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memorandum

date October 26, 2016

to Lennie Roberts (Committee for Green Foothills)

from Louis White, PE

subject Vallemar Bluffs Coastal Hazards Assessment: Estimate of Accelerated Bluff Erosion due to Sea Level Rise (ESA Ref. #D160715.00)

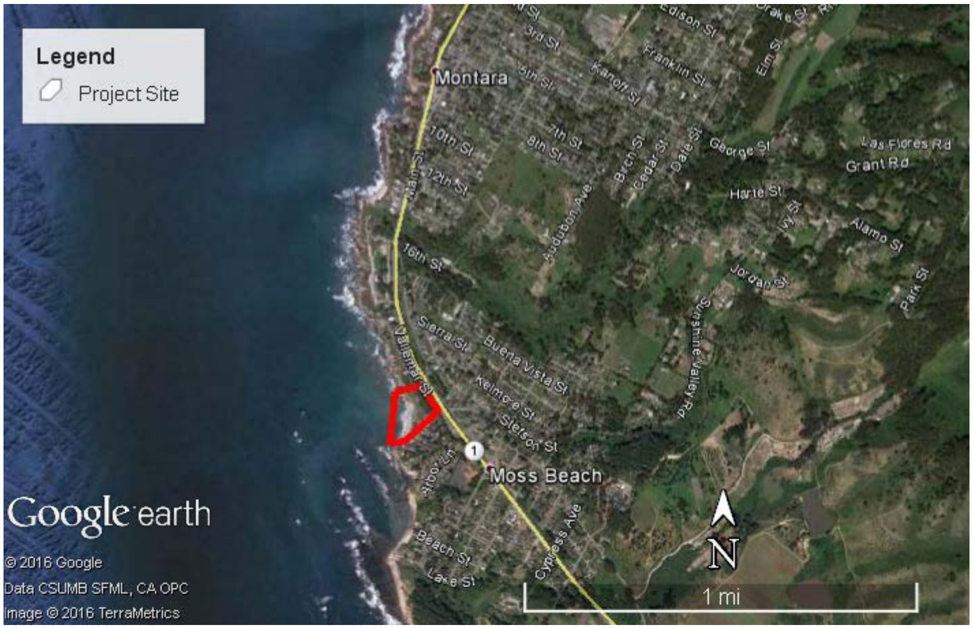
1. Introduction

This memorandum presents the findings of a coastal hazards assessment, including estimates of future bluff erosion and wave uprush elevations, at an undeveloped bluff top site in Moss Beach, California. The Committee for Green Foothills (CGF) retained Environmental Science Associates (ESA) to review existing studies for the site by others and to conduct a technical analysis to estimate the potential future erosion limits associated with sea level rise (SLR). The analysis is based on information reported by others, as well as site observations and topographic data collected by ESA, and tide and wave data accessed from National Oceanic and Atmospheric Administration (NOAA) and Coastal Data Information Program (CDIP), respectively. Although the findings presented in this memorandum are intended to be used as a comparison to recommendations by others, they are not sufficient for locating structures, and this memorandum is not intended to do so.

The work described in this memorandum was completed by ESA staff members Hannah Snow, James Jackson, PE, Damien Kunz, Matt Norcott, and Louis White, PE, with review by Bob Battalio, PE. The information presented in this memorandum is intended solely for the use and benefit of the Committee for Green Foothills. No other person or entity shall be entitled to rely on the services, opinions, recommendations, plans or specifications provided pursuant to this agreement without the express written consent of ESA, 550 Kearny Street, Suite 800, San Francisco, CA 94108.

Background

A proposed residential development project in Moss Beach, at Vallemar Bluffs, is required by the San Mateo County Local Coastal Program (LCP), Section 9.8, to consider coastal bluff erosion for a 50 year time period. The 2.5-acre site, at the intersection of Vallemar Street and Juliana Avenue, is the last undeveloped private land in the San Mateo Midcoast area (Figure 1). Seven lots, which were consolidated from a 1908 subdivision, have multiple owners who have all agreed to submit an application for development of the property as a whole. The application was recently submitted to San Mateo County Planning (County) and is now undergoing a formal review process. The Applicant has reduced the number of proposed houses to five, eliminating development on one lot closest to the cliffs. The County plans to prepare an Initial Study/Mitigated Negative Declaration for the project.



Source: Google 2016

Figure 1
Project Site (in red), located in Moss Beach at Juliana Avenue and Vallemar Street

CGF retained ESA to provide professional engineering advice on coastal erosion issues at the site, as they relate to the future potential exposure of the proposed development to coastal erosion hazards. Specifically, CGF has opined that revisions to the project are needed because the proposed development on Lot D is too close to the bluffs and will likely be subject to bluff erosion over the 50-year life of the project. CGF has also indicated that allowing this lot to be developed will severely impact coastal access along the existing informal public access trail, impact public views of the coast from Juliana Avenue, as well as impact coastal prairie habitat, which is protected under the Coastal Act and San Mateo County LCP as Environmentally Sensitive Habitat Area (ESHA).

A coastal erosion study was prepared by Haro, Kasunich & Associates (HKA) in 2015 that recommended incorporating a 28-foot bluff setback distance from the top of a slope they estimated to be stable into the development plans (HKA 2015). The recommended setback distance included the projection of their estimated historic erosion rate plus a 25% increase in the historic erosion rate to account for the effects of sea level rise (SLR) over a 50-year project design life. The HKA (2015) study estimated a historic bluff erosion rate of 0.45 feet per year, which has been questioned by project stakeholders as being too low.

Erosion gullies, or swales, filled with imported materials, including soil, concrete debris, and tree trunks, located to the north and south of the promontory immediately opposite Lot D, may introduce additional erosion hazards to the proposed project. JCP (1990) describes a gully on the south side of the promontory as an active landslide approximately 40 feet in diameter and affecting an area approximately 18 feet inland from the existing bluff top. GeoForensics (2001) describes these features as erosion gullies, or drainage swales that extend from the bluff edge toward Lot D, based on photography from 1946. They report that the gullies were filled between 1946 and 1955 according to inspection of aerial imagery.

Several technical topics were identified by CGF as needing additional consideration in the analysis, including the following:

- Historic erosion rate seems low, and should consider additional aerial photographs and methods
- Erosion process with the stratified geology, and influence of the bedrock geometry on erosion of the bluff
- Low stability of the bluffs in the vicinity of Lot D as mapped in a San Mateo County Geologic Hazards Map
- Influence of the groundwater seeps in the bluff face on erosion and stability
- Influence of the gullies and landslides in the area on erosional hazards

Organization of this Memorandum

This memorandum is organized as follows:

- Section 2: Site Observations and Data Collection – a summary of the observations during site visits, topographic survey data, and other data used in the analyses
- Section 3: Climate Change and Sea Level Rise Background – describes guidance recommendations by the State of California, including scenarios, planning horizons, and amounts of sea level rise to be assessed
- Section 4: Analysis and Results – summarizes the technical methods and results of wave runup modeling and bluff erosion modeling

Summary of Findings and Recommendations

Based on the technical analyses conducted by ESA, we present the following findings:

