Executive Summary Report

for the

Seawall Earthquake Vulnerability Study

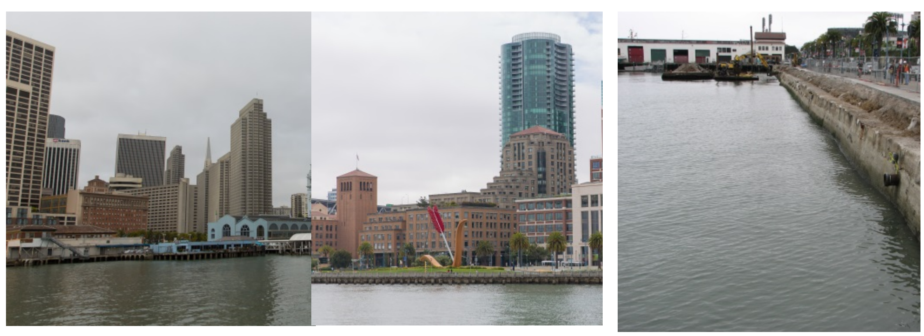
of the

Northern Seawall
San Francisco, California

July 2016

Prepared for:
Port of San Francisco

Prepared by:
GHD-GTC Joint Venture



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Seawall Earthquake Vulnerability Study

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July 2016

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List of Preparers

A consultant team headed by GHD-GTC Joint Venture prepared this report under the guidance of the Port of San Francisco, Engineering Division. A list of the consultant team personnel that worked on the Earthquake Vulnerability Study of the Northern Waterfront Seawall is provided below.

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1. Executive Summary Report

The following document presents a summary of the findings of earthquake vulnerability and mitigation alternatives for the Northern Waterfront Seawall, which stretches from Fisherman's Wharf to Mission Creek.

The Port of San Francisco ("Port") is a self-supporting, municipal enterprise agency overseeing 7-1/2 miles of waterfront property along the San Francisco Bay. The Port has initiated a program to identify and upgrade portions of the waterfront vulnerable to earthquakes, flooding, and climate change.

The City of San Francisco (City) is engaged in an effort to prepare for a major earthquake and to create more resilient City infrastructure. As part of this effort, the Port is developing a plan to strengthen the Northern Waterfront Seawall ("Seawall") to maintain viability of Port's operations, increase protection of Port and City assets, and enhance life safety in the face of degradation, flooding, earthquakes, climate change, and security hazards. The Seawall was constructed over 100 years ago within the Bay and supports reclaimed land, or fill, and as a result is more vulnerable to seismic risk. Earthquake performance of reclaimed land is an issue for coastal communities worldwide.

The Port authorized an earthquake vulnerability study of the Northern Waterfront Seawall which extends approximately 3 miles from Fisherman's Wharf to Pier 46. The Port hired GHD/GTC JV, a joint venture to lead a team of geotechnical and structural engineers, and cost estimating, economics and coastal engineering professionals to conduct a three-part Earthquake Vulnerability Study of the Northern Waterfront Seawall ("Study"). Components of the study included: assessment of available information and condition, engineering analysis to determine likely damage to the seawall and infrastructure within an inferred "zone of influence", economic impacts resulting from multiple earthquake scenarios, development of conceptual level retrofits/costs, and recommendations for implementation of improvements and/or further study.

The Port subsequently hired COWI and Langan, engineering firms with expertise in waterfront structures, to peer review the engineering vulnerability analysis and project solutions.

Study Approach

For Phase 1, the Study Team's scope of work, assisted by the Port, consisted of collection and research of available information applicable to the project locations including geotechnical investigation data and reports along the various seawall sections and adjacent locations, bulkhead wharf, pier wharf, and seawall structure condition surveys and nearby infrastructure. The information collected served as a basis for the Phase 2 assessment of the geotechnical and structural conditions applicable to each seawall section. Collection and research of available information was used to inform the flooding vulnerability assessment. In particular, the data include coastal flooding and sea level rise inundation mapping completed by FEMA, the San Francisco Public Utilities Commission, and the Port of San Francisco. Pertinent jurisdictional, policy and sea level rise guidance issued by the State and the City and County of San Francisco was reviewed and summarized.

For Phase 2, the Study Team's scope of work focused on the evaluation of earthquake performance of the seawall, bulkhead wall/wharf, and other infrastructure within the estimated zone of influence of the seawall section. Flooding vulnerability was assessed for intact and damaged seawall conditions associated with seismic events. The assessment considered existing and higher future sea levels.

For the Phase 3 work, the Study Team developed a range of conceptual mitigation alternatives to address the seismic vulnerability of the seawall, bulkhead wall/wharf, and other infrastructure within the estimated zone of influence of the seawall sections as well as the flooding hazards associated with sea level rise. The team evaluated the rough order of magnitude costs for design and implementation. Also evaluated were costs, benefits, risks and values of mitigation alternatives including construction impacts to Port tenants, Embarcadero Promenade, Embarcadero roadway, utilities, and neighbors; construction risks due to unforeseen conditions, difficult or unique methods, and constructability; environmental and regulatory permitting impacts; historic impacts; resilience and adaptability to sea level rise and other climate change hazards.

The Seawall and Seismic Risk

The Northern Waterfront Great Seawall ("Seawall") provides the foundation of the waterfront from Fisherman's Wharf in the north to Mission Creek in the south. Constructed between 1879 and 1916, the Seawall made possible the transformation of three miles of shallow tidelands into a world-class maritime waterfront that was key to the development and prosperity of San Francisco. Constructed hundreds of feet Bayward of the natural shoreline, the Seawall was built by dredging a trench through the mud, approximately100 feet wide and 30 feet deep, filling the trench with rock to create a pyramid shaped dike up to 40 feet tall, capped with a "bulkhead wall". The Seawall and bulkhead wall provide the foundation for pile-supported "bulkhead wharves" and buildings built on top of the created deck areas, notably the historic bulkhead buildings

The Embarcadero seawall generally consists of a bulkhead wall and bulkhead wharf structure as shown in *Figure 1-1 – Typical Seawall Section.*

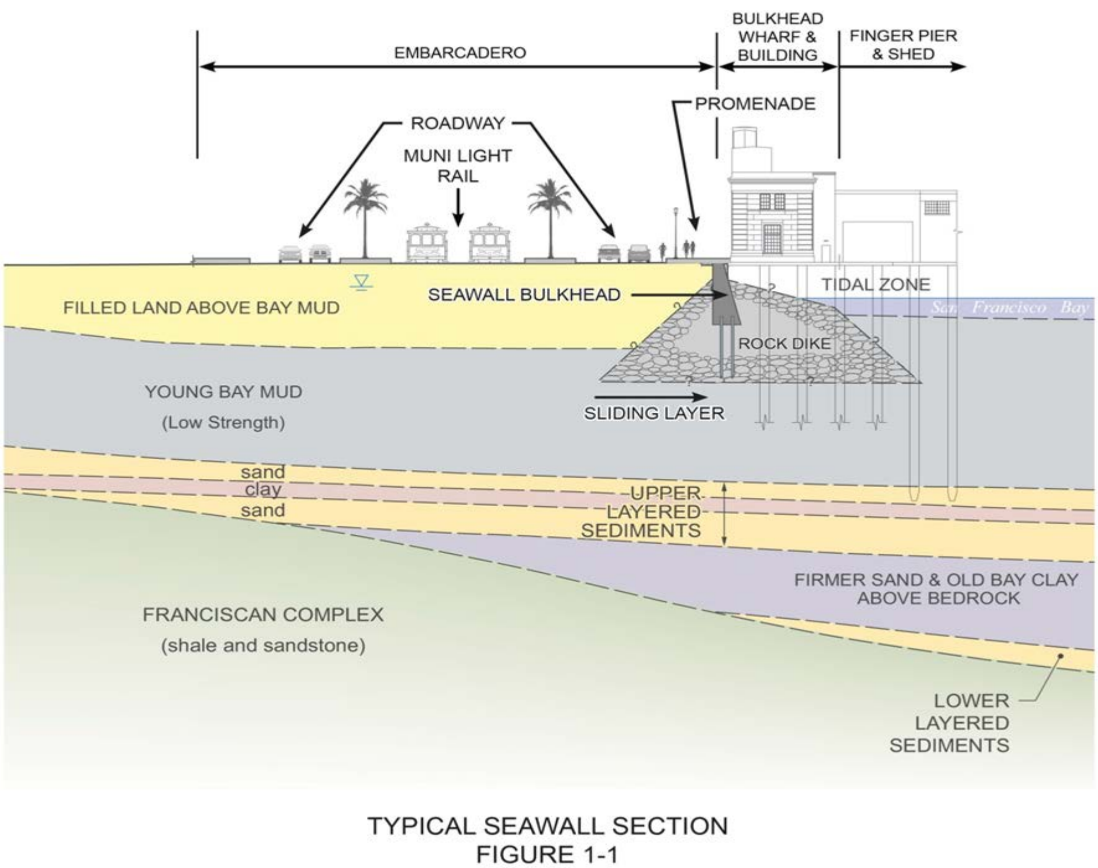
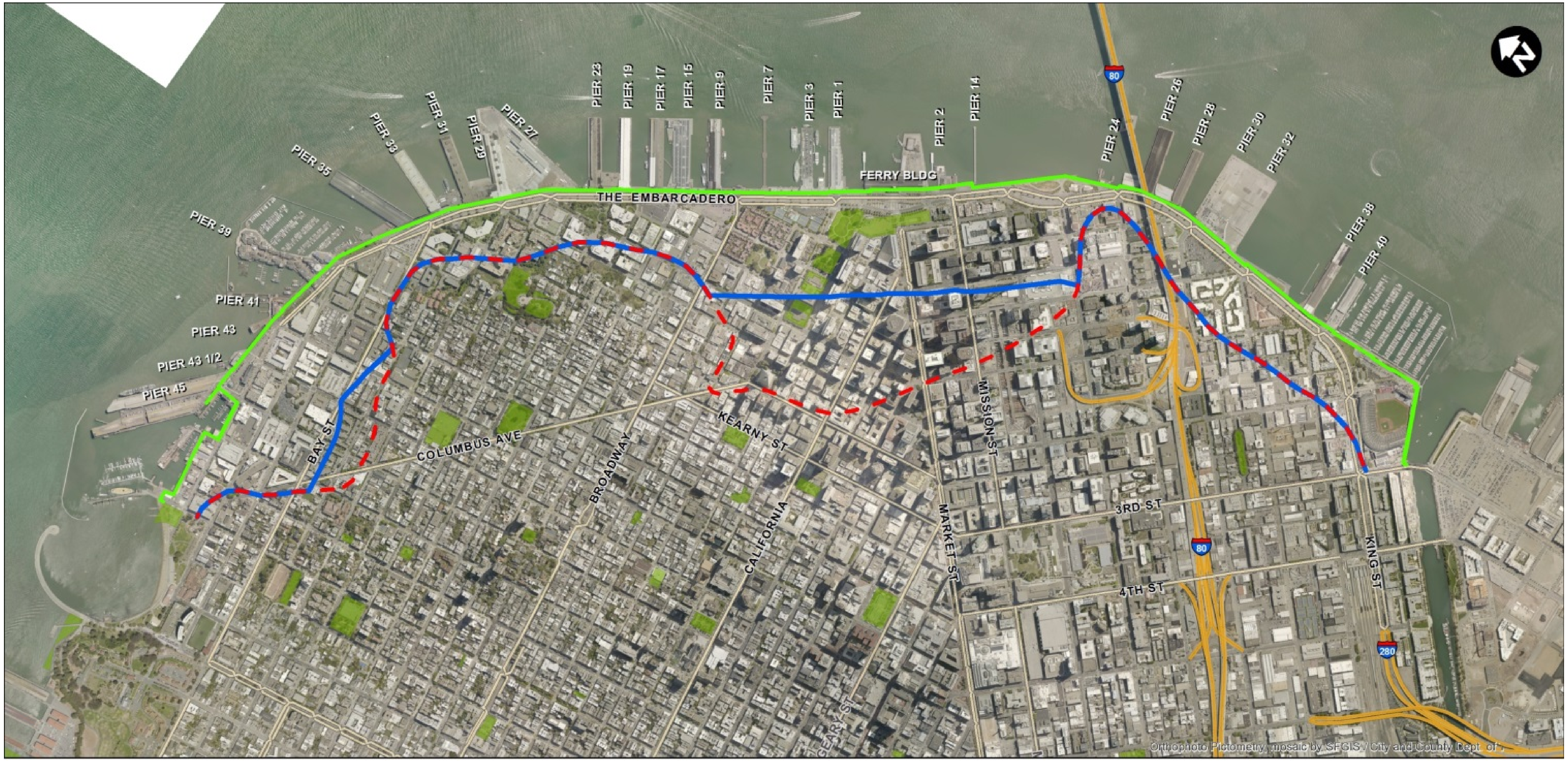


