Analysis of Options for Maintaining SR 105 near Washaway Beach

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Executive Summary and Recommendations

This report analyzes the coastal processes that are threatening SR 105 between Mileposts (MP) 18.7 and 20.8 at Washaway Beach (Figure ES-1), and evaluates options for dealing with future threats to the highway. Options are evaluated at a conceptual level to compare relative performance from a hydrodynamic and geomorphic perspective. This information is then used to identify which options should be further evaluated for engineering feasibility, cost effectiveness, socioeconomic impacts, and environmental impacts. Key findings and recommendations are summarized below.

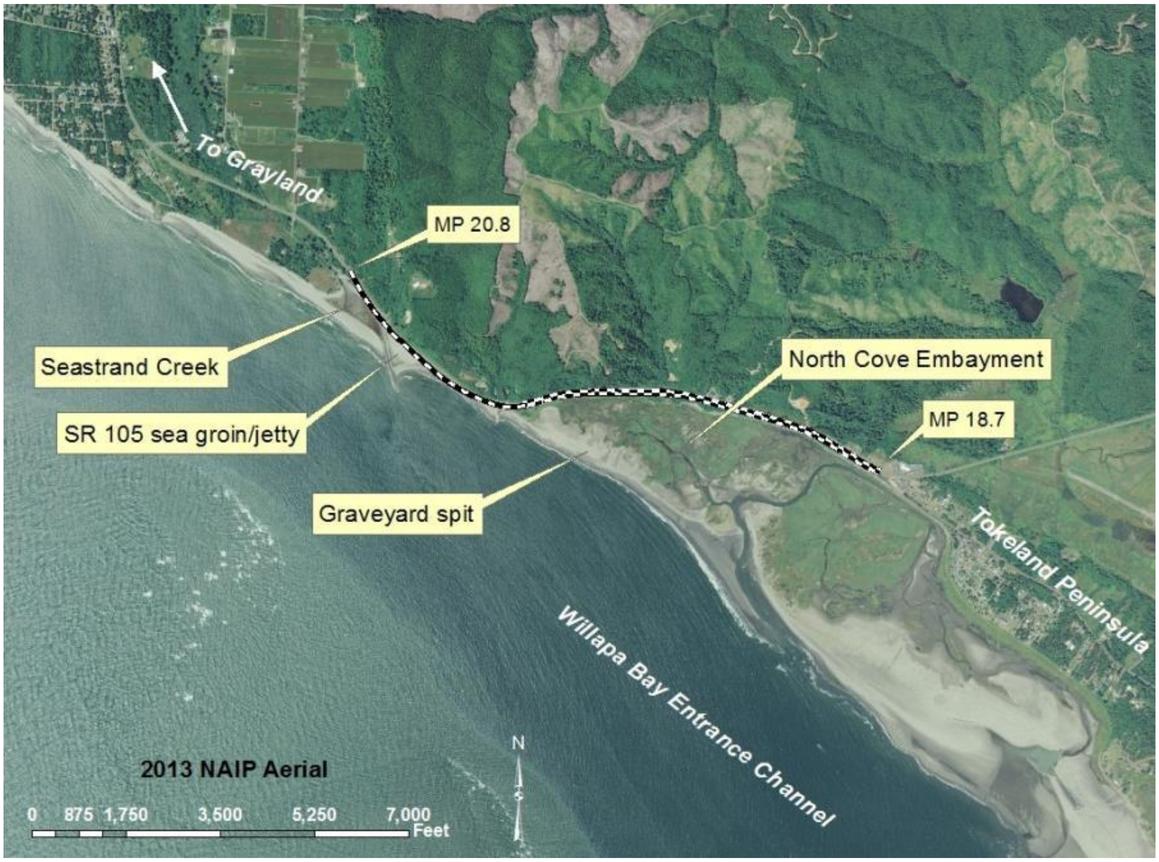

Figure ES-1. Segment of SR 105 evaluated in this report.

Repair History

This segment of SR 105 has a long history of repairs for erosion and flooding problems. These include several major capital projects as well as numerous emergency maintenance actions. Projects we could identify from available records are shown in Figure ES-2, and include:

- <u>Relocation of the highway in the 1970s.</u> The highway was moved off Cape Shoalwater (which no longer exists) to its current alignment along the base of a coastal bluff.

- Emergency armoring of the highway embankment in 1996. About 1200 feet of eroded embankment between MP 20.2 and 20.4 was armored as an emergency repair with large rock wrapped in submarine netting.
- Construction of the SR 105 Sea Groin/Jetty in 1998. A large rock groin was constructed into the Willapa Bay entrance channel at MP 20.5 to deflect currents and waves away from the SR 105 embankment. This project included sand placement to replenish the beach in the lee of the groin. WSDOT also contributed to a major wetland restoration project at Potters Slough in Willapa Bay to mitigate for project impacts.
- Shoreline armoring at the mouth of Seastrand Creek in 2006. As the beach receded north of the jetty, erosion progressed up the mouth of Seastrand Creek and eroded into the highway embankment near MP 20.7. Rock armor with clusters of toe logs was placed to stabilize the highway embankment.
- Emergency shoreline armoring south of the sea groin/jetty, 2006-2012. Shoreline erosion progressed south of the 1996 repair between 2006 and 2011, requiring at least three emergency repairs between MP 20.1 and 20.2.
- Emergency shoreline armoring south of the sea groin/jetty in 2014. Rock armor was placed to stabilize eroding embankments between MP 20.0 and 20.1 where SR 105 turns into the North Cove embayment towards the Shoalwater Indian Reservation.
- Emergency repairs to the 1996 armor in 2014 and 2015. Rock was placed along 365 feet of shoreline to shore up failing submarine net armor originally installed in 1996. Impacts to shoreline and wetland habitats were mitigated using credits from WSDOT's Tarlatt Slough wetland restoration project in Willapa Bay.
- Removal of logs from the highway in the winter of 2015. Logs washed up onto the highway along the shore of the North Cove embayment during winter storm surge tides.