- Erosion is projected to be greater than shown by HKA (2015). Impacts associated with a greater amount of erosion should be considered to avoid potential future hazards to proposed development.
- The historic erosion rate estimated by HKA (2015) should be reviewed in greater detail, and the project applicant should use a higher erosion rate not lower than the higher end of the range of estimates reported by HKA (2015). Additional information and aerial imagery should be used to establish the historic erosion rate.
- Incorporate a factor of safety into the setback distance calculation, or use a higher historic erosion rate.
- Consideration of the erosion gullies is important in assessing the potential hazards at Lot D. The gullies may not behave according to the historic erosion rate, and the presence of fill and concrete debris suggests that a landslide may be deeper than perceived from visual inspection. The potential migration of the gully into Lot D should be assessed in greater detail. Further study should assess whether the gully identified previously as a landslide would be considered active.
- Drainage of the site on the surface and through existing underground infrastructure should be considered in the stability of the bluff as it contributes to rapidly forming gullies and landslides. Future development should not place structures or drainage features in areas that are subject to future coastal erosion.
- Although a project design life established by the developers is 50 years, structures often exceed the design life, and the California Coastal Commission typically requires assessment of the hazard exposure through the end of the century at 2100 so that the project incorporates acceptable adaptation strategies.
- The future coastal flood hazard zone associated with the 100-year total water level is expected to increase in the future with sea level rise, and should be considered in the project planning and design. Results of the modeling described in this memorandum suggest that the bluff may be overtopped by 2065, with significant overtopping by 2100.

2. Site Observations and Data Collection

We based the analysis and findings presented herein on observations and data collected at the site by ESA staff, as well as publically available meteorological data archived by government agencies. The following sections summarize the site observations and the various data collected to support the analysis.

2.1 Site Observations

ESA staff observed the site conditions on September 28, 2016 and October 18, 2016. The first visit, during a low tide, included site reconnaissance and discussion of the proposed project with CGF staff and other stakeholders. At the second visit, ESA field staff collected topographic survey data of the bluff geometry, described in more detail below. Several key observations were made, which we compared to existing studies and incorporated into our bluff erosion and sea level rise analysis.

The geology of the site is stratified, with a layer of marine terrace deposits that overlays a bedrock layer known as the Montara Quartz Diorite (JCP 1990). Figure 2 shows a sandy beach with large granite cobbles and boulders is located in front of the exposed bedrock layer, which is approximately 5 to 15 feet above the top of the beach, and overlain by the marine terrace layer. Inspection of oblique aerial photography of the site archived by the California Coastal Records Project[1] indicates the sandy beach is seasonal. Photographs taken during winter and spring months show a rocky beach with waves breaking at the base of the bedrock bluff. Furthermore, the project area is mapped as an area of "low stability" and classified as unstable bluff material with erosion rate greater than one foot per year in a San Mateo County Geologic Hazards Map (San Mateo County 1975).

Figure 2
Photograph of site on beach looking north, showing the stratified geology of the bluff

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[1] http://www.californiacoastline.org/

The promontory opposite Lot D is located between two gullies: one relatively large gully filled with imported soil and debris, and a smaller gully that appears to have been formed by surface drainage and an exposed pipe. The locations of these gullies are shown in Figure 2. The large gully was described by JCP (1990) as an active landslide approximately 40 feet in diameter and affecting an area approximately 18 feet inland from the existing bluff top. JCP (1990) considered this an active landslide because signs of erosion along the bluff face were observed at the time of their study. A study by GeoForensics (2001) stated that several erosion gullies were present along the bluffs in a photograph from 1946, and extended inland from the face of the bluff as much as 90 feet. GeoForensics (1990) indicates that the gullies were filled by 1955, but have more recently been eroding. The left photo of Figure 3 shows imported concrete debris and fill located at the top of the gully that was described as an active landslide by JCP (1990). The photo on the right of Figure 3 shows the location of the “small” gully on the north of the promontory opposite Lot D, thought to be formed by surface drainage. An exposed metal pipe appears to have contributed to the erosion of the “small” gully (right panel, Figure 4). This implies that erosional factors other than average bluff retreat may contribute to future erosion hazards into Lot D.

Figure 3

Photos of the bluff top showing concrete debris and fill at the top of an active landslide (left) and the variability in the bluff edge caused by gullies (right)

Several fissures were observed in the bluff top, which indicate that the bluff edge is in an unstable geometry and is prone to failure (left panel, Figure 4). The fissures are likely a result of the overly steep geometry of the marine terrace deposit layer, and indicative of the episodic nature of erosion. The photo on the right in Figure 4 shows the gully located immediately north of the promontory opposite Lot D.

Figure 4
Photos of bluff top showing a fissure or crack in the bluff (left) and a gully presumably caused by surface drainage (right)

Areas of active erosion on the bluff, as well as groundwater seeps, were observed along the bluff. The photograph in Figure 5 shows a grayish layer of sediment with water seeping out of the face of the bluff. Areas of active erosion were observed adjacent to the wet bluff face, which may be contributing to the instability of the bluff. Areas along the bluff are also vegetated by a mix of native and non-native invasive species that may play a role in surface erosion.

Figure 5
Active erosion and seepage of groundwater on the bluff face

The photographs in Figure 6 show additional groundwater seeps and erosion that was observed below the promontory opposite Lot D. The water seeping out of the bluff runs down the slope and over the bedrock. Algae growths were observed at locations where the groundwater seeps run over the bedrock, possibly indicating that the seeps are active most of the year, and not only in the rainy season.

Figure 6
Groundwater seeps and erosion on the bluff face below the promontory opposite Lot D

A sewer manhole was observed close to the bluff edge at the project site, indicating the presence of an abandoned sewer main. The sewer main likely has little impact on the bluff and erosion unless it is actively leaking and contributing to the moisture observed in the bluff face. The primary issue with the abandoned sewer main will be in the future, when it becomes exposed by erosion of the bluff, which will require removal of debris after it is exposed or in anticipation of future erosion. The geometry of the abandoned sewer infrastructure is not known, and therefore more information is needed to make a recommendation on proposed approach to removing the infrastructure from the bluff.

2.2 Data Collection

Data collection for the project included collecting of topography at the site, reviewing existing studies, and acquiring publically available meteorological data. The following sub-sections describe the data collection.

Survey Data and Measurements

ESA collected a limited amount of topographic data at the project site on October 18, 2016, using a total station and RTK GPS equipment.[2] The survey measured the horizontal and vertical location of several site features relative to the North American Vertical Datum of 1988 (NAVD), including the:

- Edge of bluff (marine terrace layer)
- Top of bedrock
- Edge of bedrock (also called "crest" in this document)

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[2] ESA performs land surveys and collects hydrographic data to augment traditional surveying services for the purposes of geomorphic interpretation, monitoring of project performance, and other specific uses consistent with Geologic and Landscape Surveys as defined in the Professional Land Surveyors' Act (California Business and Professionals Code). ESA does not provide traditional land survey services such as property boundaries and maps for general use by others. ESA recommends that a licensed, professional land surveyor accomplish these traditional surveying services under direct contract either with the client or as a sub-consultant to ESA.