Figure 1-1: Typical Seawall Section

Today the Seawall provides flood and wave protection to Downtown San Francisco, and stabilizes hundreds of acres of filled land. The Seawall itself is a contributing resource in the Embarcadero Historic District listed on the National Register of Historic Places, as are the historic bulkhead wharf structures supported by the Seawall, and adjoining historic finger piers. Within this area are significant Port and City assets including historic architecture of the finger piers and bulkhead buildings, Ferry Building, Agriculture Building, Embarcadero Promenade and roadway, Downtown Ferry Terminal, Pier 27 Cruise Terminal, BART Transbay Tube, MUNI light rail, and key utility infrastructure, including the City's combined sewer system.

A zone of influence was defined by the Study Team for the vulnerability study and represented as the areal extent of land, piers and building structures, and other important infrastructure including the Embarcadero Promenade and Roadway, the Muni light rail line, BART facilities, and major utilities including SFPUC pipelines, PG&E, and telecommunications lines that may be impacted by the movement of the seawall in the event of an earthquake. The zone of influence is shown graphically on *Figure 1-2 – Seawall Zone of Influence Map*. The finger piers and bulkhead structures were also included within the zone of influence.



LEGEND

Seawall Bulkhead

Lateral Spread Hazard Boundary (HLA et al., 1992)

Project Study Area, within 1200 feet of the Seawall Bulkhead and within the Lateral Spread Hazard Zone

0 500 1,000 2,000 Feet

Lateral Spread Boundary Source: Harding Lawson Associates (HLA), Dames & Moore, Kennedy/Jenks/Chilton, EQE Engineering, 1992. Final Report, Liquefaction Study, North Beach, Embarcadero Waterfront, South Beach, and Upper Mission Creeek Area, San Francisco, California.

Figure 1-2: Seawall Zone of Influence Map

The Study has revealed greater than expected risk to the Seawall, which sits atop weak native soils, typically Young Bay Mud, and buttresses fill used to create the land behind the Seawall, which is subject to liquefaction during an earthquake. The Study focused specifically on the performance of the Seawall under different earthquake conditions.

When subject to moderate amounts of earthquake ground shaking, the weak soils below the Seawall begin to fail causing it to settle and move towards the Bay. This movement, called lateral spreading, is correlated to the size of the earthquake, particularly the duration of ground shaking, and can be on the order of several inches or less in a frequent earthquake, such as the 1989 Loma Prieta Earthquake[1], to several feet or more in a major earthquake with a long duration, such as a repeat of the 1906 Earthquake[2]. While not uniform throughout, lateral spreading is predicted to occur along the entire three miles and increases the expected damage to structures and infrastructure adjacent to the Seawall.

Figure 1-3 depicts the earthquake vulnerabilities of a typical section of the Seawall. Maps showing estimated ground displacement due to lateral spreading after a major earthquake are included in Exhibits A-1 and A-2. Bulkhead wharves which support bulkhead buildings, utilities, the Embarcadero Promenade and Roadway, and Muni rail lines are particularly at risk to increased damage due to Seawall movement.

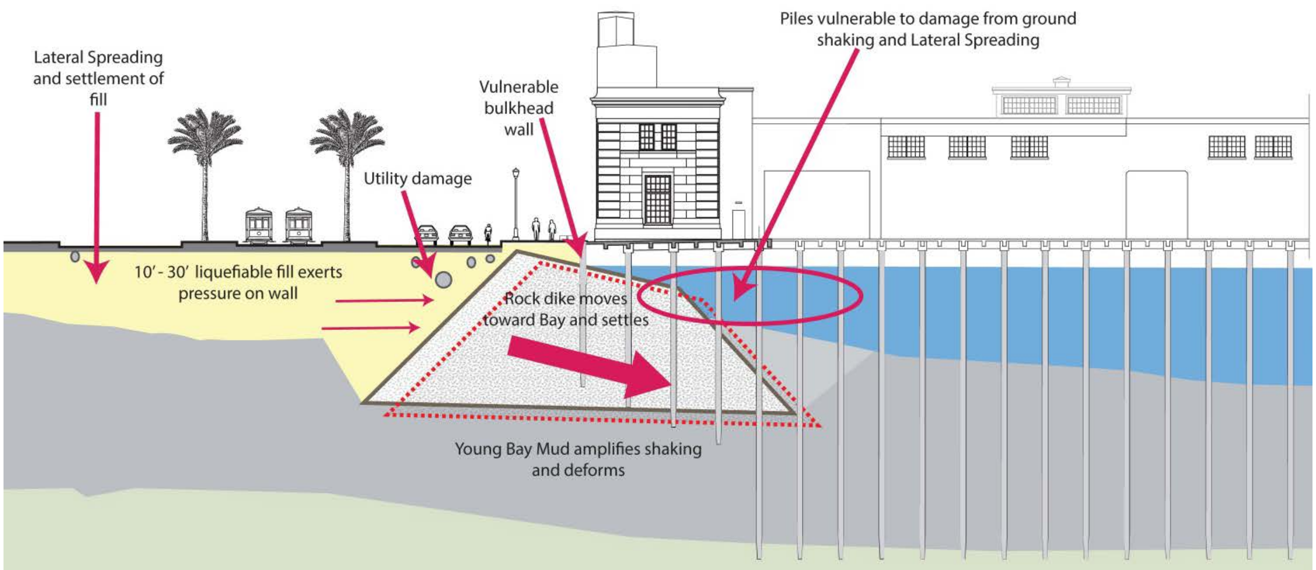


Figure 1-3: Typical Seawall Earthquake Vulnerabilities

The United States Geological Survey (USGS) 2014 Working Group on California Earthquake Probabilities concluded that there is a 72 percent probability of a strong earthquake ($M \geq 6.7$) occurring in the San Francisco Bay Region in a thirty year period between 2014 and 2043 (WGCEP, 2015). Additionally the 2014 WGCEP has

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[1] The epicenter of the 1989 M6.8 Loma Prieta Earthquake was approximately 60 miles away from the Seawall; levels of groundshaking measured nearby are similar to levels expected in a smaller earthquake located nearby, and are considered to have a 50% in 30 year probability of exceedance. Evidence of small movement of the Seawall was noted during this event.

[2] Seismologists estimate the 1906 Earthquake was a M7.8 with fault rupture of 296 miles and an epicenter several miles offshore of San Francisco. The return period for a similar event is estimated at 200 to 250 years, or a 20% in 50 years probability of exceedance.

concluded that within the next 30 years the probability of a strong earthquake (M≥6.7) occurring on regional faults is as follows: 21% for the N. San Andreas Fault Zone, 31% for the Hayward- Rodgers Creek Fault Zone, and 7% for the Calaveras Fault.

There are several principle factors that are predicted to inform the level of damage arising from an earthquake:

- The size on the moment magnitude scale (a measure of the energy released on a logarithmic scale; an earthquake of Mw 7.0 contains 1000 times as much energy as one of 5.0 and about 32 times that of 6.0);
- the distance of its epicenter to the Port;
- the duration of ground shaking;
- the character of soils supporting the Seawall and adjoining Port structures and the character of liquefiable fill material behind the Seawall;
- the age, construction and weathering of piles, beams and slabs supporting Port structures.

