, silt, and clay of about 40/40/20 percent. They can take in and percolate water readily. They are relatively deep and have a moderate to high water-holding capacity. They develop deep, wide cracks during the dry summer and provide channels for later infiltration during the rainy season. Once water has infiltrated and is stored in the soil profile, the presence of expansive clays causes the soils to expand (or swell), closing the soil cracks. The cycle of expansion and contraction is a source of soil creep. Without a pathway for surface water to runoff to the Pacific Ocean, the infiltration of runoff water sourced from slopes higher on the PBLC readily occurs and exceeds the storage capacity of surficial soils. The excess water then percolates into underlying formations, beyond the reach of transpiring plants, where it potentially provides a mechanism to facilitate more significant slide movements.

3.4 Geology

The PBLC is located on the northwest trending Palos Verdes Peninsula, which is formed on the hanging wall of the southwest-dipping Palos Verdes fault (Douglas, 2013) (Figure 8). The Peninsula is the result of uplift and formation of a doubly plunging anticline. The anticline plays an important role in the presence of the PBLC, which is located on the southern flank of the fold. The head of the landslide coincides with the crest of the anticline and the south limb is gently inclined in the seaward direction. The sedimentary rocks that form the Peninsula include the Mesozoic Catalina Schist, Monterey Formation, marine terrace deposits, alluvium, and landslide deposits.

The oldest rocks of the Peninsula consist of Mesozoic Catalina Schist, which forms the core of the anticline (Ehlig, 1992). Middle to Late Miocene marine sediments of the Monterey Formation unconformably overlie the schist, and these sediments were deposited in an ocean basin (Douglas, 2013). Widespread volcanism occurred in the early phase of deposition of the

Monterey Formation, which contributed volcaniclastic sediments to the Monterey Formation (Conrad and Ehlig, 1987). Conrad and Ehlig (1987) subdivided the rocks of the Monterey Formation into three main members, from lower to upper: the Altamira Shale, Valmonte Diatomite, and Malaga Mudstone (Figure 9). In the Pliocene, the ocean basin was subsequently folded into an anticline and uplifted what is now the Peninsula, producing an island separated from the mainland by a shallow sea (Douglas, 2013). Erosion of the uplifted island resulted in sedimentation of the shallow sea, forming a peninsula connected to the mainland. Fluctuations of sea levels in the Pleistocene simultaneous with uplift resulted in preservation of 13 marine terraces that circumscribe the Peninsula. Modern day sea level produces near vertical sea cliffs almost 150 feet high and erodes the landslide toe at relatively high rates.

The two upper members of the Monterey Formation are mostly composed of biogenic materials such as diatomite, diatom-rich shale, and phosphate-rich mudstones. The Altamira Shale member is further subdivided into lower and middle tuffaceous shale and upper cherty and phosphatic lithofacies (Figure 9) (Douglas, 2013). The tuffaceous shale is rich in volcanic ash that contains interbeds of clay and bentonite that are inherently weak. The bentonite beds are the slip surfaces of most landslides in the peninsula (Ehlig, 1992; Douglas, 2013). The clay and bentonite interbeds form aquitards or aquicludes that permit the buildup of pore water pressure. Outcrops of the tuffaceous lithofacies in the ancient Altamira Landslide Complex are predominantly composed of tuffaceous shales with interbeds of cherts, silty sandstone, and intrusive basalt sills (Douglas, 2013).

The Altamira Shale member also contains beds of tuff turbidite, ash fall, and debris flow tuffs that vary in thickness and are discontinuous over short distances (Douglas, 2013). Two distinctive tuff units occur within the tuffaceous lithofacies including the Miraleste Tuff and the Portuguese Tuff (Douglas, 2013). The Miraleste tuff is positioned in the upper part of the facies and the Portuguese tuff occurs approximately 450 feet below the top of the tuffaceous facies. The Portuguese Tuff ranges in thickness from approximately 20 to 60 feet with an average thickness of approximately 50 to 60 feet in the PBLC (Leighton and Associates, 2000). The variable thickness is the result of deposition on a hummocky sea floor interpreted to be caused by a single eruptive event (Ehlig, 1992). Most of the tuff has been converted to montmorillonite clay (bentonite) due to groundwater and heat (Douglas, 2013). The Portuguese Tuff functions as a zone of low shear strength and as an aquiclude in the PBLC (Ehlig, 1992). In the upper and middle portions of the PBLC, the landslide shear zone is positioned in a range approximately 50 feet above the tuff to coinciding with the top of the tuff. In the lower portion of the PBLC, the shear zone is positioned near the base of the tuff (Ehlig, 1992).

Several folds and faults occur in the PBLC and offshore areas, the largest of which are anticlinal folds (Figure 10). All of the folds are asymmetric, east-west trending, and anticlinal. None of the onshore folds are exposed at the surface but are identified with subsurface data. The folds are significant in that they have influenced the direction of movement of the subslides of the PBLC (Douglas, 2013). Ehlig and Yen (1997) described the western edge of the east central subslide to be defined by a near vertical fault which extends in a north-south direction along the general alignment of Portuguese Canyon. The canyon probably developed along the fault. The fault is controlled by a discontinuity in the underlying bedrock structure.

All of the geologic structures were formed during uplift and folding of the Peninsula. The crests of the anticline located at the head of the PBLC trends westward to Altamira Canyon where it underlies the hills of "Peacock Flats." This anticline retards seaward movement of the ancient Altamira Landslide. Subsurface data reveal two flexural faults in the bedrock under the PBLC that trend west to east (Douglas, 2013). One of the flexures coincides with the boundary of the eastern and inland subslides (Figure 3). These flexures cause undulations in the slip zone of the PBLC, which creates large tension cracks in the slide mass as it moves over them.

3.5 Landslide Characterization

The PBLC is the reactivated portion of a bowl-shaped area that encompasses approximately 2 square miles on the Palos Verdes Peninsula in the Ancient Altamira Landslide Complex (Figure 3). The Ancient Altamira Landslide Complex was first mapped by Woodring et al. (1946). More recent studies have moved the head of the landslide northward to include the Valley View graben (Douglas, 2013). There are differing hypotheses that postulate on the initiation and evolution of the Ancient Altamira Landslide Complex. Jahns and Vonder Linden (1972) believed that the Ancient Altamira Landslide Complex was the result of a series of semi-independent slides that formed in three separate time intervals during the 500,000 years. The oldest slides are located inland and the slides became progressively younger toward the coast.

Ehlig (1992) proposed that the Ancient Altamira Landslide Complex initiated as a megaslide that moved as a simple translational glide block unit and, with continued displacement, the original slide block became fragmented. Furthermore, he concluded that the megaslide occurred sometime prior to 125,000 years ago and was no older than 200,000 years ago. Douglas (2013) argued that the AALC contains terrace remnants that are older than 200,000 years and therefore, its origin is older. He proposed that the upper block of landslide complex separated from a paleo sea cliff dated at 780,000 years and initial movement began shortly after this date. Douglas (2013) also believes that movement occurred in episodes with the oldest block at the head and the youngest at the coast which is consistent with the Jahns and Vonder Linden (1972) model. Given that borings drilled through the PBLC have determined that the ancient rupture surface is mostly at or the near the top of the Portuguese Tuff and the rupture surface is stratigraphically continuous, Leighton and Associates (2000) favor initial translational movement as a single sheet that subsequently broke up into large blocks consistent with the Ehlig (1992) model.

The active PBLC encompasses approximately 250 acres with a maximum width of 3,600 feet and maximum head-to-toe length of approximately 4,200 feet (Douglas, 2013). The PBLC, together with the Abalone Cove and Klondike Canyon Landslides are reactivated portions of the Ancient Altamira Landslide Complex (Ehlig, 1992; Douglas, 2013). The western margin of the PBLC is poorly defined and transitory with respect to the Abalone Cove Landslide, whereas the east margin is well-defined. The internal structure of the landslide is established to be a series of randomly oriented large blocks separated by fractures and grabens (Ehlig and Yen, 1997; Leighton and Associates, 2000). Five large, semi-independent blocks or subslides were identified by Ehlig (1992), including the Landward, East-Central, West-Central, and Seaward subslides (Figure 3).

The Abalone Cove Landslide Abatement District (ACLAD) is the first Geologic Hazard Abatement District (GHAD) created (in 1981) under the Beverly Act of 1979 (SB1195). The ACLAD is governed by a board of directors elected from property owners in the district area and assesses property owners to pay for the construction and maintenance of abatement measures in the Abalone Cove Landslide area, such as groundwater dewatering wells. The ACLAD maintains an extensive dewatering well network in the area. The well network has reportedly lowered water levels in the slide area up to a maximum of approximately 60 feet (Douglas, 2007) and helped to promote overall relative land stability in the ACLAD area.

Ehlig and Yen (1997) supplemented their subsurface exploration data set with data acquired from previously drilled borings to construct a structure contour map of the basal rupture surface in the PBLC. The contour map estimates and maps the elevation of the rupture surface for the Landward, West-Central, and Seaward subslides. However, lack of subsurface data (data gap) east of Portuguese Canyon permits only inferred mapping of the rupture surface in this area. The undulating shape of the rupture surface is controlled by the structure of the underlying bedrock. The dips of the rupture surface range from approximately 15 to 25 degrees beneath the Landward subslide and flatten to less than 5 degrees in an anticlinal undulation along the southern margin near the West-Central and East-Central subslide boundaries (Ehlig and Yen, 1997; Leighton and Associates, 2000).

One significant characteristic of the basal rupture surface is the trough shaped basin formed along the eastern part of the East-Central subslide (Appendix ~~B~~C). The rupture surface steepens to 17 degrees at the northern flank of the trough with the central portion of the trough positioned just below sea level. The southern flank of the trough is gently inclined to the north and the rupture surface rises back up above sea level. Ehlig and Yen (1997) reported that a near vertical, north-south tear fault forms the boundary between the West-Central and East-Central subslides. The rupture surface of the West-Central subslide is generally uniformly gently dipping at approximately 7 degrees. An anticlinal undulation produces a 30 to 40 foot rise in the rupture surface which produces a buttressing effect on the subslide as the mass must climb to reach the crest of the fold (Leighton and Associates, 2000). The rupture surface of the Seaward subslide generally dips 5 degrees seaward and accommodates rotation of the slide blocks as wave erosion removes the toe of the active PBLC.