- Top of beach
- Profile through promontory opposite Lot D, following Section 3 of HKA (2015)

Figure 7 summarizes the key information from the topographic survey, including dimensions, elevations, and slopes of features. The dashed blue line is located approximately where we surveyed a profile across the bluff and beach. The elevation of the edge of the bluff was measured to be approximately 43 feet NAVD, with some variability along the shore. The marine terrace deposits in this location stand almost vertical and are approximately 25 feet tall. The elevation of the bedrock layer was approximately 18 feet NAVD, although it also varied along the shore, and was approximately 7 feet above the top of the beach. A small "bench" was formed on the bedrock top as it extends seaward from the base of the bluff. The bedrock bench from the bluff toe varied between about 5 feet and 15 feet along the shore, likely a function of the relative exposure to waves breaking near the bedrock and bluff. The bench was not observed toward the north end of the beach, likely because of the presence of a large promontory that extends into the surf zone and protects the northern pocket of the beach from the larger breaking waves. Boulders and large cobbles were observed in the surf zone at approximately the low tide platform, and along the beach. Several boulders were sitting on top of the bench formed by the bedrock, which were likely moved by waves during extreme coastal conditions.

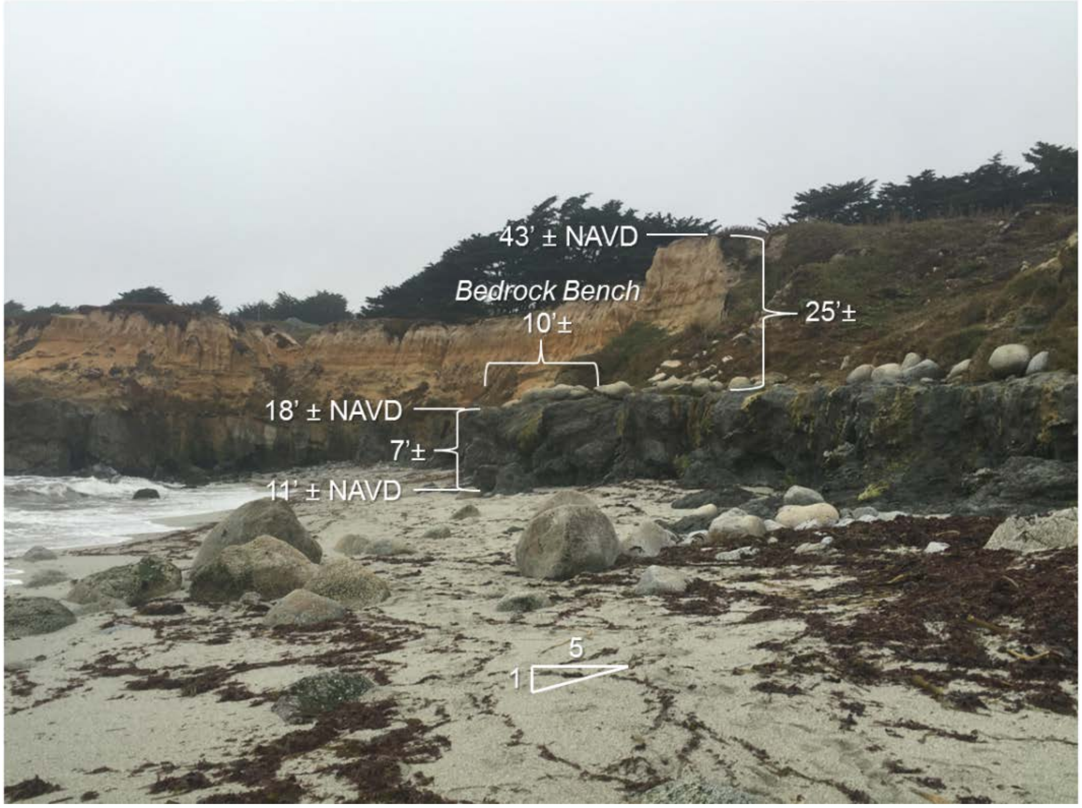


Figure 7
Approximate geometry of beach and bluff

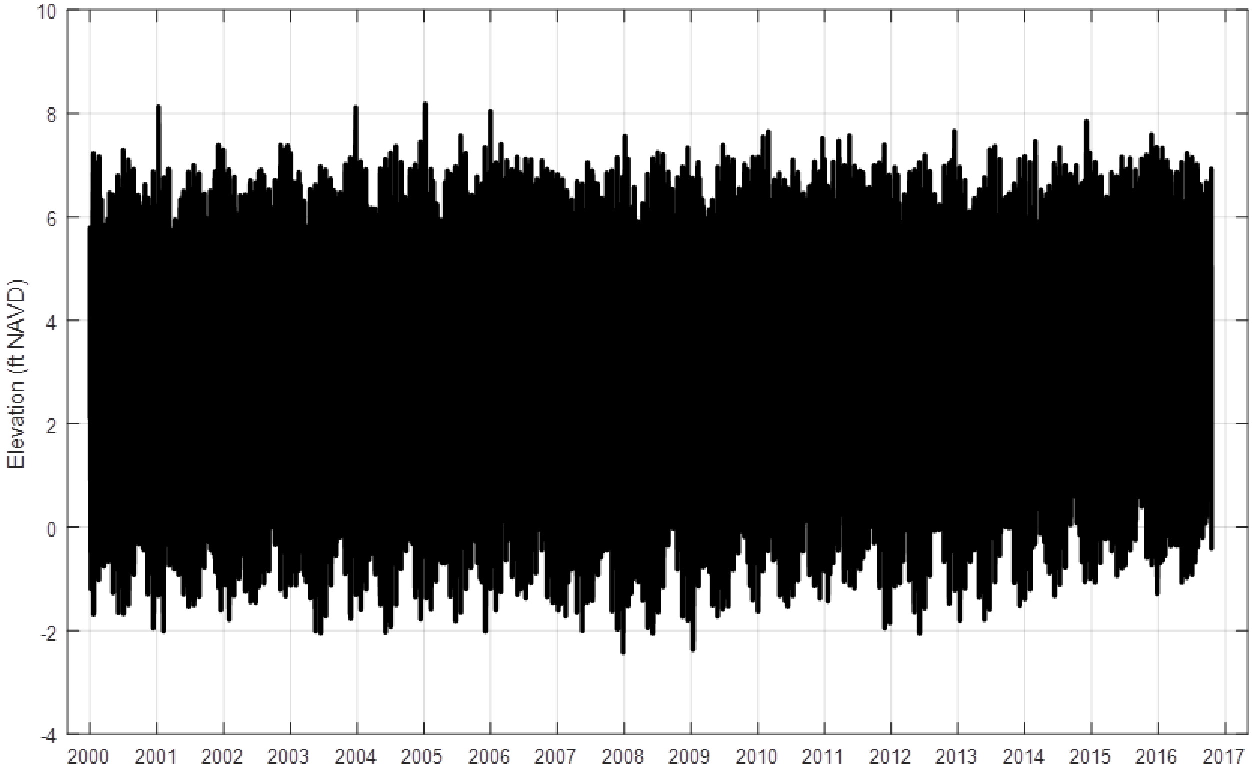
Tidal Water Levels

Tides at the site are characterized by a mixed semi-diurnal tide signal, typical of the California coast, with two high tides and low tides occurring per day, each with unequal heights. The diurnal tide range, or the difference between mean higher high water (MHHW) and mean lower low water (MLLW), is approximately 5.8 feet. Table 1 presents the tidal datums used for the technical analyses described in this report. Tide data and tidal datums were based on the NOAA Tide Gage Station 9414290 at San Francisco, California, located at the Golden Gate about 20 miles from the project site, but assumed to be representative of the actual conditions at the site. Comparison to a short record of tide data collected at Pillar Point show a small difference in the tide elevations, but was assumed negligible for the analysis we conducted. Figure 8 presents a time series of the tide data that was used in the analysis described below.