Seawall Vulnerability Hazards

The Study Team identified the following hazards during the course of the Northern Seawall vulnerability study:

- *Flooding and Sea Level Rise* – current predictions for sea level rise relative to present day levels range from an average of 12 inches by 2050 and 36 inches by 2100 to as much as 24 inches by 2050 and 66 inches by 2100. With its present configuration, the existing Northern Seawall structure will not preclude flooding of the adjacent uplands. This flooding can be mitigated by rehabilitating the existing seawall and/or adjacent infrastructure to accommodate expected sea level rise.
- *Utility Systems* - below grade utility lines (electrical, water, sewer, storm drain and telecommunications) running along the Embarcadero, with laterals crossing or penetrating the seawall and out to finger piers may be damaged during a seismic event. Many utility lines have rigid joints and connections that do not accommodate out-of-plane movement or expansion/compression. Vertical support may also be lost if the Embarcadero and promenade suffers ground displacement of underlying fill or the bulkhead wharves and finger piers are damaged.
- *Embarcadero Roadway* - liquefaction of cohesionless, non-uniform fill materials may cause vertical displacement and cracking in the roadway. Lateral spreading may also cause cracks. Fill is thickest behind the seawall bulkhead so greater displacement can be expected in this area. Moderate to significant damage to the roadway is expected following large seismic event. Post-earthquake repairs to the pavement will be needed to allow traffic to safely use the roadway.
- *Muni Metro Light Rail* - similar to the Embarcadero, damage can be expected to the rails for the Muni light rail and F-line along the Embarcadero. Settlement and possible distortion of the rails should be expected. Post-earthquake work will be required to filled in depressed areas and straighten, shim and level rails prior to reuse.
- *Essential Facility Access* - access and entry to Pier 1, Pier 9 and entry to the Ferry Building and ferry terminals also could be cutoff by seawall failure and other damage due to permanent ground displacement. This would impact ferry service and potential evacuation needs, as well as the functioning of the emergency water transport.

Earthquake Life Safety Hazards

The following structural vulnerabilities due to seismic hazard were identified during the study:

Soil lateral sliding – movement of underlying weak soil layers due to seismic shaking with accompanying significant permanent lateral displacements, most likely towards the bay. The lateral displacements associated with moderate earthquakes were found to be detrimental to the pile-supported structures along the northern seawall and the magnitude of lateral displacement will increase with shaking intensity. The lateral displacements are expected to also cause settlement along the seawall with the combined displacement resulting in structural damage to the supporting piles and parts or all of the seawall, bulkhead wharfs, finger piers and structures located landside of the seawall.

- *Bulkhead wall to wharf connections* – Bulkhead wharves are typically supported by the bulkhead wall and one or more rows of piles located bayward. The wall/wharf connections typically consist of concrete or concrete encased steel wide flange beams seated on the bulkhead wall with little or no reinforcing crossing the joint. These connections are brittle with very little shear capacity and are expected to fail under moderate ground shaking or seawall movement, leaving the deck vulnerable to partial collapse from unseating of the beams and slab from the supporting wall. This failure will primarily impact the first structural bay.
- *Bulkhead wharf pile head to deck connections* – The pile to deck connections are typically non-ductile concrete with very little capacity to undergo cyclical overloading without substantial damage and/or failure. The brittle connections severely limit displacement capacity as compared to current code required ductile concrete structures. The difference between life safety and collapse displacement capacities for these connections also appears to be relatively small with little capacity difference between the two associated seismic events. However, there is a variation between seawall sections in the ability of bulkhead wharf structures to resist the imposed displacement demands. Some bulkhead wharf sections are expected to survive a life safety seismic event while others are expected to suffer significant damage.
- *Pile damage below ground within the rock seawall* – The rock seawall is expected to remain mostly intact as earthquake induced failure planes develop beneath and cause the rock wall to move bayward and settle. Piles that penetrate the rock are expected to fracture under ground near the failure planes leading to reduced capacity and complete failure where piles are located near the Bayward edge of the rock wall. Differential settlement and partial collapse of bulkhead wharves may result. Retrofitting existing piles to prevent below ground failure is extremely difficult and may not be possible.
- *Seismic vulnerability of finger piers* - seismic damage can be expected to occur at the transition between the finger pier and bulkhead wharf. This damage is caused by a relatively stiff structure (bulkhead wharf) behaving differently than a more flexible structure (finger pier). The two structures can be separated and a seismic joint installed at the interface to mitigate damage. Seismic evaluation of the finger piers (not part of the study) is needed to determine the appropriate seismic joint configuration as well as to assess pier performance.

Vulnerability Study Findings

The primary findings from the study are:

- Most of the Seawall area is built over Young Bay Mud, a weak, saturated, and highly compressible marine clay that tends to amplify earthquake shaking and is susceptible to earthquake induced lateral spreading and settlement.
- Fill that was used to create the land behind the Seawall is susceptible to liquefaction, a phenomenon where the soil loses strength and behaves similarly to a liquid. This has previously been predicted, however, the Study confirms the potential based on current knowledge.
- Large earthquakes will likely cause most of the Seawall to settle and move outward toward the Bay due to a combination of weakness in the underlying Bay Mud and increased pressure from the liquefiable fill. The amount of movement varies across the waterfront, but in general, up to a foot is predicted in moderate to

large earthquakes and more than several feet is predicted in a major earthquake. Complete failure of the Seawall is unlikely.

- Seawall movement will significantly increase earthquake damage and disruption along the waterfront. Historic bulkhead wharf structures built of non-ductile concrete are particularly at risk to increased levels of damage. Piers are at risk to increased damage where they connect to the bulkhead wharves, and to disruption from utility damage and land access. The bulkhead wall may be compromised in some areas leading to erosion from tides and waves. Within The Embarcadero, lateral spreading and settlement associated with Seawall movement will increase damage to utilities, Embarcadero Promenade and roadway, and Muni light rail tracks.
- The bulkhead wharf and bulkhead wall piles are relatively brittle (non-ductile) and will fail in shear, typically at the top connections to supported structure or within the soil lateral sliding layer below the rock dike.
- While the Seawall has survived over 100 years in an active earthquake zone, the infrastructure has not weathered a major earthquake. Most of the bulkhead buildings and piers in the Northern Waterfront were built after the Great 1906 Earthquake; therefore, it was not a test of performance in a major earthquake. The fact that the Ferry Building was in place and survived largely intact is encouraging, but is not representative of the expected behavior of most structures and the Seawall in a repeat of a major seismic event[3]. The 1989 Loma Prieta Earthquake, a damaging earthquake that helped to transform the waterfront, was only a minor test of the Seawall itself. If a similar size earthquake occurs 10 miles away on the San Andreas Fault, rather than 60 miles away, it would likely cause much higher levels of ground shaking, Seawall movement, and damage.
- The Study includes an economic analysis which indicates that $1.6B in Port assets are at risk from earthquake damage within the Seawall zone of influence, and that $2.1B of rents, business income, and wages are generated yearly in these Port assets. Besides direct and indirect impacts to the Port, the Northern Waterfront is a major contributor to the tourism industry, valued at over $11B per year, and of significant overall economic importance to the City and Bay Area. Recent disasters have shown that reducing recovery time is the key to managing the overall impact of a major disaster, both economic and to human suffering. The performance of key Port water transportation and maritime facilities in the Northern Waterfront will be a significant player in any post-disaster recovery effort, so the accessibility and continued function of these facilities is a priority.
- It is feasible to stabilize the Seawall by improving the soils below and the fill behind, however construction is costly and disruptive. Stabilizing the Seawall will greatly improve the earthquake safety and performance of the Northern Waterfront including the existing wharves, piers, utilities, roadway, and light rail. The Study evaluated various concepts and developed rough order of magnitude costs that exceed several billion dollars. It is important to note that at this stage, these are very conceptual improvements and costs are subject to change.
- Earthquake safety and performance of the Seawall should be improved, and sea level rise and climate change must factor into the decisions. Rising seas and climate change will necessitate intervention that may include major changes to the Northern Waterfront and the Seawall over the next 100 years. A damaging earthquake could occur at any time, and there is scientific consensus that one is nearly certain to occur within the next 30 years.

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[3] The Ferry Building area was constructed early and is unique. Being located in deep Bay Mud in Yerba Buena Cove, the design consists of a large pile supported concrete bulkhead wall integral with the arched concrete foundation of the Ferry Building, itself supported by over 6,000 timber piles which stop short of firm ground. A timber relieving platform is located landside to prevent the weight of fill from squeezing mud out under the wall.

Summary of Vulnerabilities and Risks

The study identified several major vulnerabilities and risks for the Northern Seawall waterfront areas. The primary seawall vulnerabilities resulting from seismic hazard are summarized below:

- Movement of the rock dike toward the Bay and vertical settlement
- Damage and failure of the bulkhead wall from ground shaking
- Damage and collapse of the bulkhead wall/wharf structures from both ground shaking and movement of the rock dike

Other damage associated with seismic events along the waterfront can be expected to include:

- Lateral spreading of the land within the seawall's zone of influence
- Vertical settlement of the land within the zone of influence
- Breaks and rupture of utility lines
- Cracking of pavement
- Distortion of rails for Muni Metro system
- Increased damage to finger piers where connected to bulkhead wharves
- Inaccessible finger piers
- Loss of utilities serving finger piers
- Erosion of land resulting from bulkhead wall damage
- Increased flooding hazard from subsidence

Disruption associated with seismic events may include:

- Loss of finger piers until restoration of utilities and access
- Pedestrian use of Embarcadero Promenade
- Embarcadero Roadway
- Muni Metro light rail F, N & T Lines
- Ferry Service
- Bar Pilots

Economic Impact Study Findings

The Study Team reviewed the impacts of large earthquakes on Port property and the San Francisco waterfront. The economic risk was established for each seawall section associated with the following parameters:

- Revenue to the Port of San Francisco including leases, business activity and revenue, damage to commercial property, private housing and employment. The Port's properties generate approximately $2 billion in annual spending, property leases provide approximately $50 million in rent and provide $500 million in employee wages. Property lease revenue, business revenue and employee income costs are considered variable cost items that increase with time.
- Property damage and losses were estimated using bulkhead wharf structural damage plots for two earthquake scenarios, M8.0 San Andreas – median estimate (approximately 225 year return period) and a larger earthquake with a 975 year return period.
- Disruption to tourism spending in San Francisco. The City of San Francisco receives annually approximately 18 million visitors, $11 billion spending and has a $3 billion payroll.
- Replacement cost of existing Port infrastructure. Replacement costs are considered capital cost items.