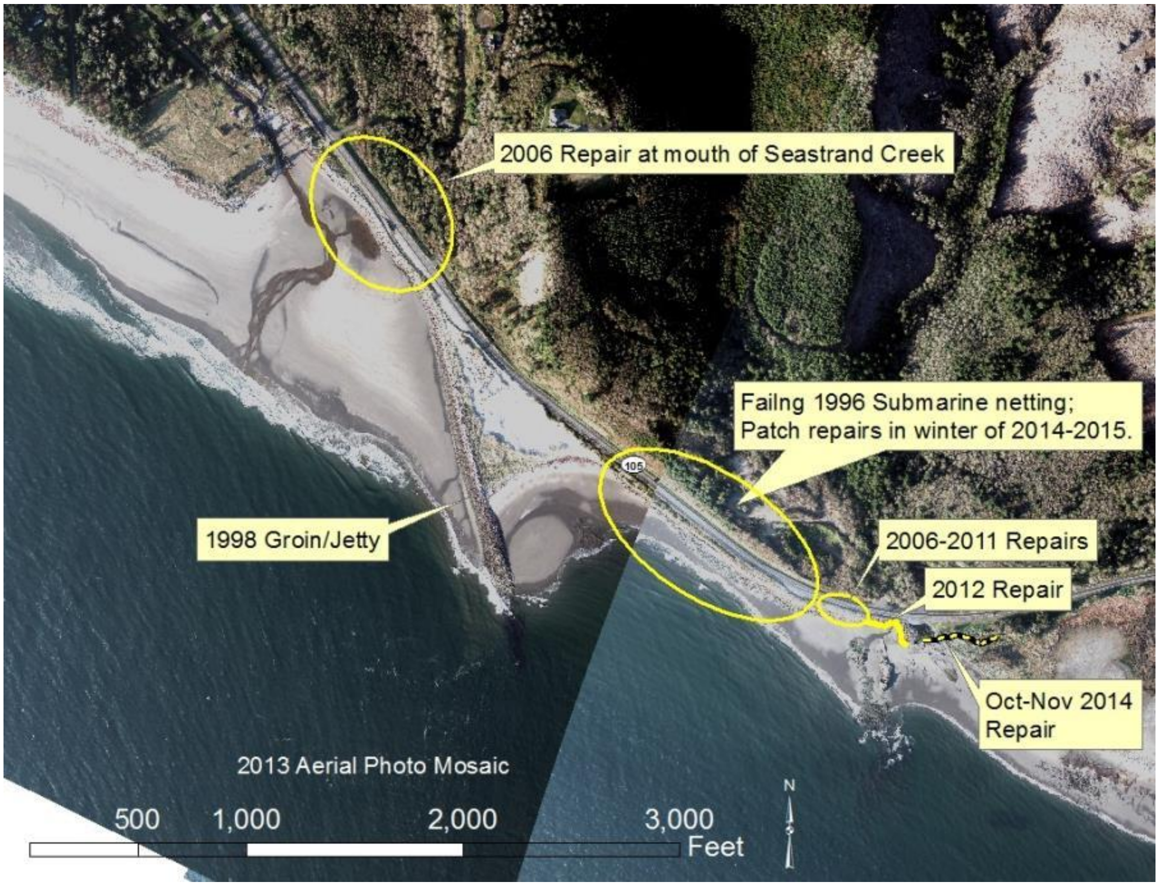

Figure ES-2. Historical repairs in the project area.

Underlying Causes of the Erosion Problems

Shoreline erosion at Washaway Beach is caused by a complex combination of coastal process, including:

- Northward migration of the Willapa Bay Entrance Channel. The entrance channel has been steadily moving northward since the late 1800s. By the late 1960s this erosion had eliminated Cape Shoalwater, leaving SR 105 pinched between the beach line and a coastal bluff.
- Increasingly severe wave climate. La Nina and weak El Nino cycles have become more frequent in recent decades, increasing the severity of storms that approach the project area from the southwest.
- Loss of sand supply for Graveyard and Empire Spits. Changes in currents in the entrance channel have eliminated most of the sand supply that historically replenished Graveyard and Empire Spits. Loss of these spits has increased wave action along SR 105 and the Tokeland Peninsula.
- Loss of windblown sand from beaches to the north. Large stretches of beach north of the project area have retreated, reducing wind-blown sand transport that feeds

dunes in the project area. Loss of these dunes has increased wave action, especially in the North Cove embayment behind Graveyard Spit.

Future Erosion and Flooding Threats to the Highway

Shoreline erosion and flooding are likely to become more severe in the future due to the following trends:

- Continued migration of the Willapa Bay Entrance Channel. The Corps of Engineers (2009a) concluded that the northward migration of the channel thalweg has slowed as it encounters harder marine terrace deposits. There is considerable uncertainty about this conclusion because the location and erosion resistance of these deposits are poorly understood. Even if the thalweg of the channel has ceased moving, wave and current erosion are still causing the channel to enlarge to the north to erode the beaches that buffer SR 105 from wave action.

- Loss of dunes and increased wave action in the North Cove embayment. Dunes on Graveyard and Empire Spit will continue to diminish in response to wave action and reduced sand supply. This has already resulted in severe intrusion of waves into marshes in the North Cove embayment, and will increase flooding, debris-wracking, and shoreline erosion on SR 105 between MP 18.7 and 20.0. Most of this segment of highway lies more than three feet below projected coastal flood elevations. The U.S. Army Corps of Engineers recently constructed an artificial dune on Empire Spit to protect the Tokeland Peninsula, but this does not protect most of SR 105 in the North Cove embayment and is already beginning to erode.

- Failure of existing shoreline armor. Emergency repair projects have armored most of the shoreline between MP 20.0 and 20.7. This will need continual maintenance as the wave climate becomes more severe. About 800 feet of armor placed in 1996 is failing and will soon require repair. A repair is currently in design for erosion that is progressing further up Seastrand Creek at MP 20.8.

- Limited effectiveness and degradation of the SR 105 sea groin/jetty. The sea groin/jetty has protected only a limited segment of shoreline at its base. The sea groin/jetty may deflect currents from the shore, but has not addressed the wave erosion that is the primary cause of recent failures at the site. Monitoring data show slumping on both sides of the dike portion of the jetty. Much of the sand that was placed in 1998 to nourish the beach south of the sea groin/jetty is gone and has not been replenished as planned.

- Severe shoreline erosion north of the project area. The shoreline continues to retreat rapidly north of the project area from high waves and tidal surges during winter storms. This erosion is particularly damaging to the community of North Cove, where several homes were most recently lost during storms in December 2014.

- Sea level rise and climate change. Projections for sea level rise on this coast range as high as +19 inches (WDOE website 2014). This includes estimates of the offsetting effect of tectonic uplift in the area. Climate change may also increase the frequency of La Nina and weak El Nino cycles that create the most severe winter storm conditions.

Options for Protecting the Highway

Section 5.0 evaluates the following options for protecting the highway:

- Option 1 – Armor and Elevate SR 105 to Maintain the Current Alignment. This option is a continuation of the current strategy of maintaining the existing highway through emergency and capital projects to armor eroding embankments, and is illustrated in Figure ES-3. This would involve continued maintenance of existing and planned armor between MP 20.0 and 20.8. The segment of highway in the North Cove embayment between MP 18.7 and 20.0 would eventually need to be elevated about 4.5 feet or protected with a shoreline berm to limit flooding as waves intrude further into the shoreline marsh. Fill and rock armor would cause impacts to shoreline, estuarine wetland, and freshwater wetland habitats throughout this stretch of highway. This option carries significant risk that maintenance of the highway could become unsustainable in the face of sea level rise, increased storm severity, and continued shoreline retreat north of the project area.

- Option 2 – Groins. Rock groins have been used in the past and could be considered again, in order to protect the portion of SR105 behind North Cove. The rock groin that was installed previously has only protected the portion of the highway immediately landward of it. Should groins be considered again, a series would be needed to adequately protect the most vulnerable portion of the highway from erosion. The geometry and configuration of the groins would need to be carefully modelled to maximize their effectiveness. However, the groins would not address the potential flooding of the highway at low spots behind North Cove. There would be direct and indirect impacts to wetlands. It is estimated that a minimum of 24 acres of direct impact would occur.

- Option 3 – Beach Nourishment. Beach nourishment could, in theory, be used to protect the SR105 embankment from wave action. Beach nourishment would take the form of building a linear dune feature, outwardly similar to the "dune restoration" project recently built by the Corps for the Empire Spit, immediately to the south. The height and width of the feature would be based on the estimated maximum wave height, with consideration given for ongoing sea level rise. Material for the feature could be acquired locally, as was done for the Corps' project, which pumped a sand and water slurry from deep in Willapa Bay, up onto the land. Impacts would include direct impacts to tidal wetlands where the feature was placed, and indirect impacts to tidal wetlands where eroded sand would settle, and impacts to the location where sand would be dug from the bottom of the bay. Risks would include underestimating the replenishment rate. Half of the sand used in beach nourishment for the 1998 groin project was lost in the first summer following placement. All of that sand is now gone and has not been replenished. The risk with beach nourishment is that the material would wash away quickly and not be replaced, leaving the highway unprotected as now.

- Option 4 – Highway Relocation. We examined one potential highway relocation route that was originally proposed during the planning of the 1998 groin/jetty project. This route follows various forest roads up the Cedar River valley before crossing a ridge to meet SR 105 north of the area currently threatened by coastal erosion. This route avoids risks associated with coastal erosion, but will involve considerable impacts to freshwater wetlands as well as high costs for right of way acquisition and construction. It also changes access to and from the Shoalwater Indian Reservation and the Tokeland Peninsula. Other routes may be possible, and this option will need to be further developed with substantial transportation planning, stakeholder outreach, and environmental impact analysis if WSDOT decides to further pursue relocation.