Geologic cross-sections presented by Ehlig and Yen (1997) show that the topography (as of 1995) was nearly parallel to the underlying active rupture surface. The sections indicate that the thickness of the landslide mass is relatively uniform and averages approximately 100 feet above the rupture surface. However, Douglas (2013) states that, in places, the landslide complex is over 200 feet thick. Ehlig and Yen (1997) estimated that the total volume of PBLC mass is approximately 40 million cubic yards. Subsurface data indicate that the rupture surface is underlain by bedrock east of Portuguese Canyon and Ancient Altamira Landslide Complex debris west of Portuguese Canyon (Leighton and Associates, 2000). As a result, there are deeper slide and multiple slide planes present beneath the subslides located west of Portuguese Canyon, which coincides with the West-Central and East-Central boundary.

Borings drilled by Ehlig and Yen, 1997 indicate that the Portuguese Tuff is at depth beneath the rupture surface throughout the northern portion of the PBLC. The portion of strata that are positioned between the rupture surface and the underlying Portuguese Tuff consists of relatively stronger strata derived from Catalina Schist debris and siliceous biogenic material. The rupture surface occurs along a sheared bentonite bed approximately 30 to 40 feet above the top of the Portuguese Tuff in the PBLC except for the northernmost portion and at the coast (Ehlig and Yen, 1997). The clay material of the rupture surface consists of both calcium-rich and sodium-rich montmorillonite clay (Ehlig and Yen, 1997; Leighton and Associates, 2000). The sodium-rich clay holds more water and is weaker than clay calcium-rich clay. Due to this fact, Ehlig and Yen (1997) proposed a lime injection program to increase the amount of calcium cations in the clay, which would strengthen the rupture surface clay. However, Leighton and Associates (2000) determined that the rupture surface consists of a substantial amount of calcium-rich clay and the lime injection may not yield desired stabilization results.

3.6 Hydrogeology

Studies of the PBLC have consistently concluded that water moving in the subsurface is a significant contributing factor to the PBLC landslide instability. Subsurface water exists in the pores of soils and unconsolidated sediments and in fractures that exist in both unconsolidated sediments and hard rock. When water does not completely fill the pores that exist in soils, the moisture condition is referred to as "unsaturated." The balance of the pore space is filled with soil vapor, which is typically in communication with the surface. When water completely fills the pores spaces, the moisture condition is termed "saturated." Like any other free water surface (such as a pond or lake surface), a water table surface has a pore pressure, or static head, of zero. The water pressure increases linearly with depth below the water table. Water pressure can also build up as groundwater rises and encounters an overlying low-permeability zone that "confines" the groundwater. In this case, water in a drilled borehole would rise up above the level at which it was first encountered. If the water rose sufficiently high enough to encounter the surface, the water pressure would be termed "artesian."

Subsurface water includes water in soils that exists under conditions less than saturation above a water table and water that exists under saturated conditions below a water table or below a confining layer. Subsurface water is part of the continuous circulation of water between the ocean, atmosphere, and land called the hydrologic cycle.

3.6.1 Groundwater Recharge

At the PBLC, water enters the subsurface by:

- Direct precipitation and infiltration through soils
- Drainage of surface water from locations upslope and subsequent infiltration and percolation
- Percolation of water from private residential on-site wastewater treatment systems such as septic systems
- Groundwater flow from upgradient locations, termed "underflow"

A preliminary groundwater balance was developed for a golf course project proposed for an area in the east-southeastern PBLC (Leighton and Associates, 1998). The information available to support this analysis was limited but deemed sufficient to provide a first order approximation of the amount of water entering and leaving the proposed project site (the golf course project was never completed).

Rainfall data from the Los Angeles County Fire Station at the top of the watershed on Crest Road were used for the water balance calculations. Based on historical precipitation data for the years 1947 to 1996, the average annual rainfall at the station was estimated to be 14.1 inches. This represents the amount of water (after deductions for the amounts that runoff, evaporate, or transpire from plants) that can potentially infiltrate and percolate into the subsurface of the PBLC. The area of the PBLC watershed is approximately 620 acres (Section 6.2) (Figure 5). The resulting volume of water that falls on the PBLC watershed in an average year is approximately 728 acre-feet of water (1.175 feet x 620 acres), the equivalent of about 234 million gallons of water.

As calculated from the estimates presented in Leighton and Associates (1998), approximately 10 percent of the rain that fell on their proposed project area in an average rainfall year recharges and becomes groundwater. Extrapolating that percentage to the case of the PBLC area results in approximately 71.8 acre-feet, or 23.4 million gallons, of recharge. In addition, Leighton and Associates (1998) also determined for their proposed project site that the average annual rainfall of the 10 wettest years was 26.3 inches. In the 10 wettest years, Leighton and Associates (1998) calculated that approximately 29 percent of the rain that fell recharged and became groundwater. Using a wet-year rainfall of 26.3 inches for the PBLC, the recharge to groundwater that results on the PBLC watershed area would be about 388 acre-feet, or 127 million gallons. These recharge estimates do not separate the rainfall water that infiltrates and percolates directly from water that runs off from upgradient locations and subsequently infiltrates and percolates into the Red Zone of the PBLC. Rather, these values represent estimates of the recharge that occurs over the entire watershed. These recharge values are likely conservative, and a more detailed analysis would likely reveal that the percentage of rainfall that results in recharge is higher than estimated by Leighton and Associates. This is because an important limitation of the method used by Leighton and Associates (1998) is the assumption that rainfall stored within the soil is subject to evapotranspiration until the soil moisture capacity is exceeded. However, existing conditions at Portuguese Bend include desiccation cracks, fractures, and fissures caused by landslide movement that may permit water to migrate beyond the depth of evapotranspiration before the soil reaches its moisture capacity. This limitation in the method may result in an underestimate of groundwater recharge.

Leighton and Associates (1998) also estimated the contribution to groundwater recharge by septic systems based on (1) the presence of 80 homes upslope of the project, (2) an estimated annual indoor consumption of 1,350 cubic feet of water per month, and (3) the assumption that all indoor water flowed to the septic system. The resulting contribution to subsurface water by percolation from private septic systems was estimated to be about 30 acre-feet per year. Based on the estimates for total project area recharge presented by Leighton and Associates (1998), septic tanks contribute about 30 percent of the total groundwater recharge in dry years, and about 7.2 percent of the total groundwater recharge in the 10 wettest years. While additional study of the PBLC groundwater budget is merited to clarify the water budgets of both shallow and deep groundwater, the preliminary water budget work suggests that there is a substantial amount of recharge into the PBLC, particularly in wet years, and that groundwater recharge from septic tanks can be significant in dry to average water years.

During periods of heavy rainfall, large quantities of runoff flow onto the landslide from the tributary canyons. Field observation indicates that, although the water from these canyons was conveyed across the landslide through a combination of natural and improved drainage courses, it appears that significant sections of ~~CMP~~corrugated metal pipe (CMP) used for surface drainage are broken and inoperable and that significant quantities of runoff infiltrate and percolate into the ground within and around the periphery of the PBLC. Douglas (2013) stated that "In Portuguese and Paint Brush Canyons, the lower reaches of the canyons have been destroyed and 100 percent of the storm water from these canyon flows directly into the head of the Portuguese Bend landslide." Our field observations are consistent with this statement.

Leighton and Associates (1998) estimated the amount of recharge contributed by irrigation. Because the northern border of their project area was at the upper end of the watershed, it represented a no flow groundwater (and surface water) boundary in their analysis. In other words, no water flowed south into the area from north of the boundary. As a result, all groundwater flowing south into their proposed project site was the result of groundwater recharge from areas between the north end of the study area (and watershed) and the project site itself. The same is true for the PBLC. All groundwater inflow into the PBLC results from recharge occurring upslope. Leighton and Associates (1998) estimated that up to 77 acre-feet per year could be entering their project area from upslope irrigation recharge. Extrapolated to the PBLC, and similar to septic tanks, irrigation return flow represents a significant source of groundwater recharge to the PBLC. This component of recharge should be investigated further in a water balance study developed to support the final design of a land stabilization solution.

3.6.2 Groundwater Occurrence

Groundwater generally occurs in two water-bearing zones at the Site. “Shallow” groundwater typically flows above the bentonite layers (shear zones) that form the main slip or rupture zones (failure surfaces) and is fed by general recharge, preferential recharge through local fractures, recharge through the canyon bottoms, and recharge that occurs where the canyons dump storm water onto alluvial fans, head slopes, sag ponds, and hummocky areas of the slide area. Douglas (2013) reported that wells pumping from this layer respond quickly (days to weeks) to major rain storms. A second water-bearing zone consisting of “deep” groundwater originates in the upper part of the drainage basin and is largely confined to below the rupture zones. This deep groundwater is confined and groundwater builds up pressure over time. Douglas (2013) also reported that wells drilled deep enough often encounter pressurized groundwater zones below the basal rupture surface.

Leighton and Associates (1998) reported that unconfined groundwater of the shallow water-bearing zone occurs across the Site, and that it has historically been observed at depths ranging from approximately 5 to 15 feet below ground surface (bgs), at monitoring wells PBS-7, B88-4, and B96-12, to approximately 90 to 110 feet bgs, at monitoring wells PBS-2, PBS-3, C-4, C-5, and C-6. In general, the shallowest occurrences of groundwater have been observed in the Landward subslide, above the heads of the East-Central and West-Central subslides. The deepest occurrences of groundwater have been observed north of the active landslide area (monitoring wells C-4 through C-6), and underlying the north-south trending topographic ridge where monitoring wells PBS-2 through PBS-4 are located.

The horizontal hydraulic gradient of the unconfined groundwater of the shallow water-bearing zone trends north to south and has a magnitude of approximately 0.10 foot of vertical head loss per horizontal foot (Leighton and Associates, 1998), similar to the general site topographic gradient. Experience indicates that, in general, horizontal groundwater hydraulic gradients typically range from 0.01 to 0.00001. By comparison, the gradient at the PBLC is therefore unusually high. High horizontal hydraulic gradients can be indicative of low-permeability conditions, areas of intensive groundwater recharge, high topographic relief, and/or groundwater extraction. Under homogeneous conditions, the direction of groundwater flow is generally parallel to the direction of the hydraulic gradient, in this case north to south. Appendix ~~B~~C shows the contoured piezometric surface of the water table at the site based on interpolation of groundwater elevations measured in wells at the site.

The occurrence of groundwater in the deep water-bearing zone beneath the rupture zone is less well understood and additional characterization of site deep groundwater is needed to facilitate a clear understanding of the hydraulic forces that deep groundwater is exerting on PBLC land stability. Ehlig and Yen (1997) reported that nested piezometers have been completed on the PBLC at four locations, and that at each location pneumatic pressure transducer readings indicate that groundwater occurs below the slide plane. Ehlig and Yen (1997) also reported that vertical hydraulic head measurements indicate that a downward vertical gradient occurs within the landslide mass and an even greater downward vertical gradient exists across the slide plane. The presence of these downward vertical gradients at the lower end of the hillslope was potentially attributed to increased groundwater recharge rates along the landscape of the landslide, including the presence of extensional ground fractures.