- Transportation: Golden Gate Bridge District and WETA Ferry, Muni, Cars, Bikes, Pedestrian.
- Maritime including the cruise ship industry and the Bar Pilots.
- Emergency response services including fire department and ferry system.
- Loss of major utility services to the waterfront and City

Total economic value was estimated for each seawall section assuming different time intervals for post-earthquake recovery to assess the maximum possible economic risk. The study indicates that the economic value of Port structures in the Northern Waterfront is $1.6B and that $2.13B per year is generated in rent, revenue and employment within those structures. A repeat of the 1906 Earthquake is predicted to cause as much $1B in damage and $1.3B per year in disruption costs. Besides those costs, the Study indicates that damage will impact disaster recovery of the City and Region by impacting ferry service, maritime berthing, utility service, transportation, and the tourism industry which is valued at over $11B per year.

Mitigation Alternatives Developed

The Study Team developed a range of conceptual engineering options to mitigate the earthquake vulnerabilities associated with the Seawall. Options were developed to limit lateral spreading and settlement of the waterfront, reduce the potential for liquefaction along The Embarcadero, and to improve performance and safety of the bulkhead wall and wharf structures. Utility improvements were not specifically analyzed, but the study considered performance and options to improve performance. The purpose is to develop measures that are technically feasible from an engineering and construction standpoint and to identify basic advantages/disadvantages including performance, cost, constructability, disruption, environmental issues, preservation, and adaptability to sea level rise and climate change. Options include ground improvement techniques to strengthen the soil below the Seawall *(Exhibit B-1*), strengthen the soil landward of the Seawall including the liquefiable fill (*Exhibits B-2 & B-4*), options to buttress the Seawall by constructing new soil-structures on the Bayward side *(Exhibit B-3*), and structural retrofits/replacement of bulkhead wall and wharves (*Exhibits B-5 & B-7*). The various options are not applicable to all sections, but taken together, form an overall array that can be further considered during development of a resilience strategy and detailed project design. The objective of the mitigation strategy is to mitigate seismic risk, protect key infrastructure and improve life safety along the Northern Embarcadero Waterfront.

The most promising mitigation options include:

Jet Grouting to Strengthen the Weak Soils Under the Seawall (Exhibit B-1): Strengthening the Young Bay Mud under the rock dike stabilizes the Seawall, greatly reducing lateral spreading and settlement of the waterfront and subsequently improving the performance and safety of the bulkhead, wharves and piers. It improves the performance of The Embarcadero, but localized damage to the roadway or Promenade from liquefaction is still expected. It also provides a strong foundation for the Seawall that can be built upon for adaptation to sea level rise.

The difficulties associated with strengthening the soil under the rock dike include: (a) Young Bay Mud is one of the more difficult soils to strengthen, (b) the project would need to penetrate through the rock dike, (c) there are historic wharves and buildings above it in many locations, and (d) to be most effective, the project would need to strengthen at least 2/3 of the width including some areas that are within the Bay. Of all the techniques available today, Jet Grouting appears best suited to overcome most of these challenges.

Jet Grouting is a soil strengthening technique that uses small diameter drilling equipment to create large diameter soil-cement columns in place, including in Young Bay Mud. The specialized drill bit includes jet nozzles connected to a high capacity pump that cut the soil and mix it with cement using a high pressure spinning action. The benefits of Jet Grouting are that the equipment can penetrate the rock dike to reach the soil below, that it can be used at an inclined angle, and that a range of equipment sizes are available. Jet Grouting is expensive and the expense grows significantly when production rates are slowed by all of the challenges at the Port. It also creates spoils through the drill hole which need to be collected and removed, an environmental concern in the water. It does appear feasible that with a combination of inclined drilling, small equipment, and spoils collection, that Jet Grouting can be accomplished where there are bulkhead buildings and wharves. Costs for Jet Grouting are estimated to range from $20,000 to $120,000 per linear foot.

Bulkhead Wall and Wharf Retrofits and Replacement: Performance of bulkhead walls and wharves can be improved using various structural retrofits. Options for the bulkhead walls include tiebacks *(Exhibit B-5*), reinforced concrete overlays, and buttressing with revetment (*Exhibit B-6*). Retrofits for bulkhead wharves include jacketing piles, strengthening deck/pile connections with dowels, strengthening beams with reinforced concrete overlays, and adding stronger and ductile piles where accessible *(Exhibit B-7)*. These types of retrofits are recommended because bulkhead wall and wharves are still vulnerable to damage from earthquake ground shaking even if the Seawall is stabilized. Without stabilizing the Seawall, these retrofits can improve life safety, but will do little to mitigate damage of the piles underground due to lateral spreading of the weak soil. Structural retrofits and ground improvement do not need to occur at the same time, allowing a phased approach, but ground improvement costs increase somewhat if retrofits occur first. Costs for structural retrofits are estimated to range from $5,000 to $30,000 per linear foot (based on standard 60 ft. width of the bulkhead wharf).

Besides retrofits, replacing bulkhead wharves is an option, especially where wharves are in an advanced stage of deterioration. New bulkhead wharves can be designed to meet current code without stabilizing the Seawall by using high strength and ductile piling, such as steel pipe piling, in combination with higher strength concrete decks that can better withstand earthquake ground shaking. This approach was used at the Brannan Street Wharf and is being contemplated for the new Downtown Ferry Terminal where the structure is being designed to meet essential facility performance criteria. The increased structure demands from lateral spreading and settlement of the Seawall generally increase structure costs by 20% to 50% based on site conditions and performance criteria. It must also be noted that lateral spreading and settlement may impact the utilities and access to these structures.

Stabilizing the Seawall with Jet Grouting is possible after constructing new bulkhead wharves, but it does complicate construction and add to expense. Costs for new bulkhead wharves range from $30,000 to $60,000 per linear foot (based on standard 60ft widths).

<u>Improvement of Liquefiable Fill Landside of the Seawall (Exhibit B-2)</u>: Improving the liquefiable fill within The Embarcadero will reduce the earthquake pressure on the Seawall and lessen the amount of Seawall movement somewhat. The primary benefit, however, is to minimize damage to utilities, roadway, and light rail tracks, especially when combined with Jet Grouting to stabilize the Seawall. Improvement techniques include stone columns, densification, chemical grouting, and soil mixing. All of these techniques are disruptive and would require closure of The Embarcadero roadway and Promenade for affected construction areas. Costs range from $10,000 to $40,000 per linear foot (based on 160ft width of Embarcadero).

It is noted here, that if The Embarcadero were to be raised as part of a sea level rise strategy, that strengthening of the underlying Bay Mud would be needed to prevent settlement. In this area, Deep Soil Mixing (DSM) appears the most cost effective method. DSM creates in situ soil cement columns, similar to Jet Grouting, but using large track mounted mixing paddles. It is less expensive than Jet Grouting, but highly disruptive and costs increase greatly if production rates are low, such as may be the case if portions of The Embarcadero were kept open for traffic, pedestrians, bike, and the light rail during the construction period. Where obstructions exist, such as a high density of utilities or buried structures, Jet Grouting is a better alternative. DSM can also improve the fill and should be done at the same time rather than phased.

Potential Mitigation Program and Overall Cost

Estimated costs to significantly improve the resiliency of the entire three miles of the Seawall and waterfront are on the order of $2 to $3 billion. The following are what the Study Team considers as the most promising mitigation options to fully improve earthquake resilience of the northern waterfront:

- ground improvement of the Seawall foundation using jet grouting techniques
- a combination of structural retrofits and replacement of bulkhead wall and wharf structures
- mitigation of liquefaction in The Embarcadero using stone columns
- select utility replacement and relocation

With consideration of sea level rise, it is estimated that costs could reach $5 billion to fully incorporate adaptation measures needed for the next 100 years. While this Study considers these other waterfront resilience needs, there is an urgency to advance Seawall seismic strengthening efforts given that a major earthquake could occur at any time and is very likely to occur within the next 30 years.

An early implementation strategy that may be considered first includes ground improvements and bulkhead wall/wharf retrofits at key areas of the Seawall necessary for disaster recovery efforts, bulkhead wall/wharf replacement where key assets must perform and ground improvement is not practical, structural retrofits to improve life safety, and flood protection improvements to low lying areas just south of the Ferry Building.

Summary and Next Steps

The primary objective of the program is to safeguard the public, focusing on the bulkhead walls, wharves, supported buildings and promenade sections. At a minimum, performance of these structures requires improvement such that although there may be significant damage, occupants are able to safely leave the buildings. The structures should not collapse during or following a large earthquake. The Study results point to the need to make substantial investments to improve earthquake safety and performance of the Seawall. Because earthquakes are unpredictable and scientific consensus indicates that a major earthquake is very likely to occur sometime within the next 30 years, major improvements will be required as soon as practical.

The primary goal of the preliminary level of seismic analysis conducted in the Study was to contribute to the subsequent structural performance assessments and overall seismic vulnerability assessment leading to the identification of key Port structures that would benefit from further, and more refined, site-specific evaluations. For these critical assets, it is anticipated that additional site investigations and engineering analyses would be conducted in support of potential mitigation and retrofit strategies, and more detailed cost-benefit analyses of individual facilities. The Study results will be used to advance the Port and City's resiliency goals for the waterfront, and to work with Port tenants, City and public agencies to plan Seawall seismic improvements.