TABLE 1
TIDAL DATUMS FROM SAN FRANCISCO TIDE STATION 9414290

Datum	Elevation (feet NAVD)
Highest Observed Water Level (HOWL)	8.7
Mean Higher High Water (MHHW)	5.9
Mean High Water (MHW)	5.3
Mean Tide Level (MTL)	3.2
Mean Sea Level (MSL)	3.2
Mean Low Water (MLW)	1.2
Mean Lower Low Water (MLLW)	0.1
Lowest Observed Water Level (LOWL)	-2.8

Source: NOAA NOS Station 9414290, San Francisco, CA



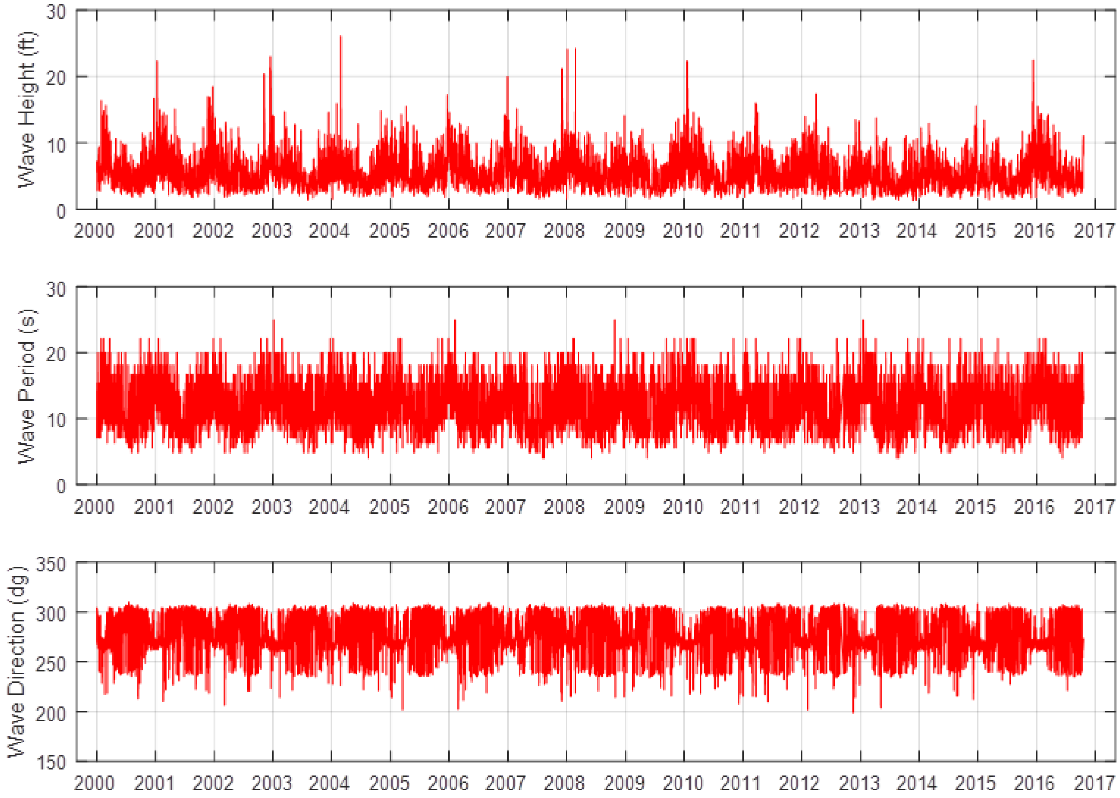
Source: NOAA (2016)

Figure 8
Measured tide elevation at San Francisco, Golden Gate, NOAA NOS 9414290

Wave Climate

Hourly wave height, period, and direction near the project site were obtained from nearshore transformed wave data provided by the Coastal Data Information Program (CDIP) California Coastal Wave Monitoring and Prediction System (O'Reilly et al. 2016). The data comprises the output of a spectral transformation model, at a virtual point located in about 45 feet of water approximately one-half mile offshore of the project site. Figure 9 presents hourly wave data, transformed from deep-water measurements using transformation coefficients computed by CDIP.[3] Note the seasonal patterns, with large wave heights and long periods approaching the site with a narrow band from the west-northwest in the winter, and smaller waves with shorter periods approaching from a wide band ranging from west-southwest to northwest. The wave data is an important consideration in the analysis, as it is a driver of the beach elevations, flood elevations and erosion processes.

Recent nearshore wave data from CDIP and historic water levels at the San Francisco tide gauge (NOAA station 9414290) were used as input to the coastal erosion model and flooding calculations. Since these same meteorological and climatic conditions affect water levels and waves, these conditions are correlated. In fact, the worst coastal hazards are typically associated with coincident occurrences of high waves and high storm surge and the effect on coastal hazard responses such as total water level are not necessarily linear (FEMA 2005; Garrity et al. 2006).



Source: CDIP; O'Reilly et al. 2016

Figure 9
Wave height, period and direction record for offshore of the project site at depth of 15 meters

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[3] Data were furnished by the Coastal Data Information Program (CDIP), Integrative Oceanography Division, operated by the Scripps Institution of Oceanography, under the sponsorship of the U.S. Army Corps of Engineers and the California Department of Parks and Recreation, http://cdip.ucsd.edu/

Historic Erosion Rate

Estimation of the historic erosion rate for the project site was beyond the scope of our study, and therefore we relied on prior estimates by others. Our primary source for the historic erosion rate was the HKA (2015) study, which estimated the historical bluff recession rates over time using a 1908 surveyed subdivision map, a vertical photo from 1986, and 2014 field measurements. The HKA (2015) study based their setback analysis on a historic erosion rate of 0.45 feet per year, based on comparing the 1908 survey to the 2014 field measurements, and also reported a range in the erosion rate between 0.36 and 0.64 feet per year based on comparing the 1986 photograph to the 2014 field measurements.

Through comments provided to ESA by CGF, stakeholders have expressed concern in using the 1908 subdivision map as the baseline for the erosion rate calculations because it is not known how accurately the coast was surveyed, including the actual location of the bluff edge at the time of the mapping. GeoForensics (2001) performed a “least-squares regression” analysis on several aerial images acquired for the project site, and projected the computed erosion rates into the future to estimate the future location of the bluff edge. However, it appears that the GeoForensics (2001) study did not consider SLR, and it does not explicitly report the computed historic erosion rates, although the data and linear fits are presented in graphical format. Inspection of the graphs suggests historical erosion rates that vary from about 0.3 feet per year up to 0.75 feet per year in some locations. Selection of the cross-section plays an important role in the calculated erosion rates, because the location of the bluff edge is variable. Other studies nearby for the Fitzgerald Marine Reserve estimate historic bluff erosion rates of over one foot per year and recommend a minimum setback of 100 feet for new development (Brady/LSA 2002).

Overall, we recommend the conducting a more complete bluff erosion analysis to estimate the historical erosion rates at the site. This study should utilize all available aerial images of adequate quality, and use different standard methods to estimate the rate, including a least squares regression and other available software, such as Digital Shoreline Analysis System (DSAS) (Thieler et al. 2009).