Ehlig (1992) (as cited in Ehlig and Yen, 1997) reported on a well that was constructed and screened at the toe of the Klondike Canyon landslide and yielded artesian groundwater flow. The interpretation was given that slope stability analyses pertaining to the Seaward subslide need to consider that confined groundwater conditions occur beneath the slide plane.

Ehlig and Yen (1997) generally concluded that groundwater occurrence beneath the site slide rupture plane was consistent with groundwater recharge occurring at the upper end of the hill slope and subsequent deeper migration beneath the slide plane towards the ocean.

Groundwater occurrence at the regional scale is shown in Appendix ~~B~~C. Crest Road located north of the PBLC is approximately located at the topographic crest of the hill and is the approximate location of the surface water and groundwater flow divide. Surface water and groundwater that occurs north of Crest Road generally flows inland towards the Pacific Coast

Highway. Surface water and groundwater that occurs south of Crest Road generally flows southward, through the PBLC, and toward the Pacific Ocean. Surface water that falls or flows south of Crest Road has the opportunity to infiltrate and percolate into the subsurface of the PBLC and become groundwater. This is the water that is the focus of concern regarding PBLC land stability.

Leighton and Associates (2000) present a detailed cross-sectional view (UU-UU') that traverses through the main body of the PBLC from the upland area where the scarp of the slide headwall is located to the Pacific Ocean. The relationship is shown between the existing surface topography (existing grade), the interpreted water table (indicated by inverse triangles), and the interpreted recent below-grade active failure surface of the PBLC, as interpreted in 1999. As depicted, the water table surface is located above the interpreted active failure surface with a gradient that roughly mimics the gradient of the surface topography. The area of greatest thickness of the saturated zone within the PBLC was reported to be located inland (north) of PVDS. The maximum interpreted saturated zone thickness is approximately 90 feet, and the top of the saturated zone, at the point of maximum saturated zone thickness, was reported to be located about 100 feet bgs (Leighton and Associates, 2000). Though additional work needs to be accomplished to evaluate and delineate the specific occurrence of groundwater in the PBLC, the previous work done to evaluate the occurrence of groundwater in the PBLC provides the conceptual basis to evaluate and select technologies that can be used to stabilize land movement.

3.6.3 Water Wells

Limited documented information is available on the number, construction details, and spatial distribution of the water wells in the PBLC. Information provided by the City of Rancho Palos Verdes indicates that up to 20 water wells have been constructed and installed within the PBLC. Except for four recent wells installed in 2016, no information could be located which documents the well construction details, last surveyed location, purpose of well (monitoring or dewatering), date of installation, well temporal monitoring data, or the current status of the well. That limitation represents a significant data gap that should be aggressively addressed moving forward. A map of currently known extraction well locations is presented as Figure 11.

A well inspection survey should be conducted, including well soundings and video survey where necessary, in order to construct one consolidated, comprehensive database of site water well information and to provide the basis to initiate a monitoring program moving forward. An assessment should be prepared of the adequacy of the well network for spatial and temporal monitoring of groundwater within the PBLC. Based on that assessment, the monitoring well network should be augmented and a monitoring program initiated and maintained to provide data that will guide and evaluate the performance of the selected program to stabilize the PBLC. Regular, periodic well inspection surveys are also recommended to evaluate the impact of land movement on the monitoring network and the need for monitoring network maintenance.

Ehlig and Yen (1997) report that groundwater elevations in the East-Central subslide area are thought to have risen about 50 feet between the slide activation in 1956 and 1968. They attributed the rise in groundwater elevations to an increase in the rate of groundwater recharge within the landslide area caused by the disruption of drainage patterns and the opening of fissures and cracks following the 1956 onset of movement. Water well elevation data presented for four PBLC wells with close correlation of groundwater elevation increases to high rainfall months indicate that groundwater recharge is occurring within a month of high rainfall events. In other wells, particularly one located in the East-Central subslide area, the lag between rainfall occurrence and water elevation response was longer, up to 5 months.

Changes in groundwater elevation with time and in relation to rainfall events vary depending upon the well (Leighton and Associates, 2000). This suggests that multiple processes are involved in the delivery and removal of groundwater from the site and highlights the need to institute and formalize a monitoring program with the ability to record short and long term cyclic events. Such a formalized monitoring program and the resulting database would facilitate the collection, storage, and data interpretation critical to developing a detailed comprehensive understanding of the mechanisms which control the stability of the PBLC.

3.7 Geotechnical Modeling

Slope stability evaluations of the PBLC have been performed in the past in support of development of various remedial measures (e.g., Ehlig and Yen, 1997; Leighton, 2000). Past studies, however, were subject to significant limitations. For example, prior models of the PBLC were two-dimensional cross sections and hence could not capture the true three-dimensional nature of the PBLC. Stability evaluations could not replicate the observed conditions. Attempts were made to back-calculate shear strength parameters, but different results were obtained for each two-dimensional cross section evaluated, further impeding development of viable remedial measures.

Recently (over the past five years), significant advances have been made in three-dimensional modeling of slope stability. It is now possible to develop a three-dimensional stability model of a multi-acre site such as the PBLC based upon three-dimensional surfaces rather than two-dimensional cross sections. Review of available studies as discussed Sections 2 and 3 indicates that, with reasonable data processing, available information is suitable and sufficient to develop a preliminary 3D stability model of the PBLC using the following surfaces:

- Ground surface (topography)
- Groundwater elevation surface
- Basal shear plane surface

The ground surface topography of the PBLC was provided by the City (Section 2). The groundwater surface map produced by Ehlig and Yen (1997) was selected as the most comprehensive and representative for the modeling effort. Groundwater elevations were laterally extrapolated to the perimeter of the model area (approximately 10 percent of the lateral model area) based on the mapped water level data measured within the PBLC area. The 1997 basal rupture surface map also from Ehlig and Yen (1997) was selected as the most appropriate basal shear plane map for the modeling effort. Basal rupture surface elevations were also laterally extrapolated (approximately 10 percent of the lateral model area) based on mapped data measured within the PBLC area.

An image of the preliminary three-dimensional stability model of the PBLC is shown in Figure 12. This model image was generated using SVSlope from SoilVision, Inc. (https://www.soilvision.com/), which is the latest generation three-dimensional slope stability evaluation program. Additional imagery from the modeling effort is provided in Appendix ~~B~~C, including the approximate mapped limits of landsliding, several lateral cross-sections (A-A' to I-I'), and one transverse cross-section (1-1'). These images show that groundwater occurs above the basal rupture surface within the PBLC. DBS&A performed the following preliminary evaluations using the model software:

- Back-analysis of the PBLC
- Forward-analysis of the PBLC

The back-analysis was performed to estimate shear strength parameters along the basal failure surface. Cohesion was set to zero, while friction angle was iterated until the calculated FOS reached 1 (unity), which corresponds to the incipient failure of the landslide complex. An FOS greater than 1.0 theoretically corresponds to the cessation of landsliding. Each model iteration consumed approximately 3 hours of computational time. Back-analysis modeling indicates the following:

- Back-calculated friction angle equals 6.7 degrees, which is within the range of values reported in prior laboratory testing (Leighton, 2000).

- The direction of sliding (roughly north to south) is consistent with observations.

- The shape of the failure surface based on model calculations is consistent with observations and interpretations (i.e., Ehlig and Yen, 1997).

Forward-analysis was performed to evaluate the effect of groundwater elevation on the stability of the PBLC. The results indicate~~, as expected,~~ a strong correlation in which the FOS increases with a corresponding decrease in groundwater elevation (Figure 13):

- An elevation decline of 5 feet results in an increase in the FOS of approximately 3 percent (FOS increases from 1 to 1.03).

- An elevation decline of 40 feet results in an increase in the FOS of approximately 13 percent (FOS increases from 1 to 1.13).

Model limitations include the following:

- The 1997 groundwater elevation map may not be representative of current conditions; it especially may not be representative of rainy periods that precede accelerated landsliding.
- The steady-state seepage option within the three-dimensional stability model was not used due to the lack of data and their interpretation.
- It was assumed that groundwater elevation (i.e., surface) is not affected by artesian pressures, although there is historical evidence that the basal failure surface may be subject to artesian pressure (Douglas, 2013).
- As noted above, the 1997 groundwater and basal failure surfaces were laterally extended by extrapolation of existing data. Both groundwater elevation contour maps and contour maps of the basal rupture surface can be improved and refined based upon the results of supplemental investigation and data interpretation.
- The elevation of the groundwater surface that will exist upon implementation of proposed remedial measures (Section 4.6) is not known at this point.

Importantly, the preliminary three-dimensional slope modeling confirms that a reasonable reduction in the elevation of the groundwater surface (i.e., 10 to 20 feet) could result in a significant reduction in land movement in the PBLC area (an increase in FOS up to approximately 8 percent) (Figure 13).

4. Feasibility Study

The FS presented below consists of the following sections:

- ARARs
- Remedial Action Objective
- General Response Actions
- Identification and Screening of Technology Alternatives
- Detailed Analysis of Remedial Technologies
- Preferred Alternative

4.1 ARARs

In accordance with the CERCLA-analogous process for selecting an appropriate remedy being implemented in this document, remedial actions must meet the requirements of relevant federal environmental laws or more stringent state environmental laws referred to as ARARs. Remedial alternative screening must include ARARs evaluation.

4.1.1 Definitions

As defined previously, ARARs is an acronym for ~~applicable~~Applicable or ~~relevant~~Relevant and ~~appropriate requirements~~Appropriate Requirements. Applicable requirements are those "cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance. Only those state standards that are identified by a state in a timely manner and that are more stringent than federal requirements may be applicable" (CFR 300.5).

If a requirement is not applicable, it still may be relevant and appropriate and address issues at the site such that their use is well suited to the particular site (U.S. EPA, 1991b). As summarized by U.S. EPA, environmental laws and regulations can in part be broadly classified into three categories:

- Laws and regulations that restrict activities at a given location
- Laws and regulations that control specific actions

There are therefore two types of ARARs:

- *Location-Specific ARARs:* Intended to protect unique or sensitive areas, such as wetlands, riparian areas, historic places, and fragile ecosystems, and restrict or prohibit activities that are potentially harmful to such areas.

- *Action-Specific ARARs:* Activity or technology based. These ARARs control remedial activities involving the design or use of certain equipment or technology or regulate discrete actions and are used in remedial technology alternatives screening.