Exhibits

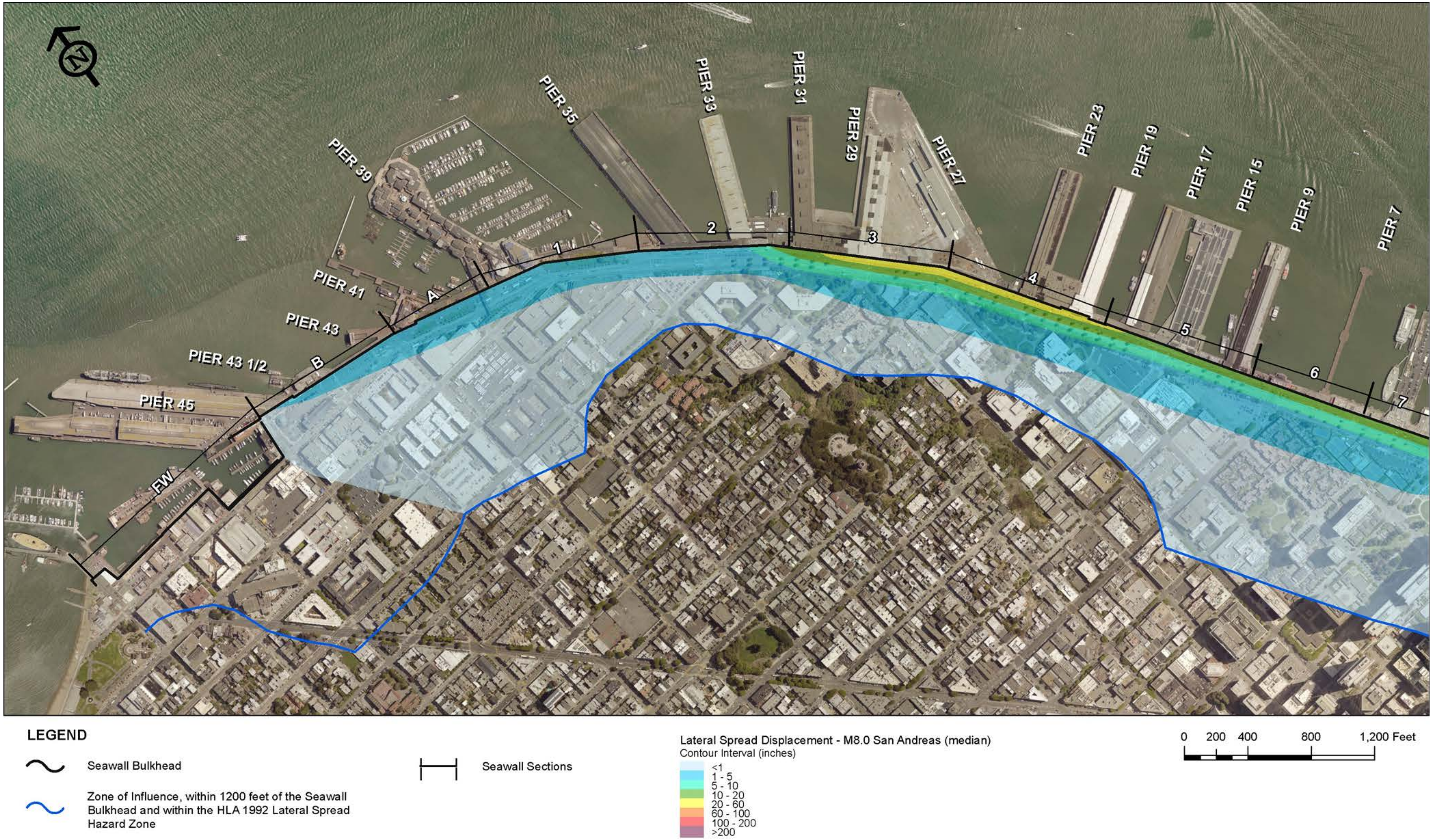

Exhibit A-1: Lateral Spread Displacement Map (1 of 2)

LEGEND

Seawall Bulkhead

Zone of Influence, within 1200 feet of the Seawall Bulkhead and within the HLA 1992 Lateral Spread Hazard Zone

Seawall Sections

Lateral Spread Displacement - M8.0 San Andreas (median)
Contour Interval (inches)

- <1
- 1 - 5
- 5 - 10
- 10 - 20
- 20 - 60
- 60 - 100
- 100 - 200
- >200

0 200 400 800 1,200 Feet

Exhibit A-2: Lateral Spread Displacement Map (2 of 2)