- Option 5 – Dynamic Revetment. This option uses a relatively new design concept, which mimics naturally occurring cobble and gravel beaches. The design relies on the mass of cobbles and the interstices between them to absorb and dissipate wave energy. It maintains shape due to being extremely well-drained, although maintenance is required over time as the cobbles get displaced. A dynamic revetment would be quick and relatively inexpensive to install, being primarily a surface feature. The location of the dynamic revetment would depend on how much of the highway is to be protected. The dynamic revetment could either be placed up against the highway embankment or it could be placed out along the latest shoreline erosion scarp, preventing additional shoreline retreat. If placed on the existing shoreline, an artificial dune would be built, to serve as the (root) for stabilization. The revetment itself could be up to 65 wide on the top, based on work done in Oregon in a similar environment. This would be the initial shape, with the expectation that the top width would narrow as the cobble/gravel berm is re-shaped by waves. The risks include underestimating the frequency of maintenance necessary. This could lead to funding shortfalls. Impacts include direct impacts to tidal wetlands (being covered by the revetment) and indirect impacts to wetlands by deflecting waves and causing erosion.

Recommendations

This segment of SR 105 faces increasingly severe wave erosion and coastal flooding that will eventually require major capital projects to maintain the viability of this transportation corridor. Table ES-1 summarizes the pros and cons of the options evaluated in this report. We recommend the following options for further analysis of engineering feasibility, cost effectiveness, socioeconomic impacts, and environmental impacts:

- Option 1 – Armor and Elevate SR 105 to Maintain the Current Alignment. This option identifies actions that will be needed to maintain the current highway alignment if no other measures are taken to reduce wave energy in the project area.

- Option 4 – Highway Relocation. This option would require extensive new right-of-way acquisition with associated major costs and new environmental impacts. Nonetheless, it is the only option that completely avoids threats from wave erosion and coastal flooding, and eliminates risk associated with uncertain maintenance activity.

- Option 5 – Dynamic Revetment. This treatment has been used successfully along the Oregon Coast and other areas, and has good potential to protect the North Cove Embayment from erosion. Figure ES-3 shows how a dynamic revetment could be used in combination with elements of Option 1 to maintain the existing highway alignment. It would reduce the amount of new shoreline armor needed in this area, and may minimize the need for raising the highway. A dynamic revetment along the toe of the existing submarine netting near the groin could also reduce maintenance needs for existing armor.

We do not recommend the Option 2 Groins for further analysis because it would not fully address increased inundation of the North Cove Embayment and would involve extensive permitting to address high impacts to near-shore habitats. The existing groin has been only marginally effective, and the US Army Corps of Engineers rejected groins as a feasible alternative for protecting the adjacent Tokeland Peninsula.

Option 3 Beach Nourishment could be a complementary treatment for other options, but we do not recommend it as a stand-alone treatment because of the high frequency of maintenance expected and the potential vulnerability to the highway when sand is critically lost between maintenance cycles.

Table ES-1. Pros and cons of treatment options.

Treatment Option	Advantages	Disadvantages	Relative Habitat Mitigation Costs	Relative Construction Costs
1. Maintain existing alignment; elevate and armor North Cove segment	Keeps highway in current location; minimal disruption to local communities. Impacts confined to areas close to the existing right-of-way.	Requires ongoing maintenance of revetments; will get progressively more difficult and expensive as sea levels rise and storms become more severe.	High Would destroy nearshore habitat, estuarine wetlands, and freshwater wetlands along the highway embankment.	High
2. Groins	Diverts tidal current away from shore.	Does not address inundation of low portions of the highway; Difficult to permit due to potential habitat loss.	Very High Would destroy tens of acres of estuarine wetland; deep scour holes at the ends of the groins would also destroys nearshore habitat and sand flat habitat.	Very High

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Treatment Option	Advantages	Disadvantages	Relative Habitat Mitigation Costs	Relative Construction Costs
3. Beach Nourishment	Easy to construct; sand readily available in Willapa Bay.	Prone to rapid erosion; requires annual maintenance; requires excavation of sand from adjacent Willapa Bay; leaves highway vulnerable if damaged between maintenance cycles.	Low Impacts of footprint on beach and near shore habitat would be offset by protection of many more acres of wetland and dune habitat that is being eroded in the North Cove embayment.	Moderate
4. Highway Relocation	Removes highway completely from erosion hazard zone.	Extensive engineering, right-of-way acquisition, and environmental impacts on a new alignment; disruption to local communities; reduces access to Shoalwater Tribal center and Tokeland Peninsula.	Very High Would impact estuarine, freshwater wetlands, and forested wetlands. May allow recovery of habitat along abandoned alignment.	Very High

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Treatment Option	Advantages	Disadvantages	Relative Habitat Mitigation Costs	Relative Construction Costs
5. Dynamic Revetment	Easy and quick to construct; will protect the highway from further erosion; permitting may be less complicated than other options.	Requires periodic (roughly every 10 years) maintenance to replace lost rocks.	Low to Moderate Impacts of footprint on beach and near shore habitat would be offset by protection of many more acres of wetland and dune habitat that is being eroded in the North Cove embayment.	Moderate

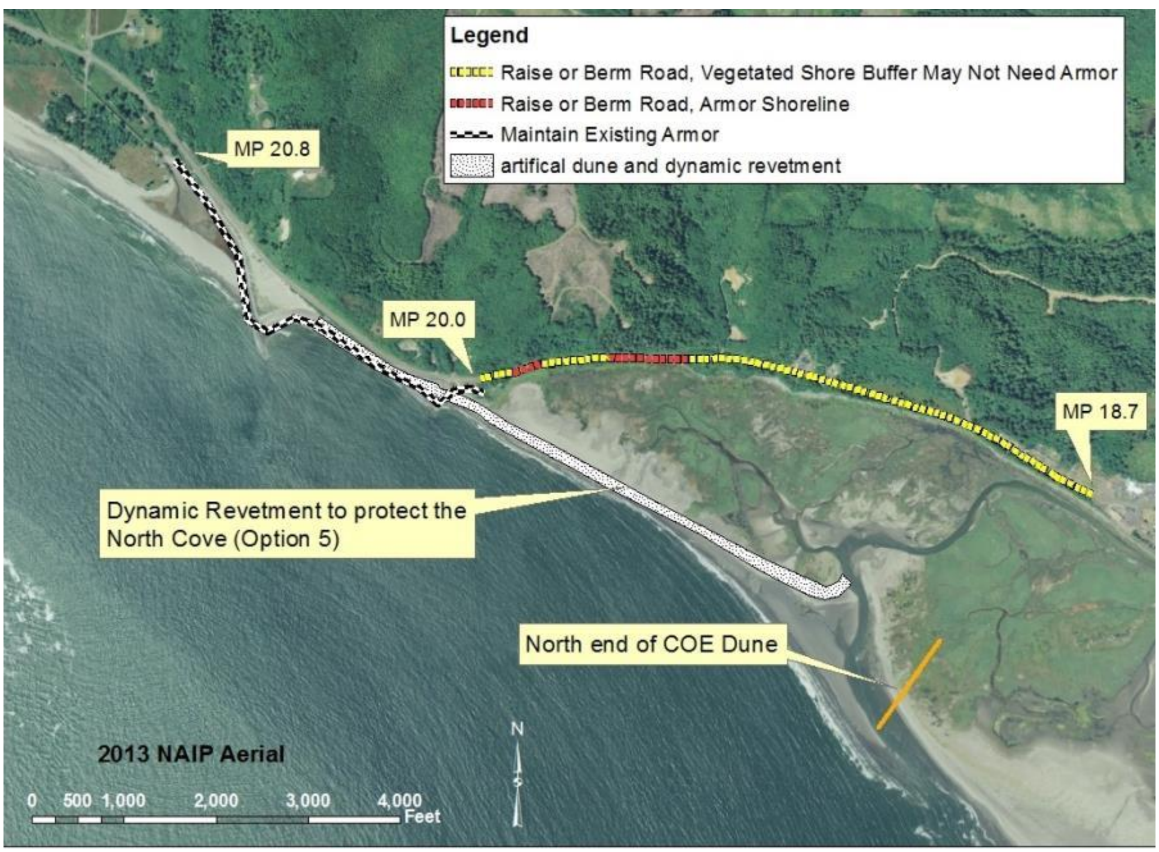


Figure ES-3. Long-term projects needed to maintain existing alignment of SR 105.