To-be-considered criteria (TBCs) are also identified in addition to ARARs. TBCs are advisories, guidance, policies, and/or proposed regulations or standards that might be applicable or applicable in the future. Finally, local permitting requirements and ordinances are also applicable when performing remedial actions.

4.1.2 Identified ARARs

ARARs are summarized in Table 1 and include:

1. 1961 California Lake and Streambed Alteration Program
2. 1968 California Anti-degradation Policy
3. 1969 California Porter-Cologne Act
4. 1970 California Environmental Quality Act (CEQA)
5. 1970 California Endangered Species Act (CESA)
6. 1972 Federal Clean Water Act (CWA)
7. 1973 Federal Endangered Species Act (ESA)

8. 1973 USFWS Habitat Conservation Plans
9. 1993 USEPA Non-point Pollution (NPS) Management Guidance
10. 1995 SWRCB Water Quality Policy, Enclosed Bays and Estuaries
11. 1998 California Coastal Zone Management Act
12. 2002 SWRCB Lake and Streambed Alteration Program 1602
13. 2004 SWRCB Water Quality Enforcement Policy, Enclosed Bays and Estuaries
14. 2007 RWQCB Los Angeles Basin Plan
15. 2011 California NPS Pollution Control Policy
16. 2011 SWRCB NPDES Program
17. 2015 SWRCB 303(d) Listing Policy of 2004, amended 2015
18. 2015 California Division of Occupational Safety and Health regulations (Cal-OSHA)
19. 2015 SWRCB/RWQCB 401 Water Quality Certifications and Wetlands Program
20. 2017 City of Rancho Palos Verdes Grading permit program
21. 1991 Natural Communities Conservation Plan (NCCP) (draft)

4.2 Remedial Action Objective

As discussed in Section 1.3, the specific purpose of this FS is to identify ~~and select a~~viable conceptual solution options for the City's consideration that will accomplish the following overall project goals:

- Provide the geotechnical conditions that reduce the risk of damage to public and private property and would allow for the significant improvement of roadway infrastructure, safety, and stability.
- Significantly reduce human health risk and improve safety in the City.
- Significantly reduce sediment deposition into the Pacific Ocean that is causing unacceptable turbidity in the coastal and marine environment.
- ~~Make all reasonable efforts to identify a~~Select remedy ~~which~~options that will be consistent with the City's NCCP~~ and the Habitat Conservation Plan (~~/HCP, specifically Section 4.1.2~~)~~..

Remedial action objectives (RAOs) as defined by CERCLA and adapted for this FS are one or more defined, specific project end-points or specific goals. The single RAO defined for the Project Area is as follows:

- RAO1: Significantly reduce project area land movement

The project area is defined as the southeastern PBLC area (Red Zone) where land movement has consistently been measured at the greatest rate. A significant reduction in land movement in the project area would address each overall project goal. Infrastructure operation and maintenance, including repair, redesign, and stabilization of PVDS, could be conducted with a more regular, less frequent, and more cost-effective schedule. A stabilized roadway would clearly be much safer for motorists and ensure the expedited transit of emergency vehicles as necessary.

Infrastructure in the project area could also be upgraded, including sewer, water, and electrical lines, with significantly reduced land movement. Once land movement is significantly reduced, the coastal ~~shorecliff~~shore cliff would no longer be regularly driven into the surf zone by ongoing mass movement upslope; thus, sediment turbidity in the coastal and marine environmental would be decreased. In addition, the proposed remedy will stabilize the ~~Preserve land.~~ land within the City's Palos Verdes Nature Preserve. Further, remedy options will be identified consistent with the NCCP/HCP.

4.3 General Response Actions

General response actions (GRAs) as defined by CERCLA and adapted for this FS describe broad, general categories of technologies that will satisfy the RAO and provide a framework for identifying specific remedial technologies for screening and detailed analysis. The GRAs identified to address the RAO are:

- ~~Stormwater control~~
- Subsurface dewatering
- Stormwater control

- Engineered slope stabilization measures
- Eliminate septic system discharge

4.3.1 Subsurface Dewatering

Preventing new water from entering the PBLC can be achieved by stormwater control and extracting existing groundwater in the subsurface as much as possible to reduce soil saturation and reduce continued landslide movement. Preliminary three-dimensional slope modeling confirms that a reasonable reduction in the elevation of the groundwater surface of 5 to 15 percent would result in a significant reduction in land movement in the PBLC area (Section 3.7). Subsurface dewatering through groundwater extraction should be conducted where surface water infiltration and groundwater recharge has historically had the greatest impact, such as in the head scarp area, the project area perimeter, and/or within the interior of the project area. Groundwater extraction could be coupled with regional stormwater capture as discussed below to optimize the effectiveness of the overall subsurface dewatering effort.

Subsurface dewatering is typically conducted with either or both horizontal and vertical groundwater extraction wells. Horizontal groundwater extraction wells are also termed horizontal drains, directional drains, hydraugers, or hydro-augers. In geotechnical engineering, the term horizontal drains is typically used.

Vertical groundwater extraction wells are also termed pumping wells or dewatering wells. Dewatering wells are installed using conventional well-drilling rigs using such drilling methods as air or wet rotary tri-cone, auger, percussion, or sonic. Extraction well installation needs to be designed and field-supervised by a licensed Professional Geologist, Engineering Geologist or Geotechnical Engineer. Wells would be located based on an understanding of area hydrogeology and stratigraphy.

~~4.3.1~~4.3.2 Stormwater Control

Preventing stormwater infiltration is a key to reducing overall slope failure and ongoing surface water loading to the project area. Stormwater originating upslope in ~~upper~~ Portuguese Canyon, upper Paintbrush Canyon, and upper Ishibashi Canyon (east of Peacock Flat) has historically been flowing directly into the head scarp of the PBLC just south of Burma Road where surface fractures are present.

Stormwater infiltration also recharges groundwater, to varying degrees, in the upper, central, and lower canyon areas, which then flows in the subsurface downgradient to the southeastern PBLC area where land movement is the greatest. Stormwater with the potential to result in significant recharge in these areas mustshould be captured, and/or controlled, and discharged to the ocean to prevent future recharge to surface fractures and groundwater.

Stormwater discharge from lower Klondike Canyon also recharges groundwater in the vicinity of the southeastern Red Zone near where land movement is typically occurring at the greatest rate. Stormwater in lower Klondike Canyon should be captured and discharged to the ocean to prevent further groundwater recharge to this area of the PBLC.

GRAs that are used to address stormwater control can include typicalone or any combination of surface water infrastructure such as box culverts, channels, gabions, drainage ditches, subdrains, velocity or energy dissipation structures, sedimentation basins, pipes, and drainways. Much of this type of regional drainage infrastructure is typically constructed with concrete, supplemented with metal or plastic piping, and designed for gravity flow.

GeotextilesHowever, due to the sensitive surrounding flora and fauna, alternatively, geotextiles and engineered composite materials, such as geosynthetic clay liners (GCLs), can also be used for stormwater control where applicable in areas requiring substantial infiltration control. GCLs and geotextiles can also be used in constructed or restored wetlands environments or stream restoration designs. Stormwater control GRAs also include segmented pre-fabricated channels that can be specified, transported to a work area, and connected in series to form a streamway or channel with controlled flow.

Surface water control measures also includes infilling of surface fractures on an annual basis as a maintenance item before winter rains commence. Surface fractures in the PBLC head scarp area can be filled in a number of ways, for example a grouting operation involving a long-reach

~~concrete~~ boom pumping truck delivering a ~~cement grout.~~slurried earthen filler material. The principal goal is to remove preferential pathways through which rain or runoff water can rapidly percolate to the deep subsurface past the zone of plant root uptake and subsequent transpiration.

~~4.3.1~~ EnineeredSubsurface Dewatering

~~In addition to preventing new water from entering the PBLC by stormwater control, existing groundwater in the subsurface must be extracted as much as possible to reduce soil saturation and reduce continued landslide movement. Preliminary three-dimensional slope modeling confirms that a reasonable reduction in the elevation of the groundwater surface of 5 to 15 percent would result in a significant reduction in land movement in the PBLC area (Section 3.7). Subsurface dewatering through groundwater extraction should be conducted where surface water infiltration and groundwater recharge has historically had the greatest impact, such as in the head scarp area, the project area perimeter, and within the interior of the project area. Groundwater extraction should be coupled with regional stormwater capture as discussed above to optimize the effectiveness of the overall subsurface dewatering effort.~~

~~Subsurface dewatering is typically conducted with either or both horizontal and vertical groundwater extraction wells. Horizontal groundwater extraction wells are also termed horizontal drains, hydraugers, or hydro-augers. In geotechnical engineering, the term horizontal drains is typically used.~~

~~Vertical groundwater extraction wells are also termed pumping wells or dewatering wells. Dewatering wells are installed using conventional well-drilling rigs using such drilling methods as air or wet rotary tri-cone, auger, percussion, or sonic. Extraction well installation needs to be designed and field-supervised by a licensed Professional Geologist, Engineering Geologist or Geotechnical Engineer. Wells would be located based on an understanding of area hydrogeology and stratigraphy.~~

~~4.3.2~~4.3.1 ~~Engineered~~ Slope Stabilization Measures

Numerous engineering measures for slope stabilization are currently in use in California. The feasibility of implementation regarding a specific engineering measure depends upon several factors. For example, in some situations, an extent of landsliding, geologic and groundwater conditions, the composition of the landslide mass, and/or the thickness of the landslide mass may limit implementation of a certain measure, while in other cases, terrain, topography, the cost of implementation and maintenance and/or environmental constraints may be a deciding factor. Engineered slope stabilization measures that could be considered for PBLC include the following:

- Buttressing (engineered fill)
- Mechanically stabilized earth (MSE) wall
- Drilled piers (caissons)

~~4.3.3~~4.3.2 Eliminate Septic System Discharge

~~Septic~~As discussed in Section 3.6.1, septic tanks contribute a significant amount of groundwater recharge in relatively dry water years. A centralized sewer system that eliminates septic tanks in the PBLC area would significantly reduce future dry weather groundwater recharge. A centralized sewer system is needed in portions of both the City of Rancho Palos Verdes and the City Rolling Hills within the Portuguese Bend watershed (Figure 7).

The properties within the PBLC area between Peppertree Drive and PVDS currently use septic tanks. A centralized sewer system would be beneficial in this neighborhood that is directly adjacent to the northwest portion of the project area. Recharged groundwater in this neighborhood flows downgradient directly into the project area.