In the analysis described in this memorandum, we used the HKA (2015) erosion rate of 0.45 feet per year so that the results from the ESA methods can be compared to HKA (2015). We also considered the implications of a higher erosion rate of 0.64 feet per year reported by HKA (2015) in our analysis. Finally we also considered the implications of a higher historic erosion rate, for which we selected one foot per year.

3. Climate Change and Sea Level Rise Background

3.1 Climate change scenarios

The accumulation of greenhouse gases in the Earth's atmosphere is causing and will continue to cause global warming and resultant climate change. For the coastal setting, the primary exposure will be an increase in mean SLR due to thermal expansion of the ocean's waters and melting of ice sheets.

State planning guidance for coastal flood vulnerability assessments call for considering a range of scenarios (OPC 2013; CCC 2015). These scenarios bracket the likely ranges of future greenhouse gas emissions and ice sheet loss, two key determinants of climate whose future values cannot be precisely predicted. Scenario-based analysis promotes the understanding of impacts from a range of scenarios and identifies the amounts of climate change that would cause impacts.

The guidance recommends using scenarios that represent low, medium, and high rates of climate change. Recent studies of current greenhouse gas emissions and projections of future loss of ice sheet indicate that the low scenario probably underrepresents future SLR (Rahmstorf et al. 2012; Horton et al. 2014). Also, note that even if SLR does not increase as fast as projected for the high scenario, SLR will undoubtedly continue beyond 2100, such that the medium scenario is likely to yield the same amount of SLR. It just would occur a few decades after 2100 instead of at the turn of the century.

While the interim state recommended SLR scenarios have not yet been finalized, we are expecting the state to recommend dropping the "low" SLR scenario. This study thus focuses on the Medium and High SLR scenarios. The assumptions that form the basis for these scenarios are:

- ***High Scenario*** – The high scenario assumes population growth that peaks mid-century, high economic growth, and development of more efficient technologies. The associated energy demands would be met primarily with fossil-fuel intensive sources.
- ***Medium Scenario*** – The medium scenario assumes same population, economic, and technologic growth as the high scenario, but also assumes that energy would be derived from a balance of sources, thereby reducing greenhouse gas emissions.

3.2 Planning Horizons

The planning horizons analyzed for this project are 2065 and 2100, selected to inform the potential impacts to the project site for mid- and late-century conditions, and consistent with the CCC (2015) SLR Policy Guidance document. This set of planning horizons is recommended so that decisions about land use can be matched to the timeframe for project lifespans and to facilitate the identification of triggers for adaptation measures. Although HKA (2015) reported that the design life of the project is 50 years, which will occur much earlier than the 2100 planning horizon, it is unlikely that the development would be removed at the end of this project life. Therefore, planning horizons for a SLR analysis are typically longer than the periods associated with near-term decision-making.

3.3 Relative Mean Sea Level Rise Amounts

Two SLR scenarios were evaluated to estimate the change in coastal water levels under medium and high degrees of climate change. This conforms to state planning guidance for coastal flood vulnerability, which recommends analyzing a range of climate scenarios due to uncertainty about future climate predictions (OPC 2013; CCC 2015). For assessing the impacts of SLR on the project site, we used mean SLR projections through 2100 based on a recent study by the National Research Council (NRC 2012) for the West Coast, which was adopted by the State of California (OPC 2013; CCC 2015). Table 3 presents the values for relative mean SLR at 2065[4] and 2100 for the San Francisco Region relative to 2000. The relative mean SLR includes regional projections of both mean SLR and vertical land subsidence of 1.5 millimeters per year for the San Andreas region south of Cape Mendocino (see OPC 2013). These values of relative SLR were used in the analysis described in this memo.

TABLE 2
RELATIVE MEAN SEA LEVEL RISE PROJECTIONS FOR THE SAN FRANCISCO REGION FOR MEDIUM AND HIGH SCENARIOS

Year	Medium SLR	High SLR
2065	17 inches	35 inches
2100	36 inches	66 inches

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[4] Although the SLR projections are tabulated at years 2050 and 2100, the CCC (2015) includes a polynomial fit for the High Scenario (Equation B-3 of CCC 2015), which was used to define the SLR value projected for 2065. Similarly, we used a polynomial fit to the NRC (2012) values for the Medium Scenario to define the SLR value projected for 2065.

4. Analysis and Results

The following sections describe the technical analyses conducted to model the bluff erosion and wave runup elevations as a function of sea level rise. The bluff recession model calculates the increase in the historical erosion rate due to SLR as a function of the change in exceedance of a selected wave runup event. Therefore, this section presents the analysis and results of the total water level analysis, followed by the bluff erosion analysis and results.

4.1 Wave Uprush and Total Water Level

The total water level (TWL), defined as the maximum elevation of the wave runup or wave uprush, was estimated using methods described in a Technical Methods Manual titled *Relating Future Coastal Conditions to Existing FEMA Flood Hazard Maps*, recently prepared for the California Department of Water Resources (Battalio et al. 2016), and consistent with FEMA mapping guidelines (FEMA 2005). The "modified TAW" method computes the wave runup height above a reference water level using the TAW equation[5] with a composite slope of the backshore (i.e. an average slope is calculated over a distance between the breaker location and a point on the bluff), similar to methods described in the *Shore Protection Manual* (USACE 1984).

The modified TAW method computes a reference water level by increasing the observed tidal still water level (SWL) to include the static and dynamic wave setup as caused by waves breaking further offshore. We used the DIM method to calculate the wave setup at the breaker location to establish the reference water level for each wave runup computation. The final step is to compute the wave runup elevation with a depth-limited wave at a selected breaker location. We selected a breaker location as the mean sea level (MSL) contour on the surveyed shore profile.

Using the concurrent time series of tide elevations and offshore wave heights, we generated a time series of TWLs. Figure 10 presents an exceedance curve of the computed TWLs, which relate the TWL elevation (vertical axis) to the percent of time that the value is exceeded (horizontal axis). As shown in Figure 10, elevation 0 feet NAVD is exceeded 100% of the time for the period of observations, and the TWL of 22 feet NAVD is exceeded approximately 1% of the time for the period of observations. Note that the crest of the bedrock bluff is located at approximately 18 feet NAVD, and thus is anticipated to be overtopped approximately 3 to 4% of the time.

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[5] TAW refers to the Technical Advisory Committee on Flood Defence in the Netherlands; the TAW equation was developed by the for estimating wave runup and overtopping as part of a set of guidelines for safety assessment and design of dikes. Application of the TAW equation is also described in FEMA's Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States (FEMA 2005).