The above options will require extensive analysis, stakeholder outreach, and design to obtain funding and implement. Maintenance projects will therefore be needed in the interim to address short-term threats to the highway. Figure ES-4 identifies the most vulnerable locations in the project area. About 800 feet of existing submarine netting has unraveled and is in danger of failing during major storms. This needs to be repaired using methods similar to those applied to failing segments in the fall and winter of 2015. A shoreline armoring project is also in design to address erosion at the mouth of Seastrand Creek. The failing submarine netting should be a higher priority for repair due to the more severe wave climate and higher potential for catastrophic road failure, but both of these eroding shoreline segments will eventually need to be addressed.

Wave intrusion into the North Cove Embayment will continue to worsen, and reached a point in the winter of 2015 where logs were beginning to wash up on the road surface during storm surge tides. The most vulnerable segment is at the west end of the cove where most of the offshore marsh and shoreline vegetation has been destroyed by wave overwash (Figure ES-4). This threat can be addressed in the short term by constructing a rock berm along the highway shoulder that minimizes wave overwash and debris wracking on the road surface.

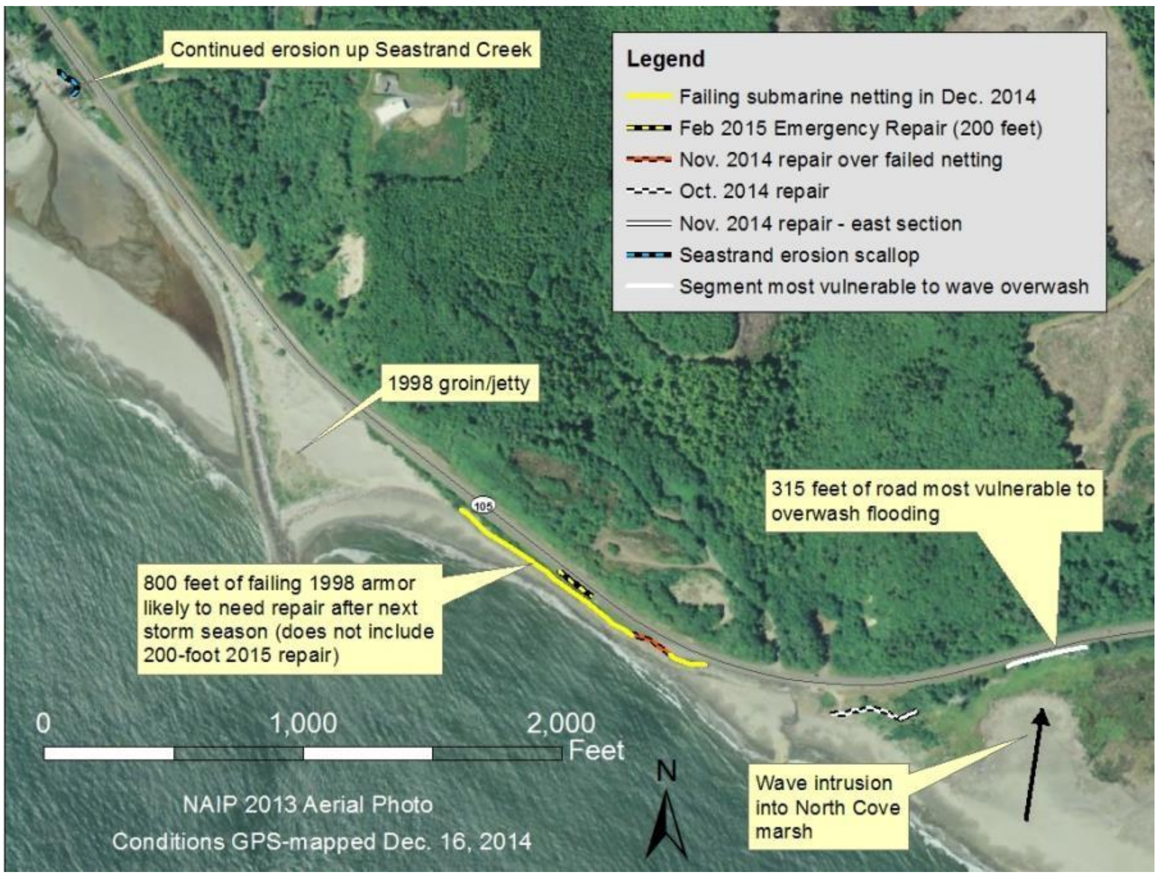


Figure ES-4. Maintenance repairs that may be needed in the near future.

1.0 Introduction

State Route 105 traverses a section of coast between the communities of Tokeland and Westport that has experienced the highest rate of shoreline erosion in the lower 48 states. The highway has been and continues to be threatened by this shoreline retreat. The highway has been moved landward and numerous emergency projects have been constructed to keep the highway intact.

The purpose of this report is to identify feasible long-term strategies for maintaining the segment of SR 105 between Mileposts (MP) 18.7 and 20.8 that faces the most severe threat. It begins with a summary of existing conditions, a history of repair projects, and an evaluation of future threats to the highway. It then analyzes a range of options for protecting the highway from coastal flooding and wave erosion. This includes an analysis of one potential option for relocating the highway away from the coast.

The report evaluates the feasibility and expected performance of options from a hydrodynamic and geomorphic perspective. This information is then used to identify the set of options that have the best potential for maintaining this segment of SR 105 and should be analyzed further for engineering feasibility, costs and benefits, and environmental impacts. Although this document does not involve an economic analysis, the evaluated options are within the general range of the costs of alternatives previously considered (WSDOT, 1997).

2.0 Environmental Setting

This section describes the coastal geology, geomorphology, and tidal and wave conditions that affect the erosion problem. Extensive background materials exist from previous projects at the site and nearby. The discussion below therefore draws heavily upon the Corps of Engineers 2009 Environmental Assessment and supporting Appendices (Corps of Engineers, 2009a; Corps of Engineers, 2009b), the United States Geologic Survey coastal erosion study (USGS, 2004), and analysis related to highway protection (WSDOT 1997; WSDOT 2004).

2.1 Geologic Setting

Willapa Bay has been an embayment in Washington's coastline since at least the early Pleistocene (Li and Komar, 1992). When sea level was lower, the Willapa Bay was more of an incised valley. Accretion of sand onto Cape Shoalwater and the Long Beach Peninsula did not begin until the rise in sea level at the beginning of the Holocene, about 12,000 years ago. Sediment from the Columbia River was the source for much of this sand.