The properties northeast of the PBLC area and south of Crest Road, primarily in the City of Rolling Hills, currently use septic tanks. A centralized sewer system would be beneficial in this neighborhood that is directly upgradient of the PBLC. Recharged groundwater in this neighborhood eventually flows downgradient into the project area. It is recommended that the

City of Rancho Palos Verdes encourage the City of Rolling Hills to construct a centralized sewer system.

4.3.5 Coastal Erosion Control

An offshore breakwater could be installed in Portuguese Bend east or southeast of Inspiration Point to dissipate offshore wave energy and reduce coastal wave-cut bluff erosion. This option was studied in detail by the USACE to address marine habitat restoration in an FS dated 2000 (USACE, 2000).

4.4 Identification and Screening of Technology Alternatives

This section describes technologies commonly used in industry to address the RAO. This section also provides an initial screening of these technologies to identify and eliminate technologies that have a sufficiently obvious flaw, based on known conditions, such that it can be determined early on in the remedy selection process that the technology could not be reasonably implemented. Technologies that are retained as the result of the analysis presented in this section are then carried forward to the detailed analysis of technology alternatives. Prior to implementation, the alternatives would require further engineering analysis, reports, and project plans. Screened technologies ~~are~~ discussed below are also compared to effectiveness, implementability, and cost criteria in Table 2.

4.4.1 Stormwater Control Option 1 – Repair Existing Corrugated Piping System

4.4.1.1 Description

The existing CMP system in the PBLC area could be repaired to capture stormwater and direct discharge to the ocean. The piping network was appropriately installed in the areas of greatest stormwater flow along the axes of Paintbrush, Ishibashi, and Portuguese Canyons. The loose piping segments could be re-connected and refurbished and/or replaced so that the overall system would be reinstated in its original design. Repairing and refurbishing and/or replacing the piping would be a relatively straight-forward task with readily available equipment and labor.

4.4.1.2 Screening Summary

The existing piping network has been out of maintenance for nearly 20 years. When originally installed, the piping segments were relatively easily dismantled by continuing land movement in the PBLC area. In addition, surface water flow in the PBLC was not fully captured by the piping network since the upslope headworks were apparently ~~underdesigned.~~under-designed. The piping diameter may have been undersized as well. Also, the network likely did not cover enough area in the PBLC~~, including the upper canyons.~~. Though the original piping network was envisioned with the intention of capturing stormwater and preventing groundwater recharge, it was installed as a preliminary engineering solution. Resurrecting the former system does not address the design scale issues, and it would not fully capture stormwater. If rebuilt, the metal piping would again be subject to damage from ongoing land movement. A more substantially designed and flexible system is needed for full stormwater capture and control. As a result, this option has been eliminated from further consideration.

4.4.2 Stormwater Control Option 2 – Install Concrete Channels

4.4.2.1 Description

Traditionally, stormwater and flood control infrastructure is constructed with concrete channels and associated metal or plastic piping. Stormwater flow is captured upslope and directed to flood control basins where it infiltrates to groundwater or passes downgradient under gravity flow to a supplemental basin or concrete channel or box culverts. Concrete channels and box culverts are highly effective in capturing and directing stormwater flow and controlling design floods of a pre-specified size and frequency. Concrete channels and culverts are an established technology with available equipment, materials, and labor.

4.4.2.2 Screening Summary

Concrete channels and culverts are effective in geotechnically stable areas. However, where there is land movement, concrete structures are prone to damage from tensional cracking, shearing, subsidence, upheaval, and associated stresses. Once damaged, the channels would no longer prevent groundwater infiltration. Routine maintenance and repair would not be cost-effective in the long term. In addition, concrete structures do not typically allow for native habitat ~~development~~to thrive nor do they receive widespread aesthetic acceptance. However, concrete structures are highly effective and efficient on controlling flow and may be appropriate in some portion of the PBLC area such as the ~~upper~~ canyons~~, along~~ south of Burma Road, or in mid-canyon areas that are not prone to land movement. As a result, this option has been retained for further consideration~~.~~ in limited areas of the PBLC.

4.4.3 Stormwater Control Option 3 – Install Liner and Channel System

4.4.3.1 Description

A canyon liner system consisting of engineered flexible geotextile composite fabrics or GCLs would allow for both stormwater infiltration control and habitat development within the PBLC and Preserve properties. Some associated engineering components would also be needed in mid-canyon high-flow or flow-convergence areas such as velocity dissipation structures, flow control channeling, streambank stabilization, vegetated gabions, or subsurface piping. ~~The upper portions~~Portions of Portuguese, Paintbrush, and Ishibashi Canyons would be lined to direct flow away from the PBLC head scarp area and away from the Project Area. High-flow in the mid-canyon area near Burma Road would be captured and directed by gravity flow into a single channel downgradient that ultimately connects to piping under the PVDS that discharges into the ocean. The flexible composite fabrics are not prone to damage from land movement. The mid-canyon flow control structures would be installed where land movement is minimal and acceptable. Habitat could be partially integrated into the design of the ~~upper and lower~~ canyon ~~liners~~liner system. This option could be installed with readily available equipment, materials, and labor, and designed to comply with the minimization measures set forth in the City's NCCP/HCP.

4.4.3.2 Screening Summary

This option would effectively prevent stormwater infiltration and groundwater recharge while allowing for habitat ~~development~~establishment within the PBLC and Preserve properties. This technology is readily available and could be cost-effectively installed and maintained~~.~~, and could be designed to comply with the minimization measures set forth in the City's NCCP/HCP. Once installed, the structures would be structurally flexible and not prone to damage from land movement. For these reasons, this option has been retained for further consideration.

4.4.4 Stormwater Control Option 4 – Seal Surface Fractures

4.4.4.1 Description

This option involves using a long-reach boom truck and/or conventional ~~cement~~pumping truck, or other method, to deliver a ~~grout~~slurried earthen material to major surface fractures in the PBLC head scarp area and other key areas where surface water infiltration needs to be minimized. A survey of fractures and fracture sealing would be conducted on an annual basis as a maintenance item before winter rains commence.

4.4.4.2 Screening Summary

This option could be conducted with limited or no ~~disruption~~impacts to existing habitat, with staging placed in disturbed areas, and would help reduce groundwater recharge in the project area and in the head scarp area. This technology is readily available and could be implemented for reasonable cost with industry standard equipment, materials, and labor. For these reasons, this option has been retained for further consideration.

4.4.5 Subsurface Dewatering Option 1 – Groundwater Extraction Pits

4.4.5.1 Description

This option involves completing semi-permanent linear excavations of subsurface soils below groundwater in order to facilitate groundwater extraction from low-permeability soils over the long term. Excavations would be completed with a roughly rectangular configuration where groundwater extraction is needed in the southeastern PBLC area within the project area. Extraction pits are effective in relatively low permeability formations as they allow for slow groundwater seepage into the pit and incremental extraction by automated pumping to the surface. Typically, multiple long pits aligned in parallel would be needed to effectively dewater a relatively large area. Groundwater extraction pits are typically installed where the depth to groundwater is less than 25 feet below grade so that excavation engineering and groundwater extraction is less complex. However, deeper pits are also possible.

4.4.5.2 Screening Summary

Groundwater extraction pits can be effective over the long term in low permeability formations where groundwater extraction through traditional pumping wells is too problematic due to very low well yields. However, multiple pits would likely be needed in the relatively large project area and vicinity. Multiple aligned pits would be fairly disruptive to the existing properties. Excavations are also inherently hazardous and require significant safety engineering during design, implementation, oversight, and long-term maintenance. In addition, the depth to groundwater in the PBLC area exceeds 50 feet below grade, further complicating this option and significantly increasing the implementation cost. For these reasons, this option has been eliminated from further consideration.

4.4.6 Subsurface Dewatering Option 2 – Groundwater Extraction Wells

4.4.6.1 Description

Vertical groundwater extraction wells are a proven and traditional technology for groundwater dewatering. Typically, multiple wells are installed by drilling rig in a network pattern to effectively extract groundwater from a design target area and depth. The radius-of-influence (ROI) of each individual well is estimated from field measurements and coupled with the ROI from adjacent wells so that the entire well network covers the target area with some ROI overlap. Downhole electrical submersible pumps would deliver groundwater to the surface for ultimate gravity flow or surface pump-assisted gravity flow to the ocean. Downhole pumps require electrical power. Wells installed in key areas and depths can relieve subsurface artesian pressure which can alleviate land movement.

4.4.6.2 Screening Summary

While extraction wells have been successful in the adjacent Abalone Cove area, extraction wells have had limited success historically in the PBLC area due to low soil permeability, low well yields, and pump clogging due to fine sediments and probable iron bacterial growth. Wells are also prone to deformation or vertical shearing due to ongoing land movement. In addition, the depth to groundwater in some portions of the PBLC exceeds 100 feet, which significantly increases drilling, well installation, and operational costs.

However, extraction wells can be very effective if installed in an area of little or no land movement or where groundwater is present in relatively high permeability soils. Wells would be more effective in historically slide-prone areas once land movement is significantly reduced through other technologies. Wells could effective if coupled with other technologies such as stormwater control. In addition, extraction wells are one of the few cost-effective technologies actually available for subsurface dewatering. Extraction wells also required a relatively low surface footprint for implementation, and less for operation, this being compatible with habitat conservation and aesthetic goals. For these reasons, this option is retained for further consideration.

4.4.7 Subsurface Dewatering Option 3 – Directional Subsurface Drains

4.4.7.1 Description

Directional subsurface drains are also termed hydraugers, hydro-augers, horizontal wells, or horizontal drains. This technology involves the installation of relatively long, linear well casing inclined to grade and extending up to 1,500 feet in the subsurface where conditions allow. The casing is slotted like a vertical well screen so that groundwater passively enters the screen slots then flows under gravity to the wellhead where it is directed to a pipe to the ocean. Several lengths of slotted well casing can be installed from one work area as multiple runs of separate slotted casing are oriented in a radial fan-like pattern extending up and into subsurface soils. Horizontal extraction wells could be installed at several locations in the project area and in the greater PBLC area where subsurface groundwater needs to be extracted. Drain casing can also be installed with relatively large outer casing covering smaller inner casing to help promote longevity and stability of the drain in a subsurface environment prone to land movement.