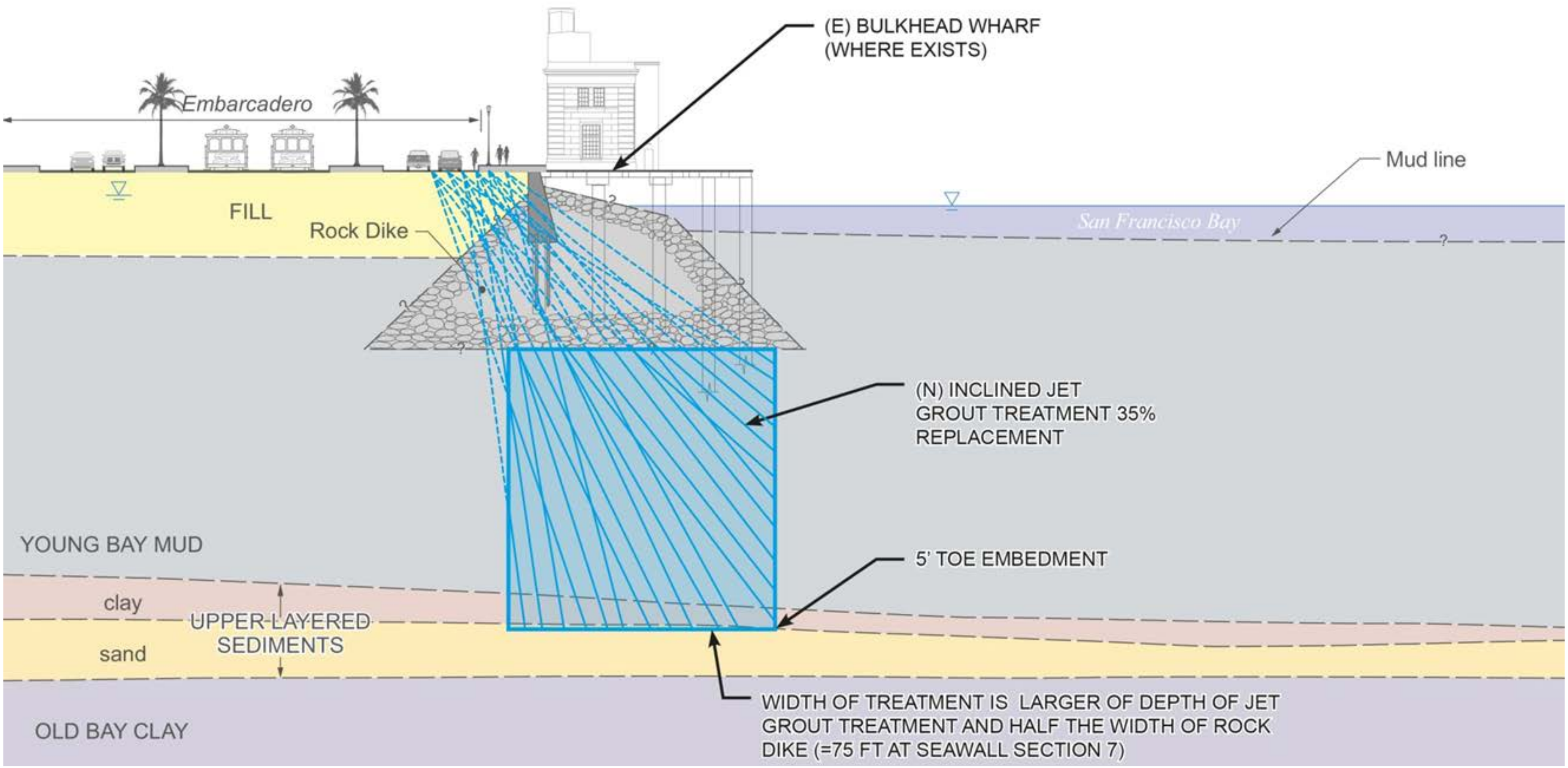

Exhibit B-1: Soil Strengthening Alternative-Jet Grout Under Rock Dike – Inclined

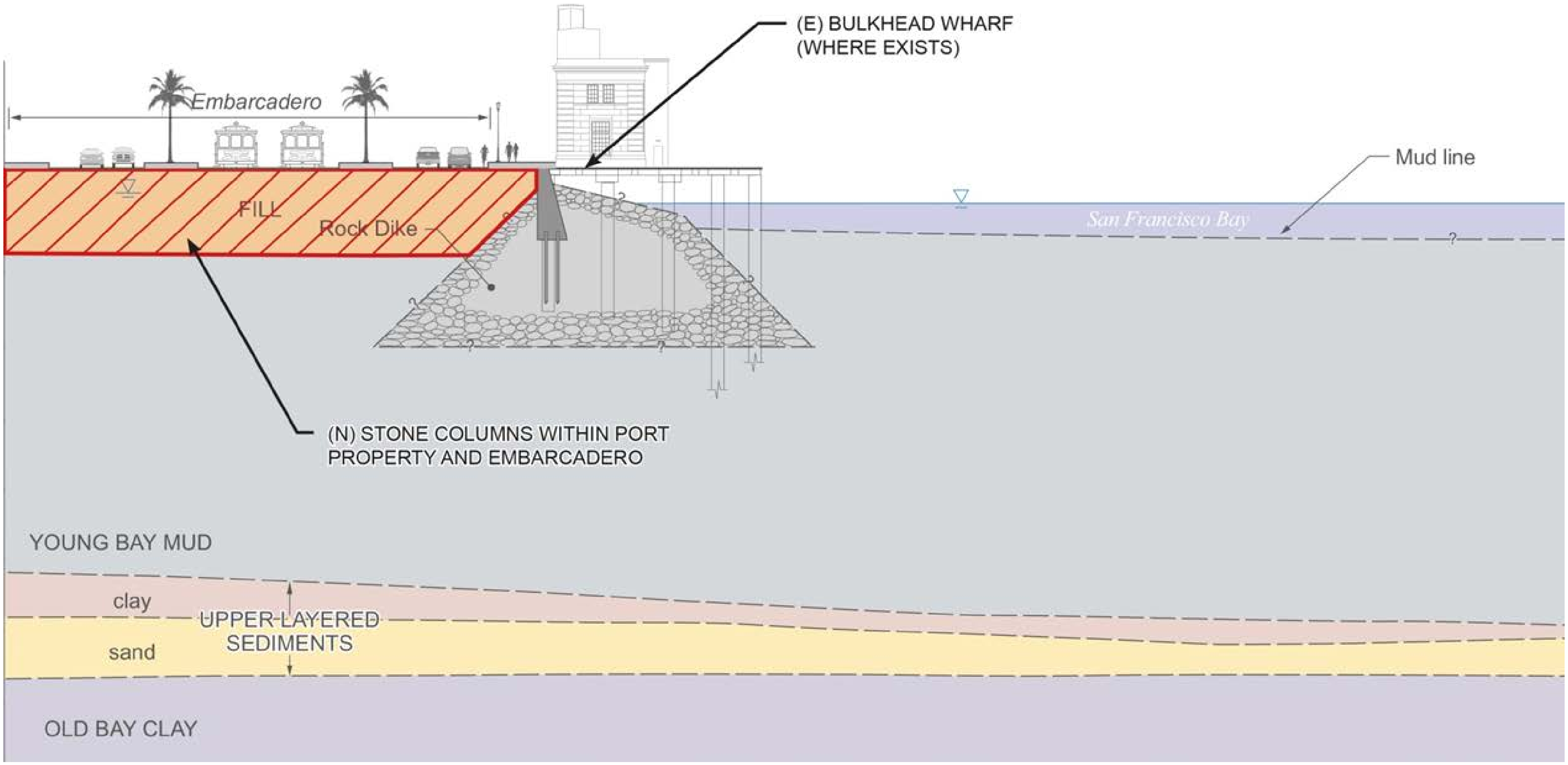

Exhibit B-2: Soil Strengthening Alternative-Liquefaction Remediation

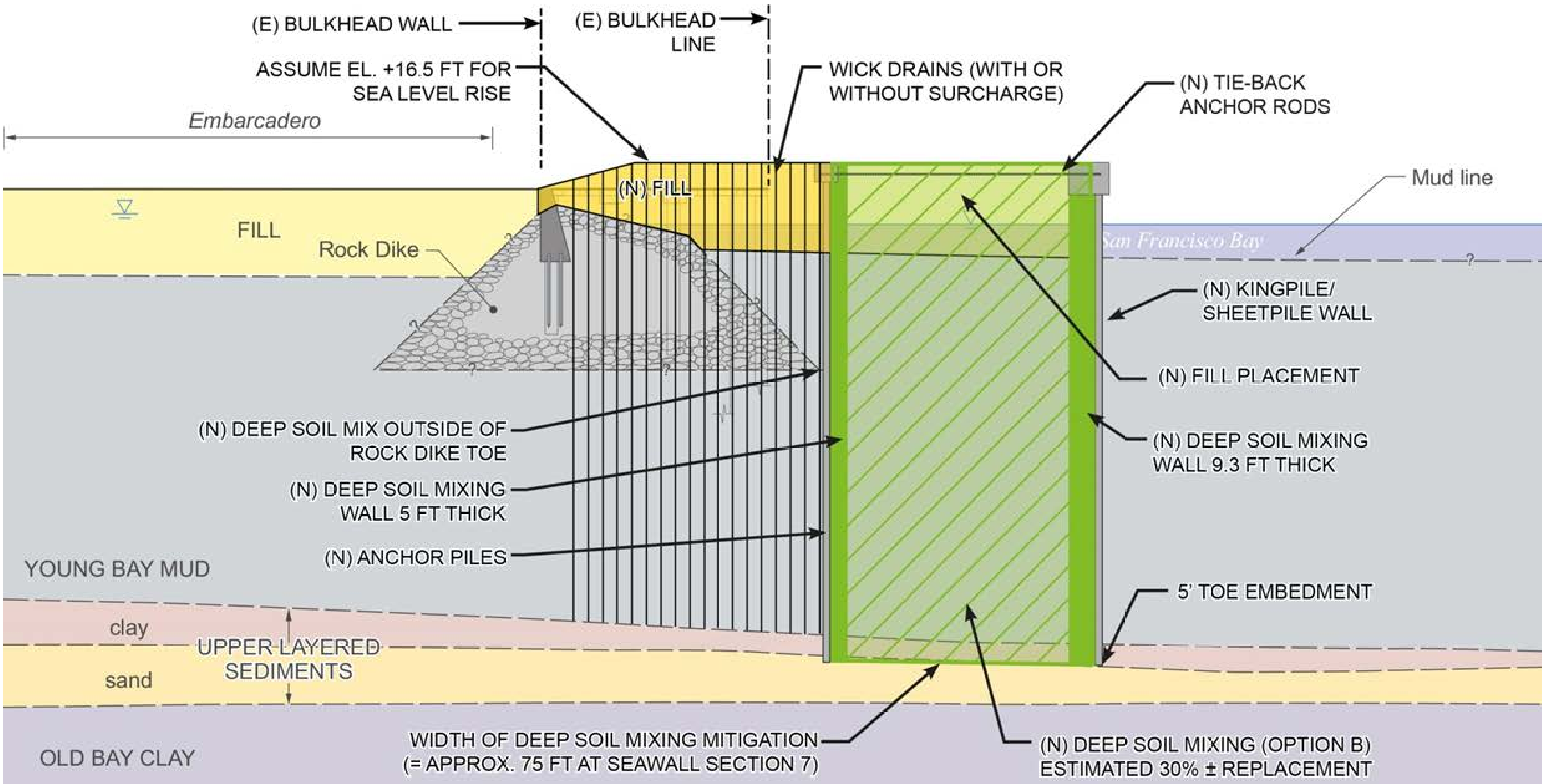

Exhibit B-3: Soil Strengthening Alternative-Anchored Sheetpile & Deep Soil Mixing

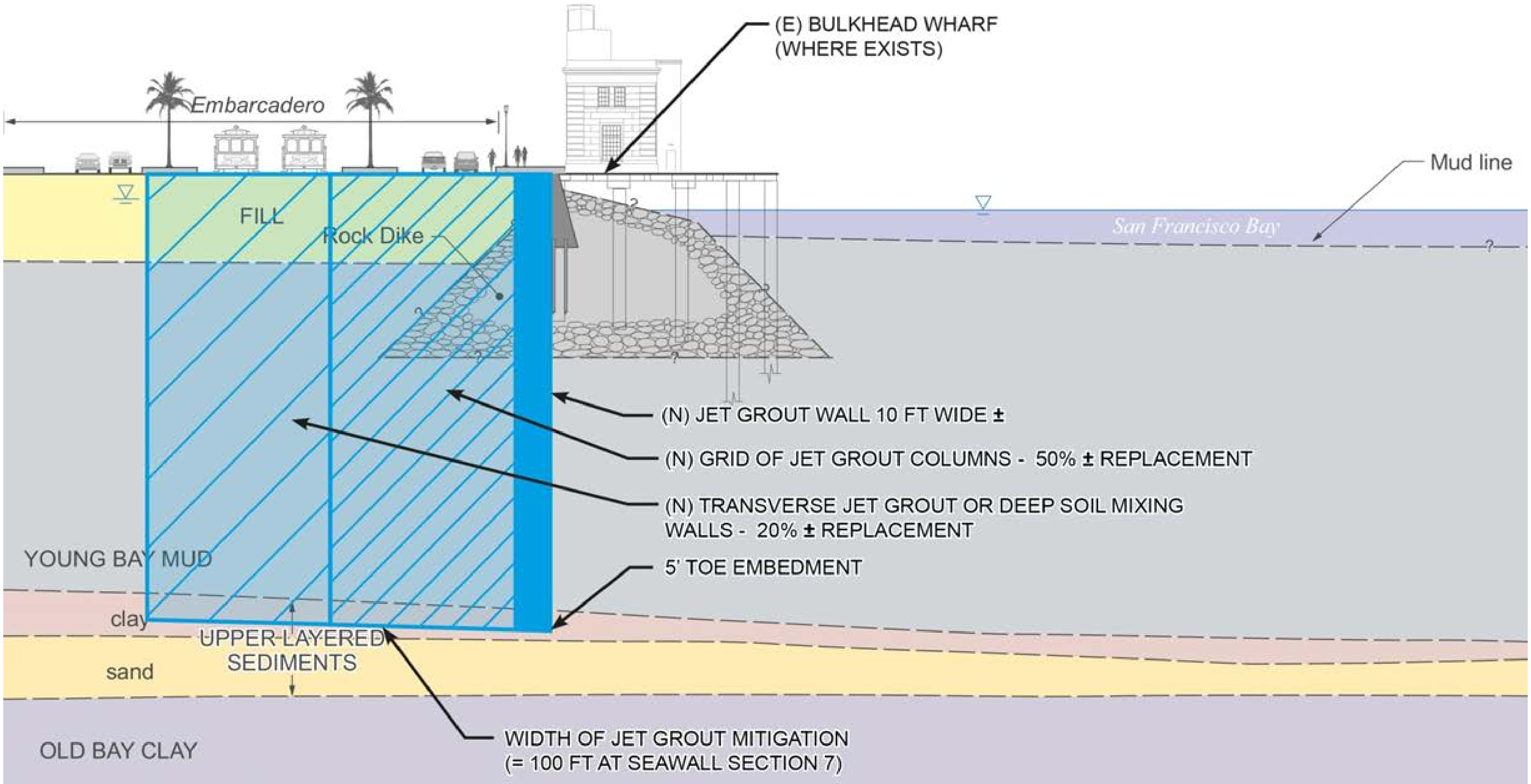

Exhibit B-4: Soil Strengthening Alternative-Jet Grouting & Deep Soil Mixing Landside