More recently, a succession of parallel beach ridges developed on the north side of the bay (Figure 1). The oldest is Kindred Island (now a peninsula due to diking and drainage modifications). Kindred Island is the most landward of the ridges, yet lies at an elevation of less than +13 feet MLLW. It dates back to about 1100 years ago. The Tokeland peninsula rises up to 15 feet above mean lower low water (MLLW) and dates back to about 300 years ago (Morton, et. Al, 2007). These two ridges coincide with ages of subduction zone earthquakes, suggesting that they formed after earthquake-induced subsidence (Morton et. Al, 2007). The Empire/Graveyard spit, and Cape Shoalwater, are the youngest of the beach ridges, and related to various controls on the Willapa Bay entrance channel (USGS, 2004).

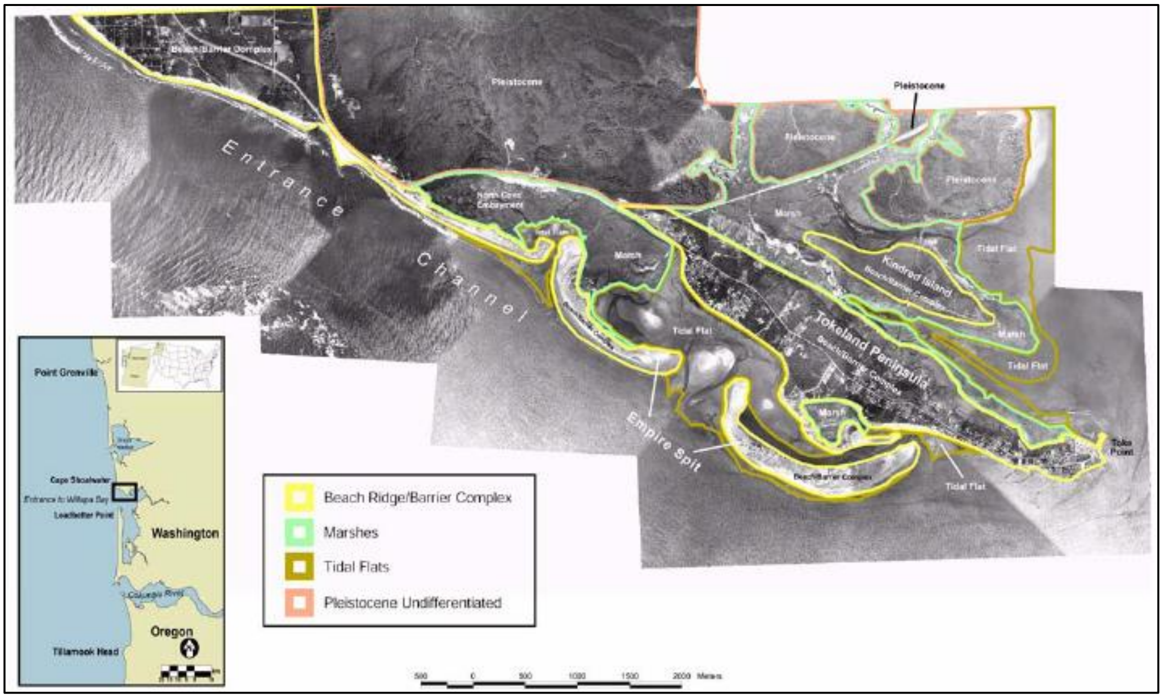


Figure 1. Holocene geology of the Washaway beach area (USGS, 2004). Note the parallel active and older beach ridges.

2.2 Morphology of the Willapa Bay Entrance Channel

Erosion at the project site is strongly related to dynamic changes in the location and configuration of the Willapa Bay entrance channel. Figure 2 shows the current configuration of the channel. The entrance channel is bounded to the north by a marine terrace underlain by erosion-resistant sedimentary deposits, and to the south by the sand spit that defines the Long Beach peninsula. A series of shoals extend off the tip of the Long Beach peninsula, and are periodically crossed by smaller channels formed by ebbing flow.

The entrance channel is a highly dynamic feature that shifts in response to changes in sand deposition patterns and currents. Prior to the late 1800s the channel was located to the south and wrapped around the tip of Cape Shoalwater (Figure 3). Between the late 1800s and the 1960s the channel shifted steadily northward as it eroded into the cape. By 1967 Cape Shoalwater was virtually gone and the north side of the channel was running along the base of the marine terrace near the current alignment of SR 105. Graveyard Spit migrated to the northeast and merged with the interior spit that forms the North Cove embayment. The spit is now a fragmented landform that extends southeast from the SR 105 embankment south of the jetty (Figure 2). It is anchored and aligned by erosion resistant terrace deposits (U.S. Army Corps of Engineers, 2009a).

Figure 2. Current configuration of the Willapa Bay entrance channel.

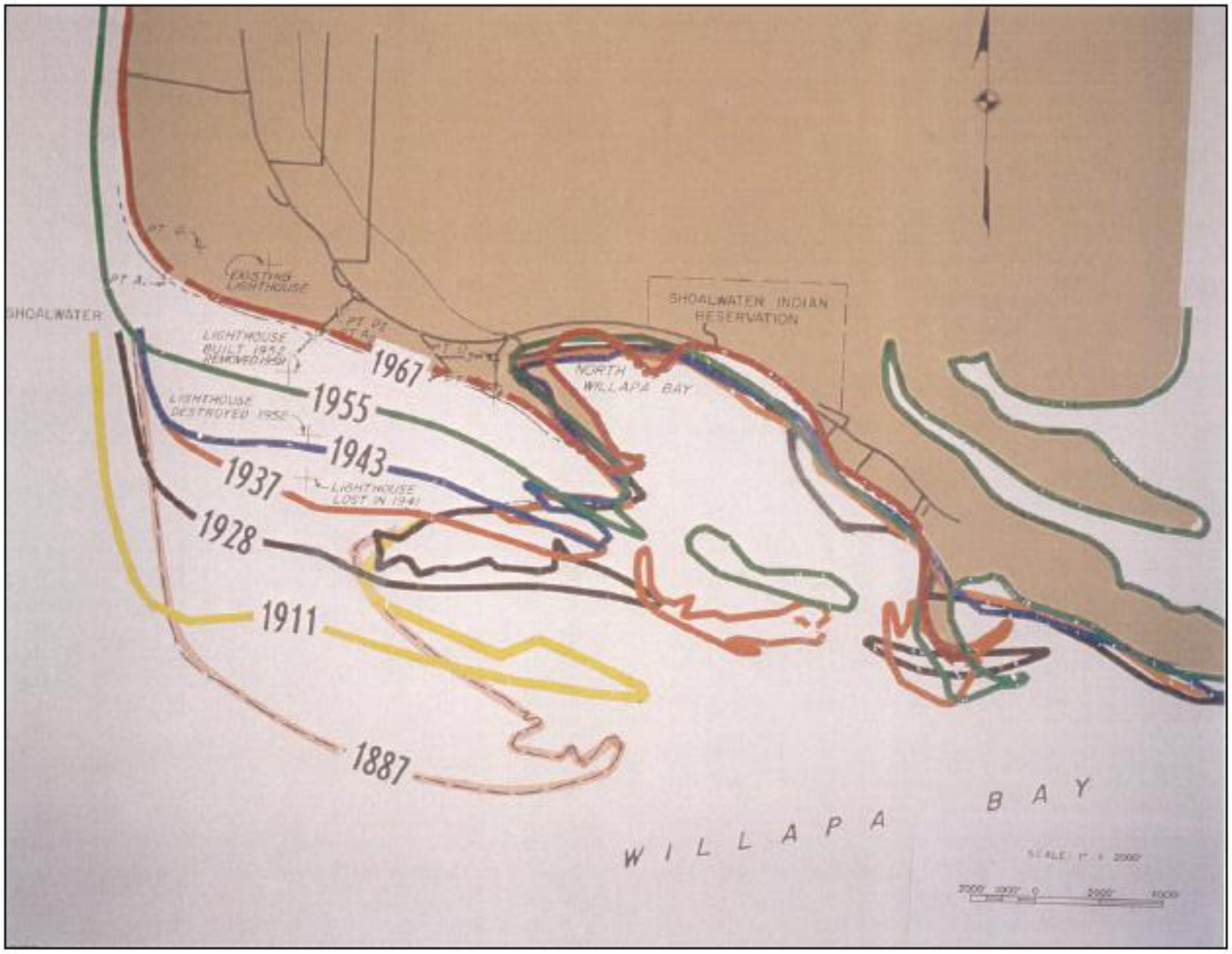


Figure 3. Historical erosion of Cape Shoalwater and northward migration of the entrance channel.