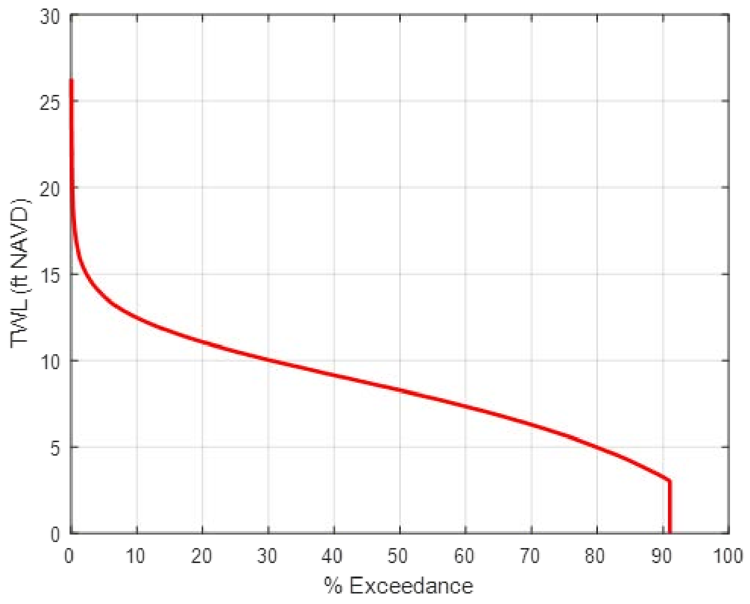


Figure 10
Exceedance curve of the total water level calculated at the site for existing conditions

We estimated the 100-year TWL for existing conditions to be approximately 31±2 feet NAVD. Figure 11 presents several extreme value distributions fit to the annual maximum TWL data for the period of record. This is slightly higher than the base flood elevation (BFE) of 26 feet NAVD mapped in the Preliminary 2015 FEMA FIRM for the project area. However, the FEMA BFE values are calculated on a limited number of transects, with values that range from 26 to 34 feet NAVD along this section of coast with similar shore morphology and wave exposure, and therefore the estimate of the 100-year TWL in this report seems in-line with the FEMA study.

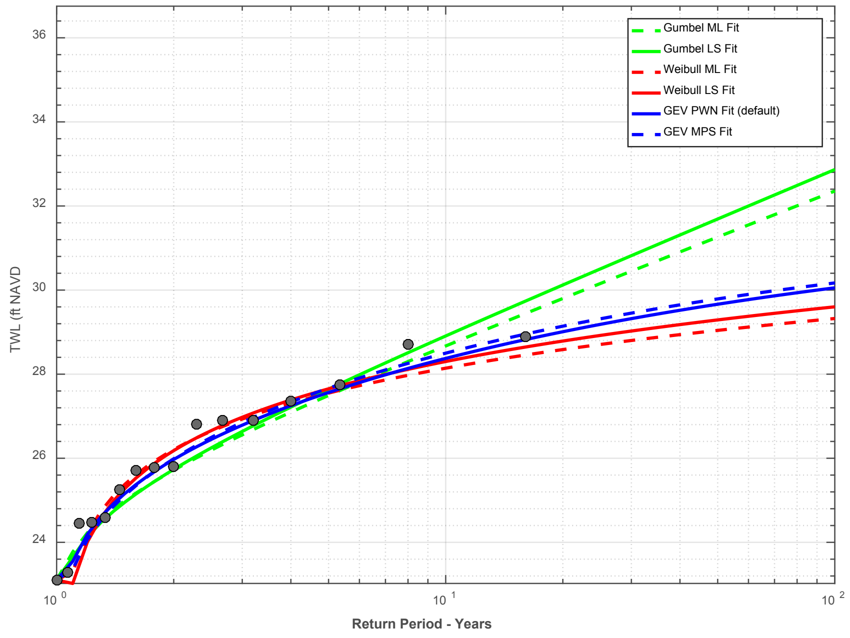


Figure 11
Extreme value analysis of the total water level time series shows a 100-year total water level up to 33 feet NAVD

The wave runup model was calibrated by comparing model output to observations made at the site on October 17, 2016. We used a photograph of the site and observations taken on October 17, 2016 during high tide to estimate a TWL of approximately 23 feet NAVD. Based on the topographic survey, the top of the vegetation shown in the photograph is approximately 23 feet NAVD, which appears to agree well with the spray of the wave. Also note that the reference water level is high compared to the beach, likely due to wave setup caused by the long period swell hitting the coast on that particular day. We ran the modified TAW model using the measured tides from NOAA and nearshore waves from CDIP for the same time period, and calibrated the runup component by adjusting a roughness coefficient so that the model output was similar to the observed data.

Photograph by Kathy Lockhart

Figure 12
Estimate of total water level based on observations made on October 17, 2016

The future 100-year TWL is expected to increase with SLR, with the potential to overtop the bluff by 2065. Recent studies have shown that the change in TWL is approximately 3 to 4 times the amount of SLR at erosion-resistant, steep backshores (Battalio et al. 2016, Vandever et al. 2016). Table 3 presents values of the existing and future 100-year TWL for the profile analyzed at the site. Note that the existing bluff edge is approximately 43 feet NAVD. During wave overtopping, long period waves can propagate a significant landward distance and impact structures with a momentum force proportional to the square of the velocity. FEMA maps the "V" zone, or velocity hazard zone, in FIRMs for coastal areas subject to waves. Construction in a "V" zone is required to meet additional building codes associated with the wave and velocity hazards. FEMA FIRMs are subject to future revisions.

TABLE 3
ESTIMATED EXISTING AND FUTURE 100-YEAR TOTAL WATER LEVEL (FEET NAVD)

Year	Medium Scenario	High Scenario
Existing	31	31
2065	37	43
2100	43	53

4.2 Bluff Retreat Estimate

The estimate of future bluff retreat was completed using an approach first established by ESA (formerly Philip Williams and Associates) and applied to several studies on the coast of California. The method estimates the increase in the erosion rate of the base or toe of the bluff as a function of the change in the TWL exceedance above the toe for future conditions. For this particular site and application, the layered geology was assessed using an additional step and assumptions. A key assumption in this analysis is that for a static sea level, the bedrock layer and the marine terrace layer erode at the same rate. We assume that the bench between the edge of the bedrock and the base of the bluff is a result of variable wave exposure and is not expected to change significantly for a static sea level. As sea level changes, the base erosion rate of the bedrock will increase, due to the change in TWL exceedance above the toe, and the bedrock bench will increase due to the increased impacts of waves on the marine terrace materials. Therefore, we computed the accelerated erosion of the bluff top as a function of the acceleration in the base erosion at the toe of the bedrock, and the increase in the bench width between the bedrock edge and the bluff. Figure 13 presents a schematic that illustrates the conceptual model of the bluff erosion for the site, where X_1 is the base erosion distance of the toe of the bedrock for a given time period and X_2 is the total erosion distance of the bluff edge for the same time period. Note that X_2 is the sum of the base erosion distance X_1 and the change in width of the bench.

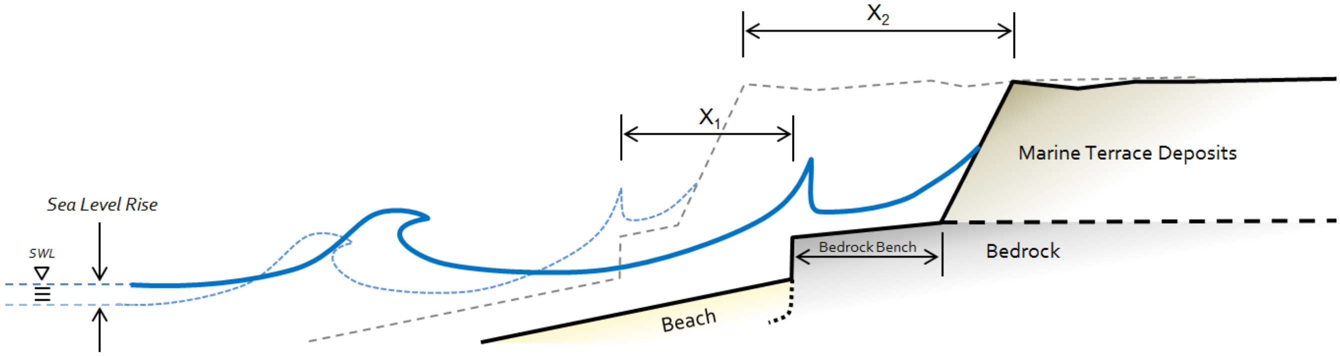


Figure 13
Conceptual model of bluff erosion at the site (not to scale)