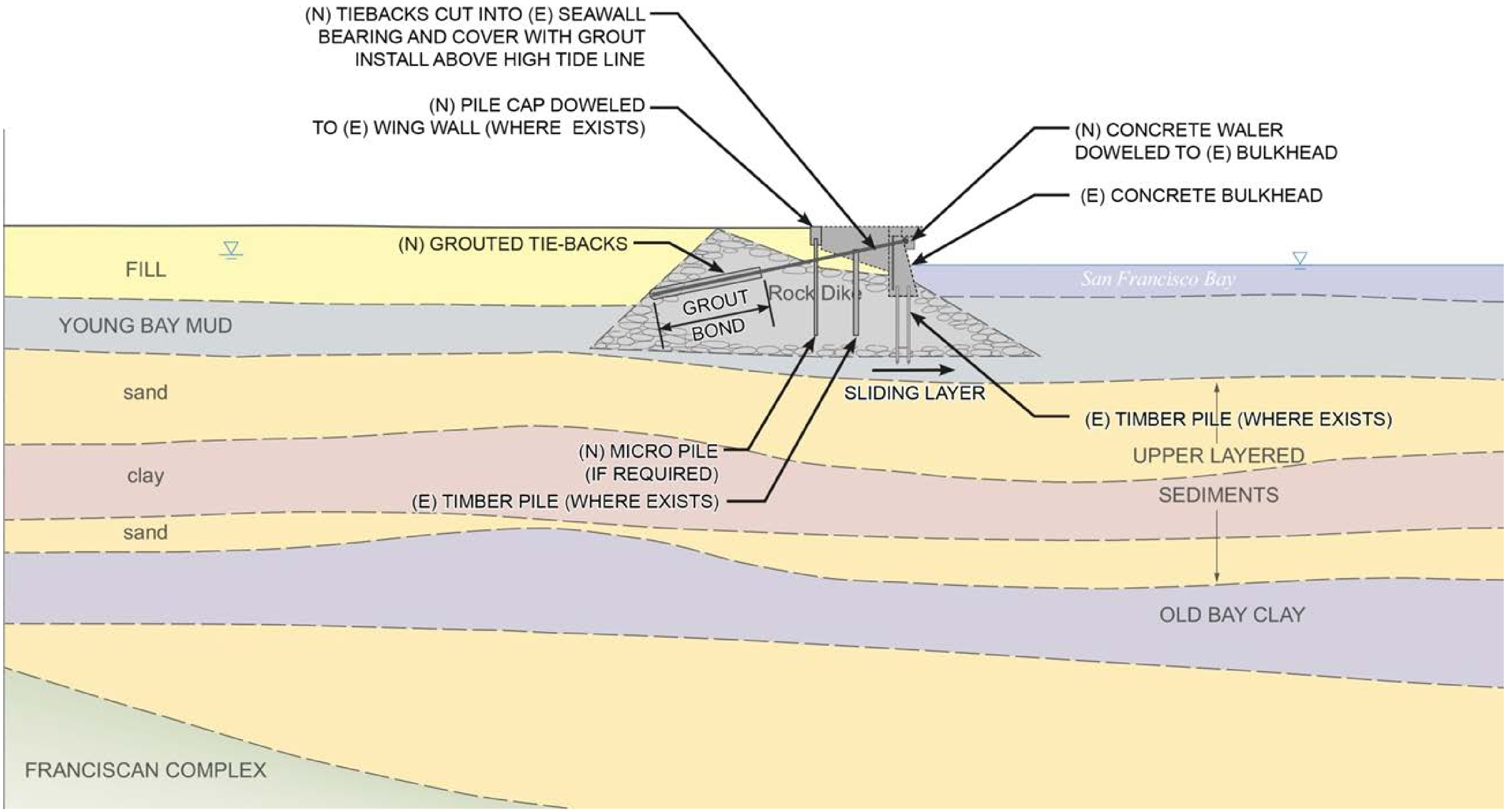

Exhibit B-5: Bulkhead Wall Retrofit - Tiebacks and Micropiles

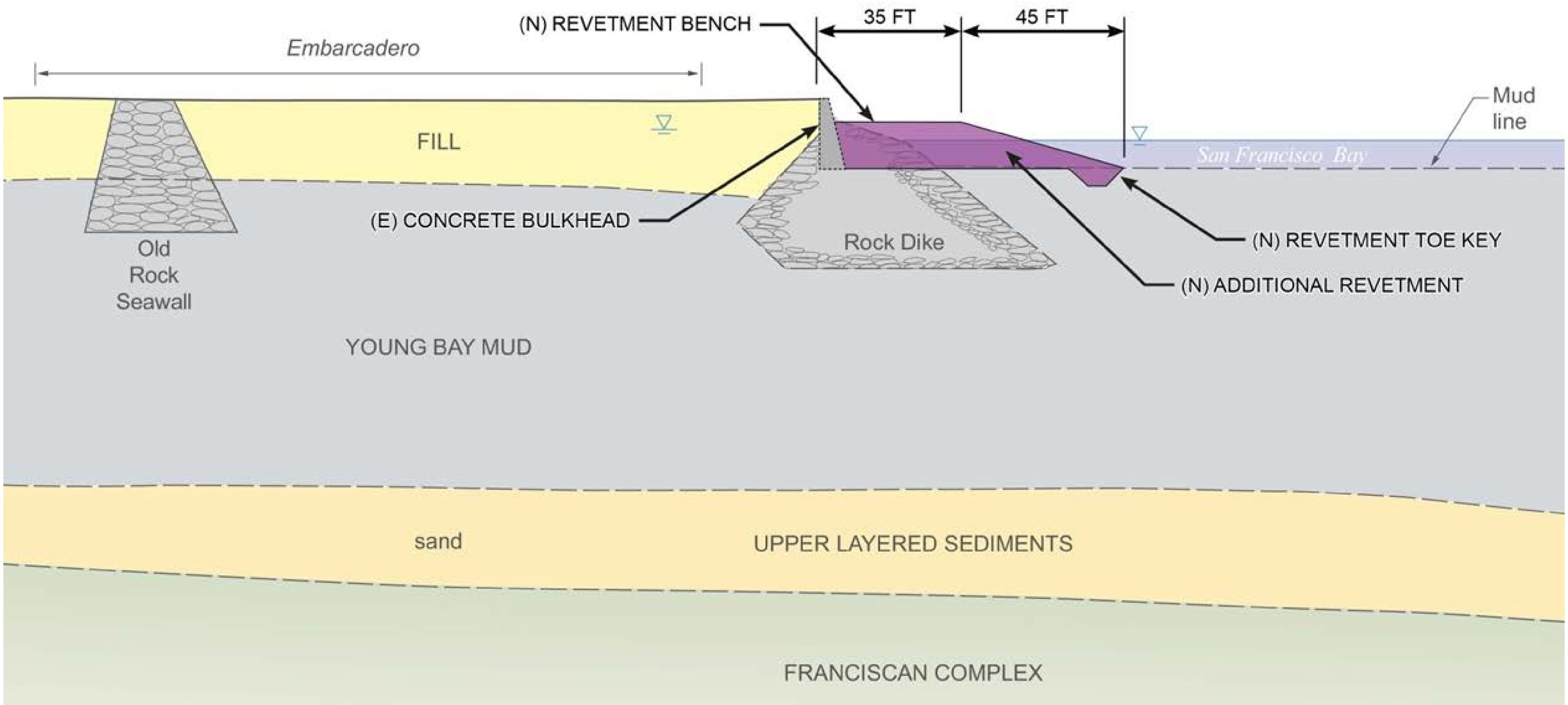

Exhibit B-6: Bulkhead Wall Retrofit - Revetment Bayside

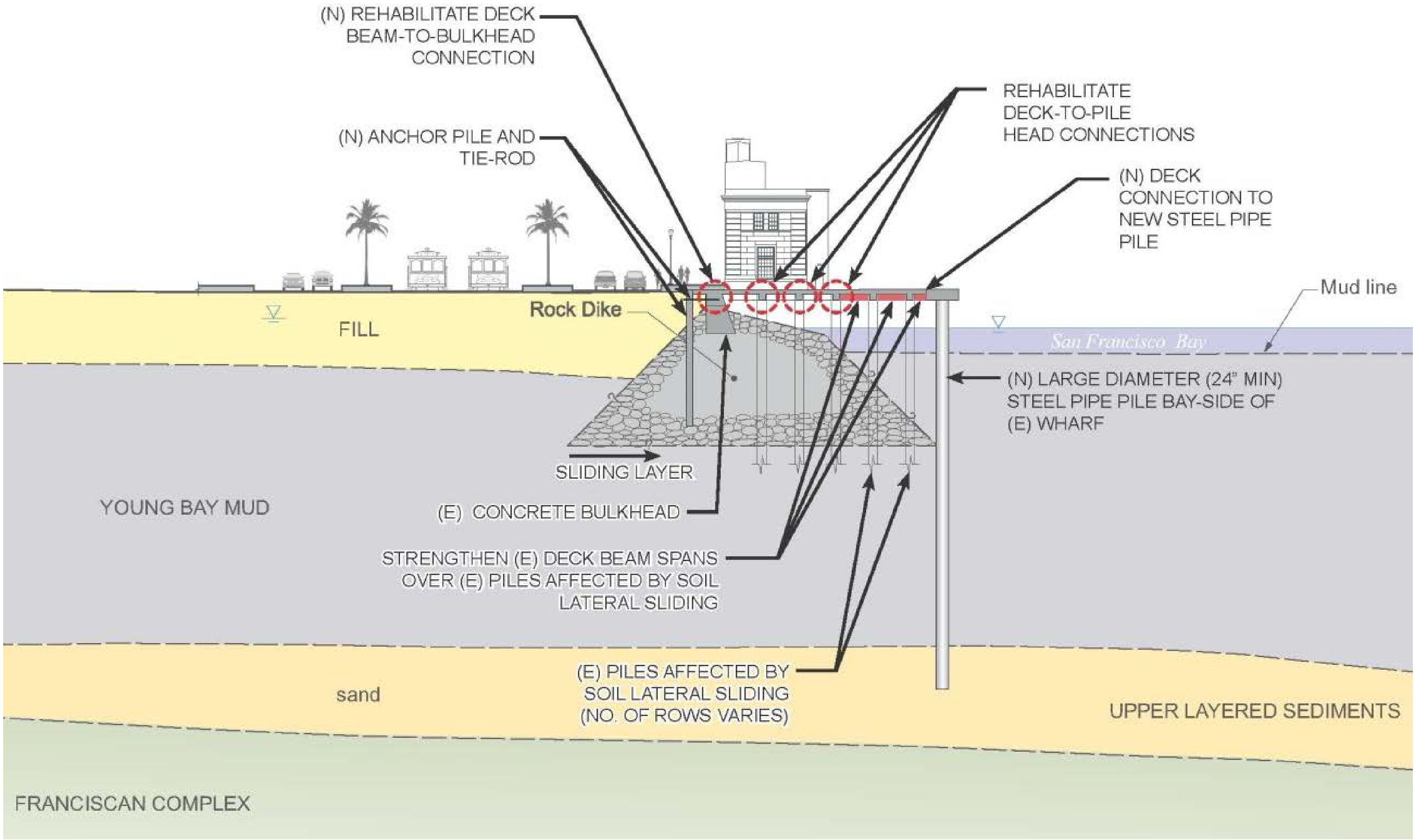

Exhibit B-7: Bulkhead Wall Retrofit - Summary of Retrofits