A series of barrier islands often referred to as Empire Spit extend to the southeast from the tip of Graveyard spit in front of the Tokeland Peninsula. Dunes on these spits have diminished in recent years in response to reduced sand supply from eroding beaches to the northwest. Breaches in 1995 and 2003 divided Empire Spit into three narrow islands (U.S. Army Corps of Engineers, 2009b). Graveyard and Empire Spits protect portions of SR 105 from wave action, so the loss of these features increases risks to the highway.

Historic cross section data indicate the northward migration of the entrance channel is slowing as it encounters the erosion-resistant terrace deposits, and there has even been some southward shifting of the channel thalweg in recent years (U.S. Army Corps of Engineers, 2009a). The alignment and extent of the erosion-resistant substrate is not fully understood, but the U.S. Army Corps has speculated that Empire Spit will continue to pivot to the northeast.

The Corps of Engineers has congressional authorization to maintain a navigation channel to Willapa Bay that is 500 feet wide and 26 feet deep at Mean Lower Low Water. Routine dredging ceased in the 1970s due to difficulties in maintaining a channel in the shifting sands at the mouth of the bay (U.S. Army Corps of Engineers, 2009b). Some limited dredging was performed in 2013 along Empire Spit to provide sand for the Corps' dune restoration and coastal protection project. Sand was also pumped from the channel for the construction of the SR 105 jetty in 1998.

2.3 Currents and Sand Transport

High tide ranges create large exchanges of water into and out of Willapa Bay, with recorded current velocities as high as 10 feet per second (fps) (Lesser, 2009). Figure 4 shows peak ebb spring tide currents simulated by the U.S. Army Corps of Engineers (2009a). In most locations the depth-averaged peak ebb tide current is on the order of 3.9 fps, with a high of about 5.6 fps near the tip of the entrance spit. Peak flood tide currents are weaker at about 2.6 fps. Pacific International Engineering (1997) measured point ebb velocities as high as 7.25 fps and depth-averaged velocities as high as 5.11 fps in the project area.

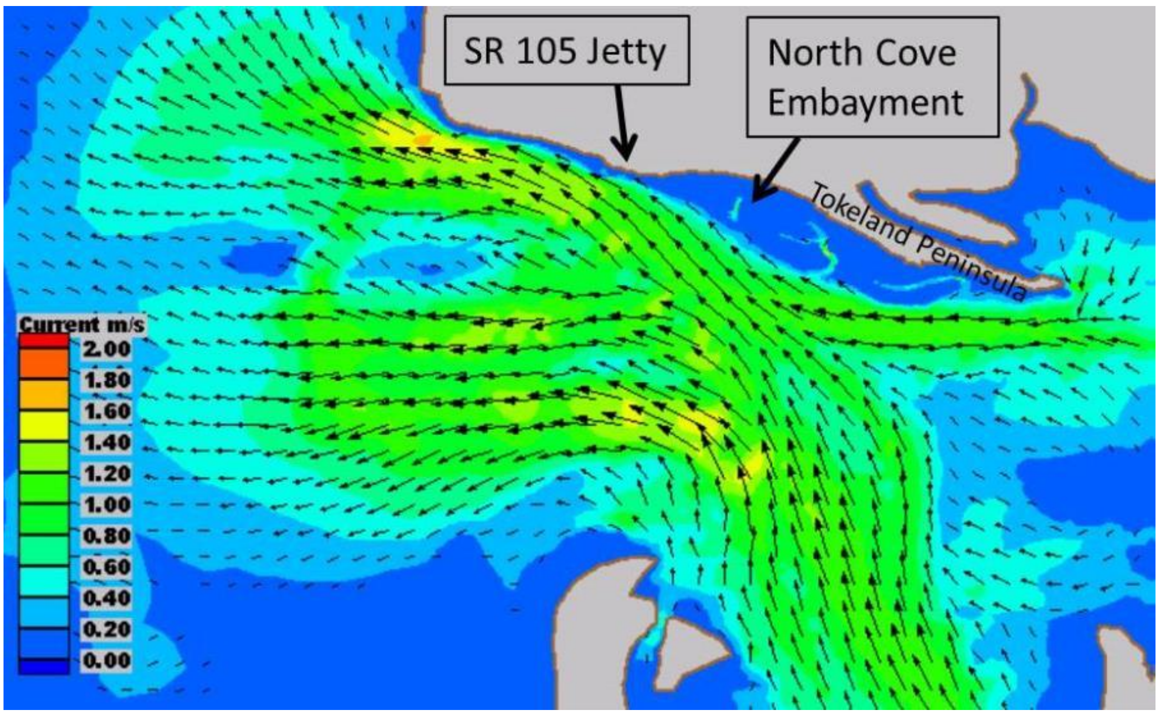


Figure 4. Peak ebb spring tide currents, 2002 channel configuration (U.S. COE, 2009a).

Lesser (2009) developed detailed models of currents and sand transport in the entrance channel. Beaches and sand spits in the project area are fed by northward longshore transport from the Columbia River. The direction of longshore transport changes from predominantly northerly in the winter to southerly in the summer. Sediments are predominantly well-sorted sand.

Sand transport along the northern margin of the entrance channel is predominantly towards Willapa Bay, but the rate of transport into the bay decreases markedly inland of the SR 105 jetty and along Empire Spit (Lesser, 2009). Model results show asymmetrical sand transport and the formation of a sand sink in the scour hole near the tip of the SR 105 jetty. This asymmetry in sand transport and the loss of sediment supply from the erosion of Cape Shoalwater have resulted in minimal transport of sand to the shallow littoral zone adjacent to Empire Spit. The only remaining supply of sand to maintain Empire Spit is the small wave-driven transport along the north side of the main channel.

2.4 Wave Climate

The U.S. Army Corps of Engineers (2009a) describes wave conditions along Graveyard Spit for the design of the Shoalwater Bay Shoreline Erosion, Flood and Coastal Storm Damage Reduction project. The wave climate offshore of Willapa Bay is severe, with measured wave heights greater than 23 feet. The wave climate becomes most severe during La Nina and weak El Nino cycles that increase the frequency of large storms tracking from the south-southwest (Northwest Economics, Inc., 2005). These typically occur every 3-5 years.

The largest offshore waves approach the project area from the southwest during winter storms, and are substantially attenuated by the shoals at the mouth of Willapa Bay. The attenuated wave heights range between 1.0 and 3.3 feet along Graveyard Spit. Local waves generated in Willapa Bay by winds from the south increase the total potential wave height along Graveyard Spit to a range of about 4.9 to 6.6 feet. Estimated wave heights for the record March 1999 storm used as a design event by the Corps of Engineers peaked at 5.2 feet along the spit. Waves also approach the site from the northwest during the summer but are generally much smaller (USGS, 2004).

Dunes on Graveyard and Empire spits further attenuate these waves before they reach the shore of the North Cove embayment and Tokeland Peninsula. Model results for the March 1999 storm show dune-attenuated waves heights of 1.5 feet along the Tokeland Peninsula shoreline (U.S. Army Corps of Engineers, 2009b). Wave heights without the dunes would increase to as much as 3.3 feet. Recent loss of these dunes therefore increases erosion and inundation risks for low areas of SR 105 that run along the shore of the North Cove embayment. Although the Corps of Engineer’s dune restoration project substantially mitigates wave heights along the Tokeland Peninsula, it does not extent north far enough to diminish wave erosion or heights directed at SR105.