4.4.7.2 Screening Summary

Directional drains have a number of advantages for the PBLC area. Numerous drains can be installed from one work area, and the resulting infrastructure is below grade so that no surface habitat is disturbed ~~at all~~ above the casing. No pumps or electrical components are needed as groundwater passively enters the drains and flows under gravity to an exit point at the work area. Several drains could be installed from the coastal bluff south of PVDS that would extend beneath the road and into and under the project area and other key areas where groundwater needs to be extracted. Additional drains could be installed further north at the base of the slopes in the upper project area to extract groundwater in the mid-canyon areas. Drains could be installed to cover nearly the entire project area subsurface if needed at a specified depth or, perhaps, multiple depths. In addition, if aligned parallel with or sub-parallel to the primary direction of regional land movement, drain casing would be less susceptible to shearing and deformation due to land movement compared to vertical wells. As land movement eventually slows due to dewatering, however, both wells and drains would be more stable over time.

The challenge would be where drains are needed at significant working depths such as depths approaching 100 feet below grade or more. The drilling and casing installation work area typically must be at the lowest point of elevation so that the casing can be inclined to grade to enable gravity flow. For example, if groundwater extraction is required at a significant depth below grade in relatively flat terrain, the work area must be designed within a temporary excavation in order to achieve the appropriate geometry during installation. In some cases, directional drilling from the surface can be used to help accommodate deeper casing depths.

Although working depth can complicate casing installation, this technology is cost effective, has relatively little operation and maintenance, can cover large areas, and is highly effective in groundwater dewatering. ~~In addition,~~ Moreover, minimal habitat loss would occur with this option, and like vertical groundwater extraction wells, directional drains are one of the few cost-effective technologies actually available for subsurface dewatering. For these reasons, this option is retained for further consideration.

4.4.8 Engineering Slope Stabilization - Buttressing (Engineered Fill)

4.4.8.1 Description

Landslide mitigation by buttressing is probably the most commonly used method of landslide stabilization in California. Depending on the size and shape of the landslide and borrow source materials available, a relatively large buttress might be required. In some cases, especially where space for construction of buttress fill is limited, other, complementary engineering measures might be required. These measures might include soil (i.e., engineered fill) reinforcement by means of geogrids and stabilization of temporary cuts for buttress fill construction by soil nails or rock anchors. These measures allow for construction of buttress fills with nearly vertical slopes and very steep temporary cuts required for construction of these slopes. Leighton (2000) proposed a major buttress along the coastline south of PVDS that is nearly half a mile across and a smaller buttress along the southern and northeastern perimeter of the project area.

4.4.8.2 Screening Summary

Buttress fills, when properly sized, keyed, benched and constructed, in most cases, stabilize landslides for an extended period of time. Slope movements, including lateral displacements, settlement and creep are, in most cases, minimal.

Past studies (e.g., Leighton, 2000) considered construction of a very large buttress fill to mitigate the PBLC. Based upon review of past studies and the results of preliminary evaluation of slope stability using a three-dimensional model, it was confirmed that a relatively large buttress fill would be required for the PBLC. Due to location and size constraints, such a buttress fill would require keying below groundwater which, in turn, would require dewatering during construction. Due to its relatively large size, a buttress fill would be significantly disruptive to protected habitat and residents during construction and would likely not be aesthetically acceptable after construction. Construction of a buttress would be burdensome and disruptive to regional transportation for an extended period of time. For these reasons, this option has been eliminated from further consideration.

4.4.9 Engineering Slope Stabilization Measures - Mechanically Stabilized Earth Wall

4.4.9.1 Description

Mechanically stabilized earth (MSE) walls (gravity earth-retaining walls) are a common and effective technology when applied in the appropriate geotechnical setting. MSE walls have been successfully applied to mitigate slope failure at numerous locations in California. An MSE wall is basically surface soil stabilized with engineered components such as reinforcing geotextiles, panels, or precast blocks installed downslope as a support or anchoring structure to mitigate upslope land movement or to counter forces associated with an upslope containment (such as from water storage). One of the primary advantages of MSE walls is that they can be constructed as modular components in a relatively short period of time compared to other technologies. MSE walls are commonly constructed in roadside slope stabilization projects, as secondary tank containment, and in dams and levees.

4.4.9.2 Screening Summary

MSE walls are cost-effective and can be rapidly constructed to mitigate slope failure or counter design forces upslope in appropriate environments such as where the rupture surface is relatively shallow, and/or where substantial footings or keying to stable bedrock is not required. At the PBLC, the depth to the basal rupture surface exceeds 60 feet in some areas. A surficial MSE wall would not stabilize land movement originating at depth. Although MSE walls are attractive from a cost perspective and are relatively simple to install, due to the depth to the basal rupture surface at the PBLC, along with the relatively large PBLC area that requires stabilization, MSE walls are not an appropriate alternative and will not be considered further.

4.4.10 Engineering Slope Stabilization Measures – Drilled Piers (~~Caissions~~Caissons)

4.4.10.1 Description

Soil improvement techniques like piles, rock anchors, soil nails, and drilled piers (caissons), are commonly used to stabilize slopes and/or to mitigate areas affected by landsliding. Given the size of the area affected by landsliding, the only potentially feasible, soil-improvement based slope mitigation option for the PBLC is mitigation with drilled piers. Drilled piers (caissons) are constructed by drilling and installing vertical reinforcement bars surrounded by poured concrete. Several rows of closely-spaced piers (typically separated by a distance equal to 1.5 to 3 pier-diameters) are installed along the bottom third of sliding mass below the basal rupture surface. Drilled piers must extend below the basal failure surface (the total depth depends on the mechanical properties of the material below the basal failure surface). Drilled piers with diameters of up to 8 feet and up to 60 feet long have been installed at various sites across coastal California in the past, including the PBLC (Section 2.1).

4.4.10.2 Screening Summary

Drilled piers can be installed in areas where access is limited or where there is not enough room to construct a properly keyed and benched engineered buttress. Preliminary evaluation, consistent with past studies, indicates that numerous large diameter drilled piers would be required for PBLC mitigation. In addition, the required caisson depth, advanced below the basal failure surface, would be excessive (at many locations over 60 feet). Therefore, the cost of implementation of this measure, and the associated disruption to the environment, traffic, and residents, is a basis for elimination of this remedial measure from further consideration.

4.4.11 Centralized Sewer System

4.4.11.1 Description

As discussed in Section 4.5.2, septic tanks contribute a significant amount of groundwater recharge in relatively dry water years. Septic tanks are located at properties in both the City of Rancho Palos Verdes and the City of Rolling Hills. A centralized sewer system that eliminates septic tanks in the PBLC area would significantly reduce future dry weather groundwater recharge. Residential septic systems would be incrementally and systematically removed only once a new centralized sewer is installed along ~~public~~ streets in the target neighborhoods. The new sewer system would be installed under the center or along the side of existing streets and connected by laterals to each home within the network. Sewer line flow would ultimately be directed to a centralized sewer treatment plant such as the Sanitation Districts of Los Angeles County Joint Water Pollution Control Plant (JWPCP) in Carson, California. This option would have to be fully evaluated in a separate engineering study to develop specific objectives, design options, costs, and regulatory requirements~~.~~ for both the City of Rancho Palos Verdes and the City of Rolling Hills.

4.4.11.2 Screening Summary

This option would help reduce groundwater recharge in both the immediate vicinity of the Project Area and in the upper canyon areas over the long term. This technology is readily available and could be installed and maintained with industry standard equipment, materials, and labor. For these reasons, this option has been retained for further consideration.

4.4.12 Coastal Erosion Control (Breakwater)

4.4.12.1 Description

An offshore breakwater installed in Portuguese Bend east or southeast of Inspiration Point would dissipate offshore wave energy and reduce coastal bluff erosion. This engineered structure would consist of a containment dike or similar feature. This option was studied in detail by the USACE in their FS dated 2000 (USACE, 2000).

4.4.12.2 Screening Summary

While this option would reduce wave erosion along the bluff south of PVDS, overall landslide mitigation would not be addressed. As a result, the landslide complex would continue to advance generally towards the south after breakwater construction. For this reason, a breakwater option has not been retained for further consideration.

~~4.4.12~~4.4.13 Summary of Retained Technologies

The following technology alternatives have been retained for detailed evaluation, after completion of the screening process:

- Stormwater Control – Concrete Channels
- Stormwater Control – Flexible Liner System and Components
- Stormwater Control – Seal Surface Fractures
- Subsurface Dewatering – Groundwater Extraction Wells
- Subsurface Dewatering – Directional Subsurface Drains
- Eliminate Septic System Discharge – Centralized Sewer System

The detailed analysis of each option is presented in the following section.

4.5 Detailed Analysis of Remedial Technologies

The evaluation criteria that were used to conduct an analysis of the candidate alternative technologies are listed below:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Short-term effectiveness
- Implementability
- Cost
- State and community acceptance

The options presented in this section are ranked and numerically scored for each evaluation criteria (Table 3). The individual scores are summed to arrive at a total technology score. The options that received the higher total scores and relative lowest cost were ~~selected~~identified as a ~~component of the final selected option (~~preferred ~~alternative).~~option for the City's consideration. Approximate order-of-magnitude costs for each option are included in Table 4.

4.5.1 Concrete Channels

- *Overall Protection of Human Health and the Environment.* Concrete channels are protective of human health but can impact the natural environment once constructed. Construction permanently displaces otherwise native habitat ~~or open~~and has an adverse impact on the aesthetic value of the open Preserve land.

- *Compliance with ARARs.* This ~~alternative~~option would likely meet most of the requirements of the identified ARARs. However, converting a blue line stream such as the upper canyon, mid-canyon, or lower canyon areas into a concrete channel would likely not be a permitted project.

- *Long-Term Effectiveness and Permanence.* Concrete channels would be effective and permanent in the long term if built in areas with little to no land movement.

- *Short-Term Effectiveness*. Concrete channels would be effective in the short term if built in areas with little to no land movement.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor.

- *Cost.* This option does not involve specialty equipment, materials, or labor and is routinely implemented for stormwater control in appropriate areas. As a result, the option should not be cost-prohibitive.

- *State and community acceptance.* This option is likely unacceptable to the state and the community because it would significantly alter the appearance of the Preserve properties and permanently eliminate habitat acreage within the Preserve.

This option would be effective and could be installed for manageable costs. Over the longer term, maintenance costs would be high to repair damage caused by land movement. However, it would likely not be permitted within a native habitat area. In addition, it is not aesthetically acceptable for placement within a ~~habitat~~ preserve with protected habitat. As a result of the detailed analysis of this option discussed above, it has been eliminated from further consideration.

4.5.2 Liner and Channel System

- *Overall Protection of Human Health and the Environment.* Flexible material lining the ~~upper~~ canyons ~~and mid-canyon~~, where appropriate, would be protective of human health and integrated into the environment after construction. Engineered substrate could be incorporated into the design to allow for acceptable habitat development within the lined stormwater channel network.