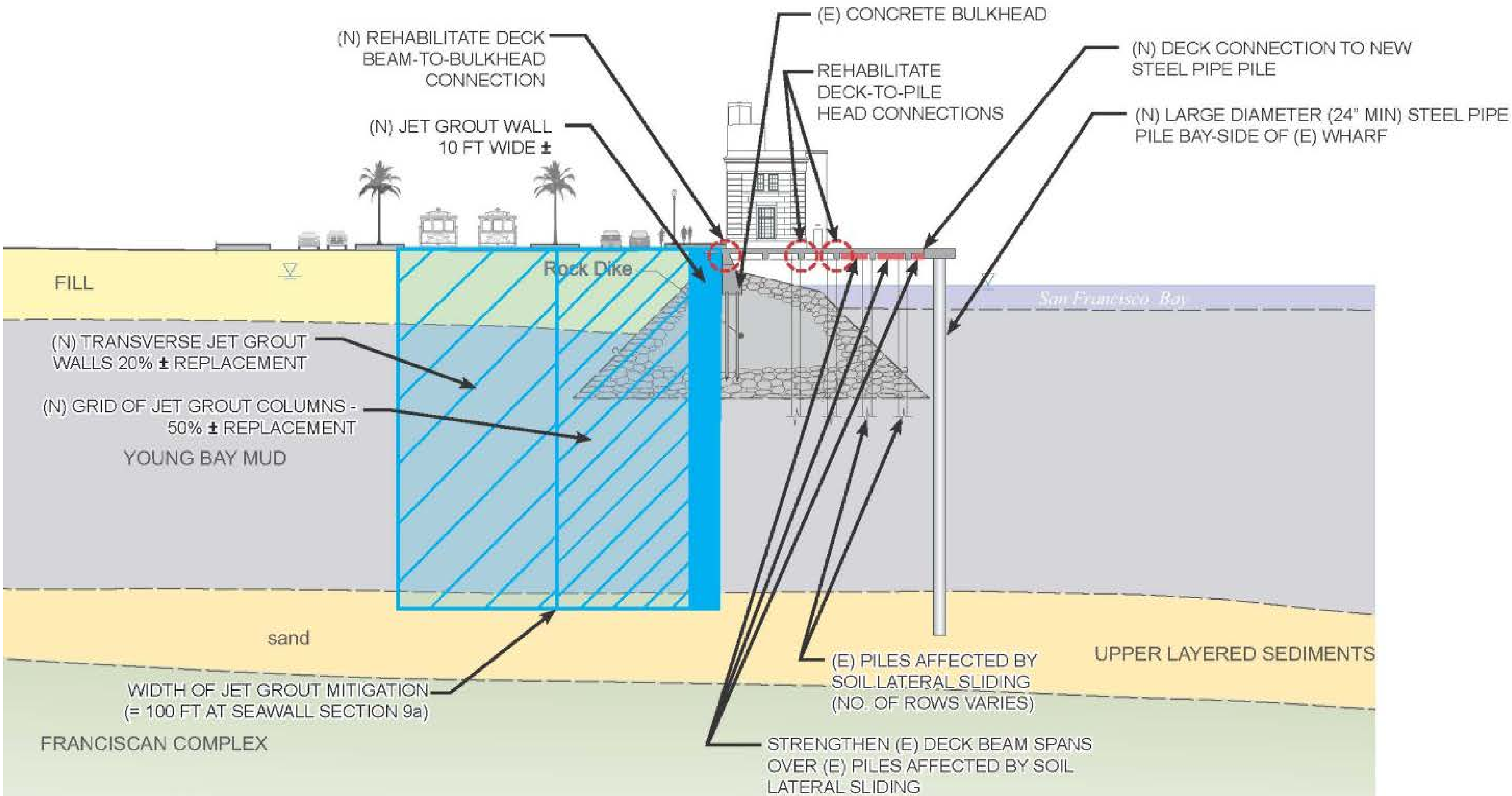

Exhibit B-8: Combined Mitigation Alternative - Jet Grouting & Deep Soil Mixing and Bulkhead Wall & Wharf

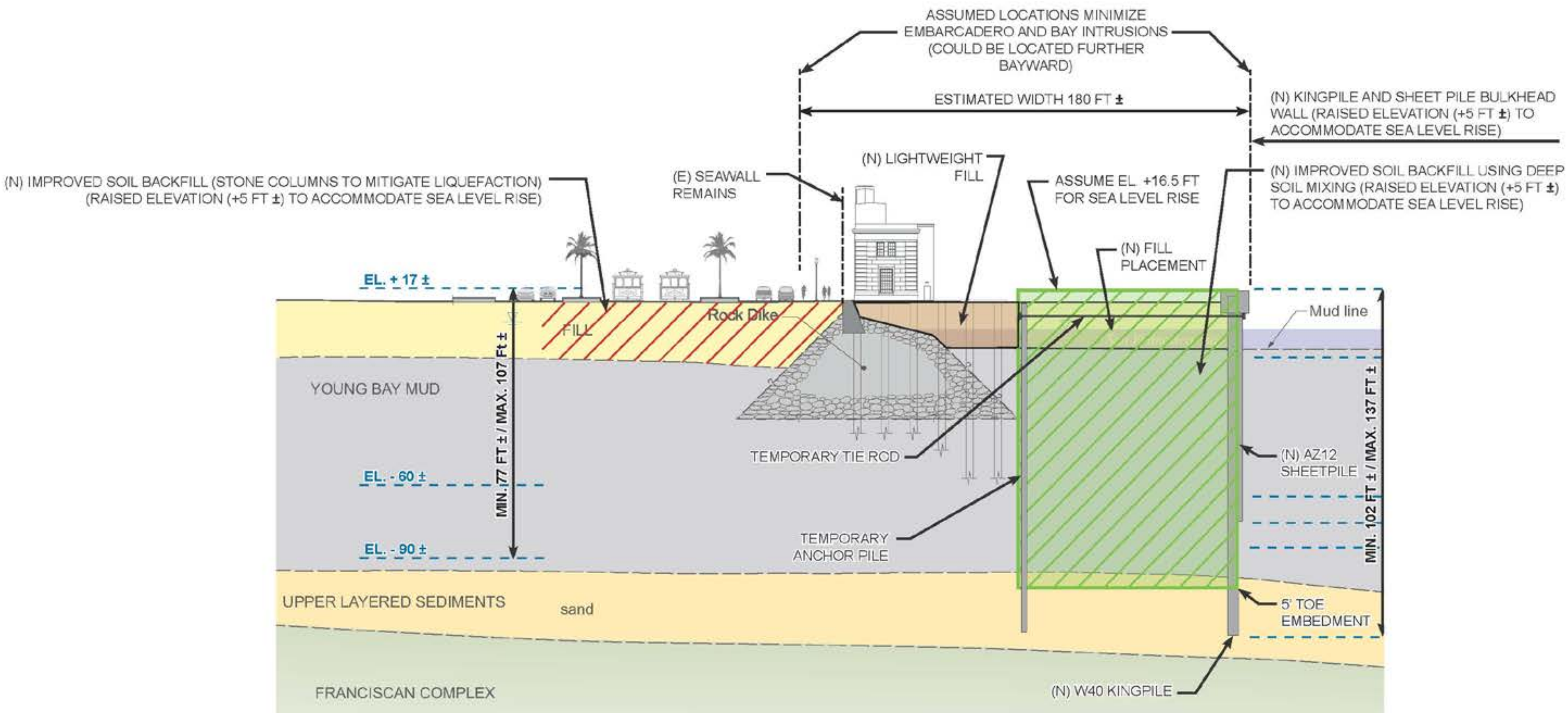

Exhibit B-9: Long-Term Strategy Option - Bayward Seawall & Raising Embarcadero

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