The armored coastline near the SR 105 groin/jetty is less sheltered by the entrance channel shoals, particularly for storms that track from the west. The wave environment in these locations is therefore more extreme than at Empire/Graveyard spit. The wave analysis performed for the groin design (WSDOT, 1997, appendix C), used a wave height of 10 feet. Combined with a maximum high tide of 11 feet, the height of the wave on the highway embankment could be at least 21 feet (MLLW), or about 20 feet NAVD88. Waves achieve this height on a regular basis, as indicated by wood debris high on the road embankment (Figure 5).

Figure 5. Debris on top of the roadway embankment, indicating recent wave heights.

2.5 Coastal Flood Elevations

Table 1 summarizes tidal benchmarks for the nearest tide gage at Toke Point (NOAA, 2013). This tide gage is sheltered from ocean waves, so these levels do not reflect the effects of wave setup and runup on exposed ocean beaches. The highest recorded still water tide level was 13.6 feet NAVD on November 14, 1981. Recent extreme tide levels include 12.8 feet NAVD on March 7, 1999 and 13.25 feet NAVD on February 4, 2006.

The Flood Insurance Study for Pacific County estimates a 100-year flood level of 14.4 feet NAVD (10.8 feet NGVD) on the west side of Tokeland Peninsula based on analysis of historical tide elevations and wave setup (FEMA, 1985). This elevation assumes the peninsula is sheltered from direct wave action by offshore dunes and does not include wave runup. The USGS (2004) projects flood levels will increase to 19.5 feet NAVD (20.3 feet MLLW) during large storms if the dunes diminish and no longer protect the Tokeland Peninsula from wave runup. The Pacific County Flood Insurance Study estimates a 100-year elevation of 27.9 feet NAVD (24.3 feet NGVD) in exposed segments of the coast north of Cape Shoalwater where waves are not attenuated by the inlet channel shoals.

Table 1. Tidal benchmarks for the project area (Toke Point, NOAA Station 9440910).

Tide Statistic	Elevation (Feet NAVD88)
Highest Observed Water Level (11/14/1981)	13.59
Mean Higher High Water (MHHW)	8.10
Mean High Water (MHW)	7.36
Mean Tide Level (MTL)	3.95
Mean Low Water (MLW)	0.55
Mean Lower Low Water (MLLW)	-0.82

2.6 Adjacent projects – Dune Restoration

In the Tokeland area, a form of beach nourishment has begun at the site of "Graveyard Spit", a transient sand spit offshore from the community of Tokeland and the Shoalwater Indian Reservation. This project is considered "dune restoration" (Corps of Engineers 2009a). A 12,500 foot linear sand dune was designed across the shallow spit platform. There is no as-built available as of this writing, but the design plan is shown in Figure 6. This project was selected out of a number of different approaches due to its relatively light environmental impact, compared to such things as rock groins and seawalls.

The initial construction used 600,000 cubic yards of sand to protect the Shoalwater Reservation and adjacent shoreline, which is on average 1600 feet landward of the dune. The sand was dredged from a location nearby and adjacent to the main entrance channel of Willapa Bay (see Figure 6). The dune was uniform in cross-section, with the design cross-section shown in Figure 7.

The design elevation of the dune crest was at 25 feet MLLW. This height was intended to prevent inundation from wave run up on the Tokeland Peninsula, and specifically at the Shoalwater Tribe Reservation. The design elevation was based on 21.6 feet MLLW, which is the sum of the still water level (tide, storm surge, setup) and dynamic water level (wave run-up). This amounts to the water elevation with a 1% chance of occurring in any given year (Corps of Engineers, 2009c). The Corps then added another 3.4 feet, stating "A barrier dune crest elevation of +25 feet MLLW will eliminate the threat of water levels from overtopping the barrier dune and the risk of flooding and erosion on the Shoalwater Reservation shoreline." Later it is also explained that to achieve the lowest "life cycle cost", "the initial dune dimensions maximize the volume of sand that is placed within the available plan area." Although not explicit, we interpret this as meaning the dune is higher and/or wider than is necessary to prevent the 1% recurrence interval high water level.

This project includes $80,000,000 for maintenance over the course of the project life, 40 years. Based on the 2000-2002 erosion rates, the Corps estimated the annual loss of sand from the dune (above +6 feet MLLW) at about 50,000 cubic yards per year. The maintenance planned for the dune was scheduled for once every 5 years, consisting of dredging 250,000 cubic yards from the designated borrow area near the channel (See Figure 6). The dune restoration lies on a platform of sand that is part of the Willapa Bay shoals, though likely much older than the surficial deposits of Empire Spit (also referred to as Graveyard Spit). The bathymetry of this location shows that the main entrance channel is 80 feet deep, and its centerline is located 4000-5000 feet from the spit. In addition, there is a shallow terrace offshore that extends 3000-3500 feet from the dune restoration to the north side of the main entrance channel.

Although the planned length was 12,500 feet, a site visit in February of 2014 indicated that the constructed length was significantly shorter - approximately 2000 feet shorter on the south end and a thousand feet shorter on the north end. Also, it was noted that significant portions of the north and south ends of the constructed dune have been eroded by waves. Figures 8 and 9 show selected views of the erosion. Erosion has truncated the dune further, and eroded the terrace underneath the dune. In addition, the crest of the dune is lowering in place through wind erosion (Figure 10). Scallops created by wind erosion, similar to that shown in Figure 10, occur on average every 80 feet on the southern half of the dune. They are less frequently spaced on the northern half of the dune. Based on the fluvial and aerial erosion, the replenishment rate needed to maintain the constructed configuration of the dune may be greater than the Corps of Engineer's estimate for replenishment.