Estimate of Accelerated Base Erosion

Methods to estimate future erosion rates that consider sea level rise are described by a limited number of studies. The Pacific Institute study (PWA 2009, Revell et al. 2011) estimated future erosion rates using the following equation,

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(1 + \alpha \frac{P_f - P_e}{P_e}\right) \qquad (1)$$

where P_f and P_e are the future and existing probability of total water level exceedance above the cliff toe elevation, respectively. Since the Pacific Institute study, a number of studies have proposed additional relationships for estimating cliff/bluff erosion rates under accelerated sea level rise (Walkden and Dickson 2008, Ashton et al. 2011). Walkden and Dickson (2008) found that the following equation applied well for the cliff backed/low volume beaches undergoing a historic trend in sea level rise at the Naze Peninsula on the Essex coast in Southern England:

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(\frac{Rate\ of\ Sea\ Level\ Rise\ (t)}{Rate\ of\ Sea\ Level\ Rise\ (historic)}\right)^{m} \qquad (2)$$

In this equation m =0.5. Ashton et al. 2011 investigated the value of m using various data sets for calibration and confirmed that $m = 0.5$ applies to cliffs/bluffs dominated by wave-driven erosion. In particular, rocky shore platforms and cliffs fronted by low-sediment-volume beaches, both of which apply for the cliffs at the project site.

ESA has further adapted the Walkden and Dickson (2008) equation, as follows:

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(\frac{A\ (t)}{A\ (historic)}\right)^{m} \qquad (3)$$

where A is the area below the total water level exceedance curve and above the existing toe elevation. This area is a combination of the duration of wave impact above the toe elevation and the intensity of that contact (how high above the toe the waves and wave runup are reaching). The exponent, m, was kept at 0.5, in agreement with the previous studies.

Application of this method to the profile at the site yielded increased erosion rates as a function of time. We computed the accelerated erosion rates for three different historic erosion rates as described in Section 2.2, and for the medium and high sea level rise scenarios as described in Section 3.

Estimate of Increase in Width of Bedrock Bench

We estimated the change in width of the bedrock bench on top of the bedrock by accounting for the change in future TWL for events with a 1- to 5-year recurrence interval. The recurrence interval of 1- to 5-years was selected to correspond to the episodic nature of bluff erosion. We modified Equation 5 of Battalio et al. (2016) to relate the ratio of negative freeboard (e.g. the height of the wave runup above the bedrock) for future and existing conditions to the change in width of the bench. For the profile we analyzed, the bench width was approximately 10 feet, and increased over time as the relative negative freeboard increased with the acceleration in SLR.

TABLE 4
ESTIMATED EXISTING AND FUTURE BEDROCK BENCH TOP WIDTH AT ANALYZED PROFILE (FEET)

Year	Medium Scenario	High Scenario
Existing	10	10
2065	20	26
2100	27	35

Calculation of Setback Distance

The setback location was estimated by adding the results of the base erosion estimate with the increase in the width of the bench, and then projecting a slope of 1.5 to 1 (horizontal to vertical) to the existing ground surface, consistent with the method described by HKA (2015) for locating the top of the stable slope.

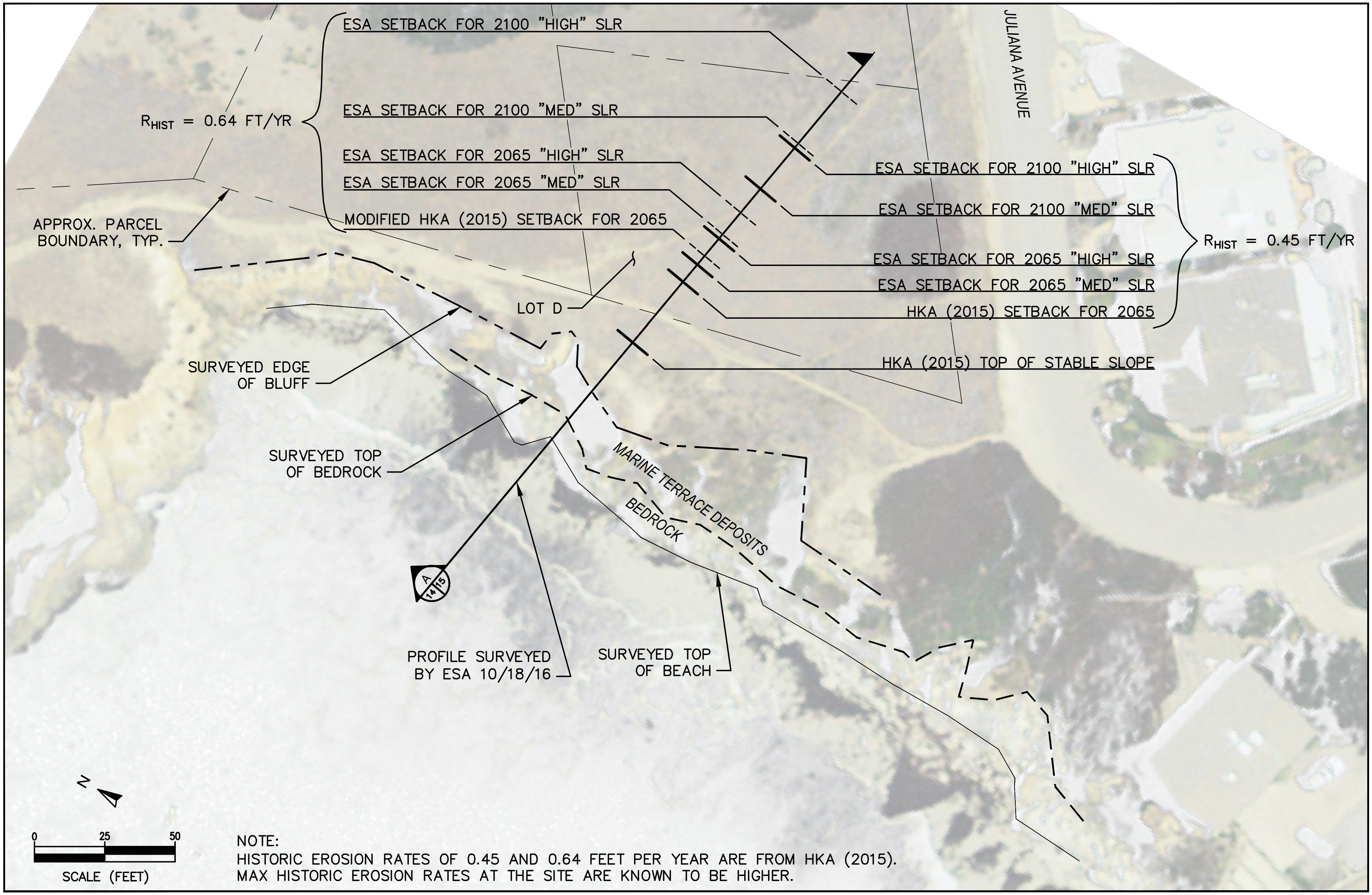
Figure 14 presents a plan view of the stable slope location and the computed setbacks associated with the medium and high SLR scenarios at 2065 and 2100 for two historic erosion rates. The setbacks shown with the solid lines are based on a historic erosion rate of 0.45 feet per year, and those with the dashed line are based on a historic erosion rate of 0.64 feet per year. These setback distances are applicable to the surveyed profile location only, and may not be representative of appropriate setback distances along the shore. Additional work is required to compute the setback line along the shore, and is beyond the scope of this study. Figure 15 shows the profile section, with an example of how the setback distance is estimated for a historic erosion rate of 0.45 feet per year. Table 5 presents the computed setback distances relative to the top of the stable slope for different historic erosion rates at 2065 and 2100.