- *Compliance with ARARs.* This ~~alternative~~option would likely meet most or all of the requirements of the identified ARARs. It is anticipated that work within a blue line stream could be permitted in part under a stream restoration program.

- *Long-Term Effectiveness and Permanence.* This option would be effective and permanent in the long term. The proposed materials are flexible and are not susceptible to damage from land movement. The surface area can be planted with native vegetation that can be designed to accommodate various root systems depending on the depth of the top soil.

- *Short-Term Effectiveness*. This option would be effective and permanent in the short term. If land movement occurs early in the program before longer term land movement is significantly reduced, a flexible liner system is designed to withstand damage by allowing some liner movement.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor.

- *Cost.* This option does not involve specialty equipment, materials, or labor and is routinely implemented for infiltration control in appropriate areas. As a result, the option should not be cost-prohibitive.

- *State and community acceptance.* This option would likely be acceptable to the state and to the community because it partially integrates habitat and stream restoration into a design for stormwater capture and control.

4.5.3 Seal Surface Fractures

- *Overall Protection of Human Health and the Environment.* Sealing surface fractures each year in the PBLC head scarp and project area, where appropriate, would be protective of human health and the environment as the contribution to overall land movement due to stormwater infiltration would be reduced.

- *Compliance with ARARs.* This ~~alternative~~option would likely meet most or all of the requirements of the identified ARARs.

- *Long-Term Effectiveness and Permanence.* This option would be effective and permanent in the long term. Additional sealing may be needed each year if additional fractures are identified. Eventually as land movement is significantly reduced, the need to continue fracture sealing would become increasingly reduced.

- *Short-Term Effectiveness*. This option would be effective and permanent in the short term once sealing material is introduced into fractures.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor. The staging area would take up relatively minimal surface area with minimal impact to protected habitat.

- *Cost.* This option does not involve specialty equipment, materials, or labor and is routinely implemented for infiltration control in appropriate areas. As a result, the option should not be cost-prohibitive.

- *State and community acceptance.* This option would likely be acceptable to the state and to the community because it does not significantly impact the surrounding surface environment or habitat., and provided that the staging area is located where little to no impact to protected habitat would occur.

4.5.4 Groundwater Extraction Wells

- *Overall Protection of Human Health and the Environment.* Groundwater extraction wells are protective of human health and the environment when properly designed, installed, and maintained. ~~Limited but manageable and temporary disruption of~~This option would result in relatively minimal impacts to the native habitat or open land~~ is associated with well installation~~.

- *Compliance with ARARs.* Well installation is routinely permitted and would meet requirements of the identified ARARs.

- *Long-Term Effectiveness and Permanence.* Groundwater extraction wells have been problematic over the long term in the PBLC area due to clogging and damage due to land movement. Wells could be sustainable and permanent over the long term if the clogging issue can be resolved through such measures as periodic sterilization with oxidants and redevelopment. In addition, groundwater yield has been problematically low in the PBLC area due to naturally occurring low permeability soils in the subsurface. However, if installed in the appropriate area and at the appropriate depth where soils are sufficiently permeable and where groundwater is present, extraction wells are highly effective in removing subsurface groundwater.

- *Short-Term Effectiveness*. Wells are effective over the short term if installed and maintained where groundwater is present in sufficiently ~~permeability~~permeable soils.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor. This technology is one of the few available for subsurface dewatering. However, low permeability soils can be problematic in the subsurface at the PBLC.

- *Cost.* This option does not involve specialty equipment, materials, or labor and is routinely implemented for infiltration control in appropriate areas. As a result, the option should not be cost-prohibitive.

- *State and community acceptance.* This option would likely be acceptable to the state and to the community because wells currently exist within the PBLC, and in adjacent areas, and are installed and maintained within a relatively small area footprint.

4.5.5 Directional Subsurface Drains

- *Overall Protection of Human Health and the Environment.* Horizontal groundwater extraction wells are protective of human health and the environment because they are installed nearly entirely in the subsurface. Installation can be conducted within a relatively limited area footprint with ~~manageable and temporary disruption of~~relatively minimal impacts to the native habitat or open land, and would not result in an adverse aesthetic value because the drains are mostly located below the surface.

- *Compliance with ARARs.* Horizontal well installation is routinely permitted and would meet requirements of the identified ARARs.

- *Long-Term Effectiveness and Permanence.* Horizontal groundwater extraction wells are effective over the long term because they are essentially a passive technology with no moving parts, relatively limited operation and maintenance, and are mostly underground where the potential for damage from surface activities is eliminated. Groundwater continues to be extracted as long as the well is not damaged from lateral land movement transverse to the well casing. Horizontal wells can be installed with concentric casings aligned parallel to prevailing land movement to help minimize damage from land movement. As the wells remove groundwater land movement is anticipated to be significantly reduced incrementally over time so that the potential for well damage is also incrementally reduced. As with vertical wells, horizontal wells could be sustainable and permanent over the long term if the clogging issue can be resolved through such measures as periodic sterilization with oxidants and redevelopment.

  If installed in the appropriate area and at the appropriate depth where soils are sufficiently permeable and where groundwater is present, horizontal extraction wells are highly effective in removing subsurface groundwater over the long-term. This technology has not been implemented in the PBLC area before, although it is highly effective when appropriately installed and monitored.

- *Short-Term Effectiveness.* Horizontal wells are also effective over the short term if installed where groundwater is present. In some installations, groundwater flow into the horizontal wells can take up to several months before discharge is observed.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor. This technology is also one of the few available for subsurface dewatering. However, low permeability soils can be problematic in the subsurface at the PBLC.

- *Cost.* This option does not involve non-standard specialty equipment, materials, or labor and is routinely implemented for groundwater extraction control in landslide repair or landslide-prone areas. Multiple horizontal wells, directed out radially and extending up to approximately 1,000 feet or more of lateral length, can be installed from one work area. As a result, this option is highly cost-effective.

- *State and community acceptance.* This option would likely be acceptable to the state and to the community because horizontal wells are mostly underground, out of sight, do not ~~displace or disrupt~~impact habitat or open space, and are installed and maintained within a relatively small area footprint. Only relatively minor surface piping would be associated with each wellhead to direct captured groundwater by gravity flow to a nearby surface water channel or pipe discharge to the ocean.

4.5.6 Centralized Sewer System

- *Overall Protection of Human Health and the Environment.* Centralized sewer systems are protective of human health and the environment as they control and contain raw sewage flow to regional treatment plants instead of directing the liquid flow into the subsurface environment.

- *Compliance with ARARs.* This alternative would likely meet most or all of the requirements of the identified ARARs. This option likely involves significant permitting from multiple jurisdictions, however.

- *Long-Term Effectiveness and Permanence.* This option would be effective and permanent in the long term. Some periodic maintenance is required.

- *Short-Term Effectiveness.* This option would be effective and permanent in the short term once constructed.

- *Implementability.* This option is standard technology that is easily implemented with readily available equipment, materials, and labor.

- *Cost.* This option does not involve specialty equipment, materials or labor and is routinely implemented in new developments and in retro-fit areas. This option involves significant planning, permitting, design engineering, and construction work, and, as a result, costs are relatively high. Moreover, permitting and construction would occur in the City of Rancho Palos Verdes and the City of Rolling Hills.

- *State and community acceptance.* This option would likely be acceptable to the state due to the elimination of ongoing liquid infiltration that contributes to regional land movement. While the community will understand and support cessation of land movement, conversion costs from OWTS to city sewer will likely be an issue that would need to be addressed by City of Rancho Palos Verdes and the City of Rolling Hills.

4.6 Preferred ~~Alternative~~Options

4.6.1 Description and Conceptual Design

Based on the evaluation and discussion presented in the previous sections, the following ~~alternatives~~preferred options have been ~~selected as~~identified for the ~~preferred remedy~~City's consideration:

- Seal Surface Fractures
- Directional Subsurface Drains
- Flexible Liner System and Components
- Groundwater Extraction Wells
- Centralized Sewer System

The sequence of the remedy ~~components~~options has been organized to correspond with an iterative construction cycle or a phased-approach to overall design, construction and installation. That is, sealing surface fractures a relatively straight-forward and cost-effective remedy that could be readily implemented before other options are pursued or while other options are in design, permitting, or construction. Second, directional drains are a conventional and cost-effective solution that could be installed while the more complex stormwater control liner and channel system would be in design, permitting, or construction. Directional drains would be installed in a phased manner to allow for additional drains installed over time once earlier designs are installed, pilot-tested, and assessed on its effectiveness.

Finally, onceafter key fractures are sealed, directional subsurface drains are in place, and stormwater control is in place, the remedy program may be supplemented with an expansion of the existing groundwater extraction well network. Wells would be installed last in the sequence so that potential well damage from ongoing land movement would be minimized as the earlier components incrementally take effect.

The first three remedy componentsoptions (sealing fractures, directional drains, and stormwater liner/channel system) would be pilot-tested before full-scale design and construction to allow for design refinement and adjustment as needed based on field conditions. Pilot testing is discussed below in Section 4.6.3. Each remedy component is further described in the following subsections.

4.6.1.1 Seal Surface Fractures

This technology consists of in-filling existing surface fractures on an annual basis primarily in the vicinity of the project area (Red Zone) and in the PBLC head scarp area to reduce stormwater infiltration to groundwater. Other areas of the PBLC such as south of PVDS or within the interior of the slide area itself could also be included if appropriate. Relatively large fractures would be infilled before the rainy winter season each year using a long-reach concrete pumping truck, conventional grout pumping rig, or other method. Surface fractures would be identified in advance each fall through an on-site visual inspection survey, recent aerial photograph review, or potentially, with photographic data collected with an aerial drone fly-over.

4.6.1.2 Directional Subsurface Drains

Directional drains have the potential to have a significant effect on lowering the groundwater surface within the PBLC project area. Drains would be installed in a phased approach to target groundwater removal in the southern project area where land movement has historically been measured at the greatest rate. Drains could be installed at two or more locations at the southern edge of the coastal bluff south of Palos Verdes Drive, for example, and would be drilled radially approximately 1,200 to 1,500 feet northwest, north, and northeast extending beneath PVDS (Figure 14). Drains in this area would be installed using a conventional, track-mounted horizontal drilling rig that can safely and reliably access the rocky beach area. Other drains could be installed north of the beach from low-lying areas south of PVDS. The drain design would have to include infrastructure to collect and discharge groundwater flow from the drains, such as piping runs to an ocean discharge location on the beach.

~~A site investigation~~An engineering study would need to be ~~conducted~~prepared to ~~determine~~support identification of exact drilling locations and drain installation geometry. Additional data gaps related to this and other options are discussed in Section 4.6.2.

4.6.1.3 Liner and Channel System

This technology consists of the following components (Appendix ~~C~~D):

- Canyon Liner
- ~~Collector Channel Junction~~
- ~~Collector Channel~~
- ~~Outlet Channel (through active slide area)~~
- Lapped Liner System
- Lapped Channel Liner Under-Drain System
- Native Vegetation ~~Islands~~

The ultimate goal of this technology is to minimize or eliminate stormwater infiltration and percolation to groundwater in the Portuguese Bend watershed and in the PBLC Project Area. The ~~upper~~ canyon liner would extend just north of the Burma Road Trail at an appropriate distance upgradient into ~~the upper reaches of~~ Portuguese, Paintbrush, and Ishibashi Canyons in order to capture and control stormwater surface flow and direct it ~~into a collector channel and outlet channel~~to the ocean (described below) (Appendix ~~C~~D). The ~~upper~~ canyon liner system as envisioned would be an impervious layer with an underdrain and an armored stone riprap surface~~.~~ in relatively high surface water flow segments. Lower Portuguese Canyon in the northern Project Area would also be lined and ~~connected to an outlet channel (described below). Both the upper and lower~~the canyon liners can be vegetated to blend into the native habitat. The depth of the top soil will determine the size of the feasible root system supporting the native habitat. The subsurface liner material, such as engineered geomembrane, could be expected to have a lifetime expectancy of at least several hundred years (Benson, 2014).

The ~~upper~~ canyon liner would ~~connect to a collector channel junction installed at Burma Road where the three major canyons (Portuguese, Paintbrush, and Ishibashi) converge near the PBLC head scarp area. The collector channel junction would slow stormwater flow and then redirect it into a main collector channel constructed along Burma Road and flowing southeastward under gravity. The collector channel junction would be constructed of vegetated rock gabions, half-round concrete piping (or equivalent) around the bend in the stream way, and associated rock armoring of the streambank. The main collector channel would be constructed of riprap, rock gabions, and an underlying lapped geotextile liner. Like the canyon liners, the collector channel junction and the main collector channel can be vegetated to blend into the native habitat.~~

~~The main collector channel would~~ direct flow into ~~an outlet~~a lower channel installed across the ~~northeastern~~northern edge of the PBLC area and leading under gravity flow to a road culvert under PVDS (Appendix ~~C~~D). Similar to the ~~upper~~ canyon liner ~~and main collector channel~~, the outlet channel would be installed with an underlying lapped geotextile liner and surface rock armoring ~~(Appendix C).~~. The outlet channel could also be vegetated to blend into the native habitat. Vegetation islands can be installed mid-stream where the overall design and flow conditions allow ~~(Appendix C).~~.

This option would also include a drainage and engineering study to support a final design that will promote surface water flow along the northern roadside of PVDS where storm water has historically been ponding and infiltrating to groundwater in the Red Zone area.

Ultimately, additional areas in the adjacent watersheds could also be lined, such as eastern Altamira Canyon or lower Klondike Canyon, where stormwater continues to infiltrate to groundwater in the vicinity of the project area. The described liner and channel system is only a conceptual design. A full engineering and hydrologic study would be needed to ~~appropriately~~support final design and ~~size~~sizing of the liner and channel system.

4.6.1.4 Groundwater Extraction Wells

Supplemental groundwater extraction wells would be installed in the project area once drains and stormwater control are in place (Figure 14). Groundwater extraction wells would be installed with conventional track-mounted or truck-mounted well drilling rigs using sonic drilling methods. The sonic method is preferred since soil sampling and characterization can be continually conducted while drilling commences, groundwater is readily observed, and well installation can proceed without the potential for drilling-induced permeability reduction associated with other methods such as mud rotary. Companion borings for geologic or geotechnical investigation may also need to be completed in advance by other methods to collect well design information such as geologic, stratigraphic, or hydrogeologic data. Groundwater monitoring wells will also need to be installed to routinely monitor groundwater levels in the PBLC area. At this conceptual stage of the overall project, based on the areal extent of the PBLC area and historical well yields, it is estimated that approximately 25 extraction wells would be needed in the project area with a network of approximately 10 to 15 additional monitoring wells within and adjacent to the project area. The number, depth, and design of the extraction and monitoring wells would be based on site-specific aquifer testing conducted to determine well design parameters as well as overall hydrogeologic and stratigraphic data based on historical work or supplemental site investigation.

4.6.1.5 Centralized Sewer System

Approximately 2 miles of new subsurface sewer lines and associated manholes and junctions need to be installed in the Portuguese Bend neighborhood east of lower Altamira Canyon and west of lower Portuguese Canyon. This area includes those roads generally southeast of Peppertree Drive and north of Palos Verdes Drive South (Figure 7). In addition, approximately 1.5 miles of new subsurface sewer lines are needed in the upper Portuguese Canyon Watershed. New sewer lines are needed in this area where upper Portuguese Canyon extends north to the northern watershed boundary at Crest Road and where upper Ishibashi Canyon splits into four sub-canyons that extend east-northeast to the northern watershed boundary. Both upper Portuguese Canyon and upper Ishibashi Canyon are located within the City of

Rolling Hills. The new sewer line installation would need to be synchronized with private lateral installation and connection as well as septic system removal in both neighborhoods. The new lines would likely be connected to nearby exiting lines that direct sewage to the Los Angeles County Joint Water Pollution Control Plant (JWPCP) in Carson. New sewer line installation and septic tank removal would have to be fully designed in a separate engineering study to develop specific objectives, design options, costs, and regulatory requirements.

4.6.2 Data Gaps

In addition, the following ~~pre-~~final design input is needed, at a minimum, to develop a detailed scope of work and engineering cost estimate for construction bidding for the City's consideration:

- Hydrologic analysis and floodplain mapping
- Geologic, hydrogeologic, and stratigraphic characterization

Hydrologic analysis, floodplain mapping, and watershed modeling are needed to appropriately characterize and specify the design flood for canyon lining and channel sizing engineering. These data include stream flow measurements, flood frequency, rainfall data analysis, and related tasks.

Geologic, hydrogeologic, and stratigraphic data are needed to understand subsurface conditions before drain and well drilling commences. Historical data are also needed, if available, including extraction well construction data, extraction well production records, boring logs, a master soil boring and well location map, groundwater elevation data (historical and current), and groundwater quality sampling data.

Data gap information is typically further specified in a data gap investigation work plan that outlines the required information and how it can be collected before final design engineering commences.

4.6.3 Pilot Testing

~~Selected components of the preferred~~The remedy options selected by the City should be pilot tested before full-scale implementation. Pilot testing should be completed to simulate full-scale implementation as much as possible while obtaining the design data needed to scale-up and cost the remedy for complete implementation. Pilot testing should be completed before full-scale implementation of the canyon liner and collector channel system, the surface fracture sealing, and subsurface drain remedy ~~components~~options. Pilot testing and associated baseline and performance monitoring is typically specified and detailed in a separate plan. The pilot test plan could be combined with the data gap investigation work plan discussed above.

4.6.4 Approximate Implementation Costs

The approximate order-of-magnitude costs (~~2017~~2018 dollars) associated with the preferred alternative is provided in Table 4. Estimated costs are based on industry literature where possible and from professional experience with similar projects.

4.6.4.1 Seal Surface Fractures

Pilot testing for a surface fracture sealing program is estimated to cost approximately $100,000. Planning, permitting, construction and initial reporting for a full-scale program is estimated at approximately $250,000. Operation and maintenance (O&M) (fracture sealing, monitoring, and reporting each year thereafter) costs are estimated at approximately $50,000. Extended for 10 years (~~2017~~2018 dollars), O&M would cost approximately $625,000. The total cost for this option is thus approximately $975,000.

4.6.4.2 Directional Subsurface Drains

Directional drains require a data gap investigation to characterize groundwater and identify the appropriate stratigraphic zone for drain installation. Data gap investigation and pilot testing for a drain program is estimated to cost approximately $656,000. Planning, permitting, construction and reporting of a full-scale program of 10 drains extending 1,200 feet is estimated at approximately $6.4 million. O&M (including monitoring and reporting each year thereafter) is estimated at approximately $125,000. Extended for 30 years (~~2017~~2018 dollars) (without major reconstruction) this component would cost approximately $11.7 million. Major reconstruction for additional drains or replacement drains would be basically comparable to the initial program cost rates and total costs.

4.6.4.3 Liner and Channel System

Pilot testing for a liner and channel system is estimated at approximately $512,000. Planning, permitting, and construction of a full-scale program of lining the upper canyons (Portuguese, Paintbrush and, Ishibashi) and lower Portuguese Canyon with a perimeter channel and culvert directing flow to the ocean is estimated to cost approximately $13.5 million. O&M (including monitoring and reporting each year thereafter) is estimated at approximately $75,000. Extended for 30 years (20172018 dollars) (without major reconstruction) this component would cost approximately $16.8 million.

4.6.4.4 Groundwater Extraction and Monitoring Wells

Groundwater extraction wells require a data gap investigation to characterize groundwater and identify the appropriate stratigraphic zone(s) for well installation. Data gap investigation and pilot testing for supplemental groundwater extraction wells is estimated at approximately $556,000 (supplemental to the drain data gap investigation). Planning, permitting, and construction of a full-scale program (20 wells to 200 feet with 10 companion monitoring wells [30 wells total]) is estimated to cost approximately $4 million. O&M (including monitoring and reporting each year thereafter) is estimated at approximately $325,000. Extended for 30 years (20172018 dollars) (without major reconstruction) this component would cost approximately $12 million.

4.6.4.5 Centralized Sewer System

Residential sewer costs are approximately $200 per linear foot overall including manholes and related infrastructure. Approximately 1.5 miles of sewer line are needed in the Portuguese Bend neighborhood and approximately 2 miles of sewer line are needed in the upper Portuguese Bend watershed area (within the City of Rolling Hills) (total of approximately 18,480 feet). Planning, permitting, and construction of a full-scale program in both the City of Rancho Palos Verdes and Rolling Hills is estimated to cost approximately $5 million. O&M (including monitoring and reporting each year thereafter) is estimated at approximately $50,000.

Extended for 30 years (~~2017~~2018 dollars) (without major reconstruction) this component would cost approximately $7 million.

4.6.4.6 Total Estimated Project Cost

The estimated order-of-magnitude cost for all components of the preferred remedy totals $31.3 million for initial planning, permitting, data gap investigation, pilot testing, design, and construction. With O&M, monitoring, and reporting extended for 30 years (~~2017~~2018 dollars) (without major reconstruction) the estimated order-of-magnitude cost totals $53.5 million.

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