TABLE 5
TOTAL EROSION DISTANCE RELATIVE TO STABLE SLOPE SETBACK FOR FUTURE CONDITIONS (FEET)

Historic Erosion Rate (feet per year)	Year 2065		Year 2100	
	Medium SLR Scenario	High SLR Scenario	Medium SLR Scenario	High SLR Scenario
0.45	36	48	71	90
0.64	50	60	92	116
1.0	70	83	133+	165+

This approach is consistent with recommended guidelines of the State to use a range in sea level projections and different time frames (see CCC 2015). While accounting for mid-century values at 2065 is indeed important and in compliance with local regulations, assessing the potential exposure at 2100 is another important step that is typically required by the California Coastal Commission in reviewing Coastal Development Permit applications. Identification of future exposure that is likely to occur late in the century is used to inform how potential adaptation strategies and approaches will be incorporated into the proposed project, so that potential future adverse impacts to the coast are minimized.

As shown in Figure 14, we expect a greater amount of erosion to occur by 2065 as compared to the results of HKA (2015). Because of the uncertainty and sensitivity of the historic erosion rate estimated by HKA (2015), we recommend incorporating a factor of safety or use a higher rate. As shown by our results, a relatively small increase in the historic erosion rate resulted in a greater amount of future erosion and larger setback distances. Although this analysis is not intended for locating structures, our findings indicate that a greater amount of erosion should be considered in the proposed project to avoid potential future hazards.

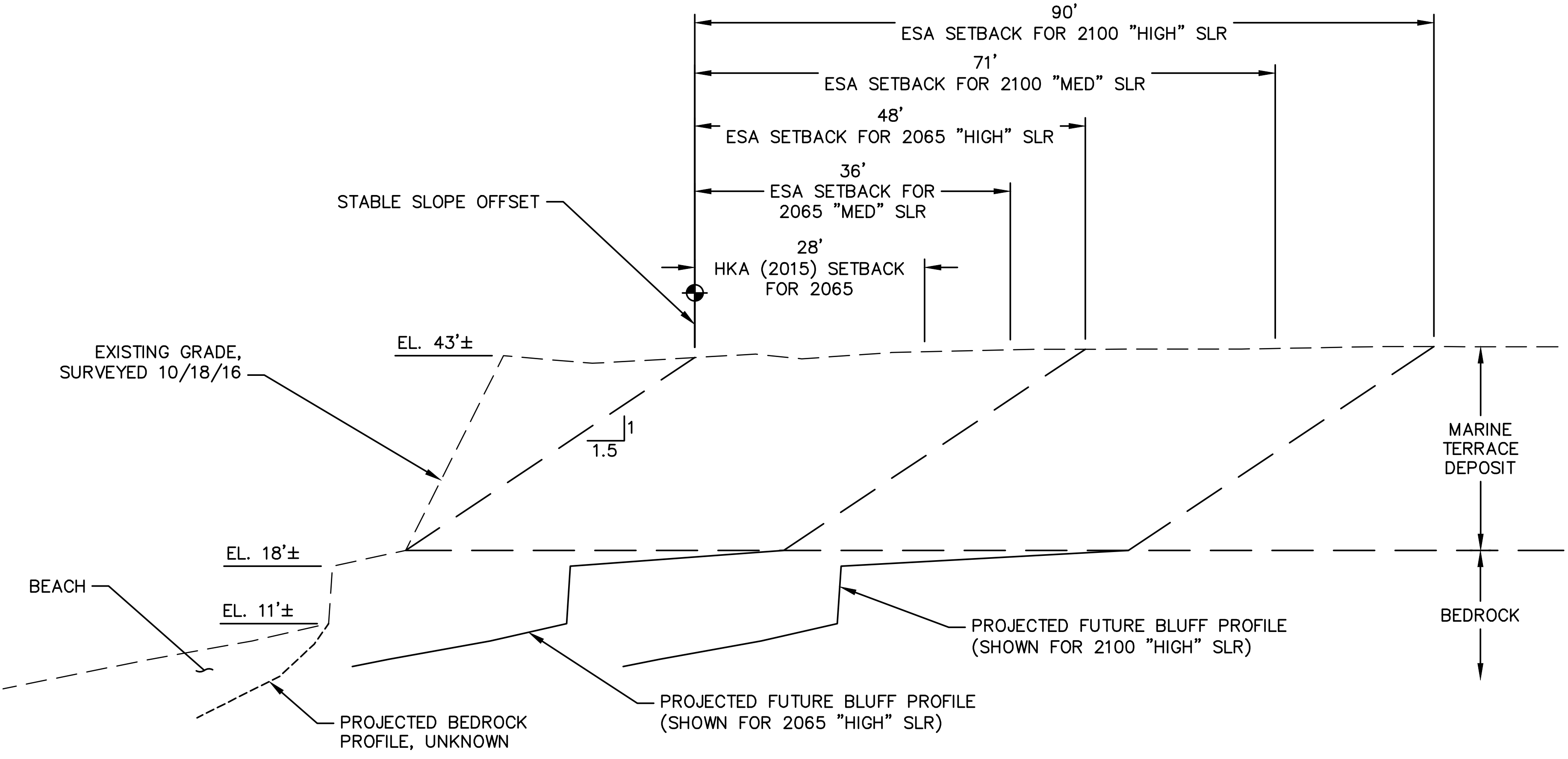


NOTE:
HISTORIC EROSION RATES OF 0.45 AND 0.64 FEET PER YEAR ARE FROM HKA (2015).
MAX HISTORIC EROSION RATES AT THE SITE ARE KNOWN TO BE HIGHER.

SOURCE: Imagery from California Coastal Conservancy (2012); ESA Survey on 10/18/16; Parcel data from San Mateo County

Figure 14

Estimated Setback Distances for Future Bluff Erosion at 2065 and 2100 for Medium and High Sea Level Rise Scenarios



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PROFILE OF BLUFF IN FRONT OF LOT D FOR EXISTING AND PROJECTED FUTURE EROSION

SECTION

1" = 20'

NOTE:
DIMENSIONS SHOWN IN THIS FIGURE REPRESENT A HISTORIC EROSION RATE OF 0.45 FEET PER YEAR. MAX HISTORIC EROSION RATES AT THE SITE ARE KNOWN TO BE HIGHER THAN 0.45 FEET PER YEAR.

SOURCE: ESA Survey 10/18/16

Figure 15
Projected Future Erosion on Bluff Profile
for Historic Erosion Rate of 0.45 Feet per Year

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