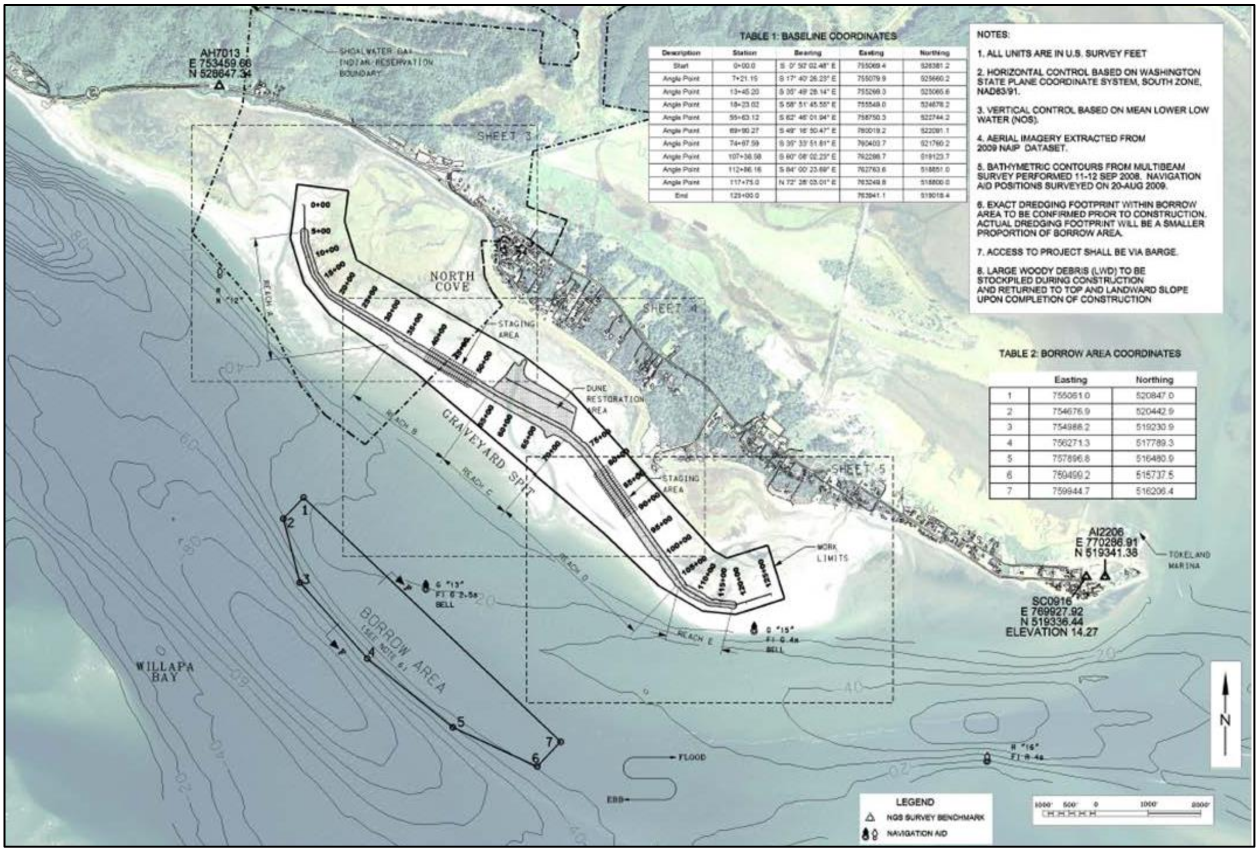


Figure 6. Dune Restoration project location and bathymetry, Tokeland Peninsula and Shoalwater Indian Reservation. (US Army Corps of Engineers, 2013).

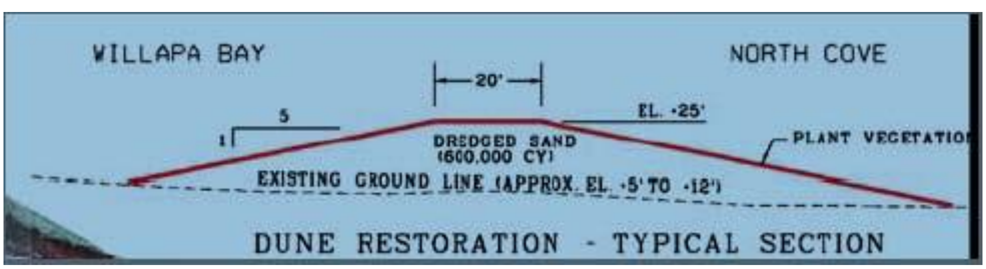


Figure 7. Cross-section from design plan.

Figure 8. Erosion at the north end of the constructed dune, February 2014.

Figure 9. Erosion at the south end of the constructed dune, February 2014.

Figure 10. Typical wind eroded scallop at crest of the constructed dune. The rod shown is approximately 4 feet in height.

3.0 Site Erosion and Repair History

3.1 Road Relocation in the 1970s

Cape Shoalwater was once a well-established landform containing forested dunes, roads, and residences. SR 105 originally cut across the cape from Westport before turning east towards Tokeland and Raymond (Figure 11). Much of this was destroyed by rapid shoreline erosion that occurred between the late 1800s and the early 1970s as the entrance channel migrated northward (Figure 3). By the early 1970s erosion of the cape was threatening the road, and the highway was relocated eastward to its current location along the base of a bluff.

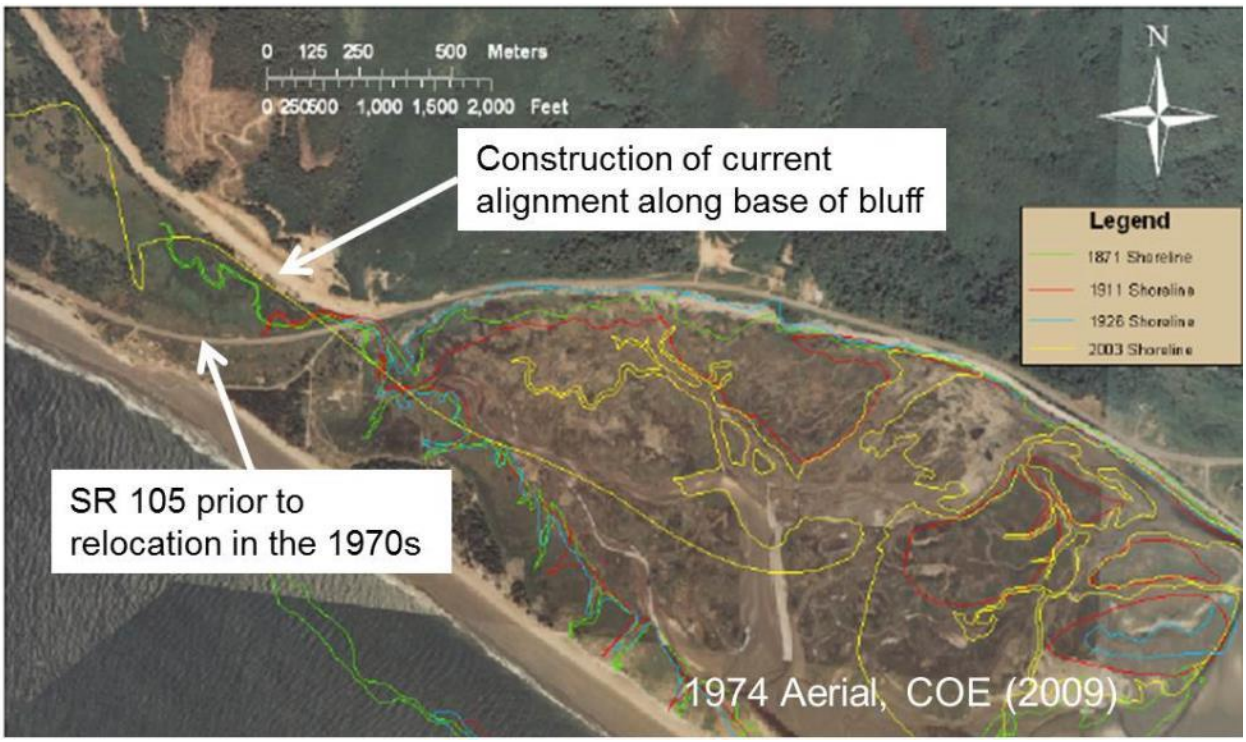


Figure 11. Historical location of SR 105 prior to relocation in the 1970s.

3.2 Shoreline Armor and Groin Construction after the 1996 Storm

By the 1980s migration of the entrance channel had exposed the new highway embankment between Seastrand Creek and the North Cove embayment to direct wave action. About 1200 feet of shoreline was armored with rock wrapped in submarine netting as an emergency project after extensive storm damage in 1996 (Pacific International Engineering, 1999) (Figure 12). After a long and contentious planning process the Washaway Beach groin/jetty was constructed in 1998 to further stabilize this segment of highway. This project consisted of a single large groin and beach nourishment designed to deflect currents and waves in the entrance channel away from SR 105. The original design included recommendations for subsequent beach nourishment on a 6-year cycle (Northern Economics, Inc., 2005), but this was never implemented due to funding issues.

3.3 Repairs after Construction of the Groin

Figure 12 shows the locations of emergency repairs that have been installed since the groin was constructed in 1998. The SR 105 groin has provided only localized protection and the shoreline has continued to retreat (Figure 13). North of the groin the shoreline has retreated as much as 700 feet since the early 1990s and has eroded up into the mouth of Seastrand Creek. The shoreline has retreated about 300 feet along Graveyard Spit south of the groin, and overwash during recent storms has removed most of the dunes that shelter the North Cove embayment from wave action.

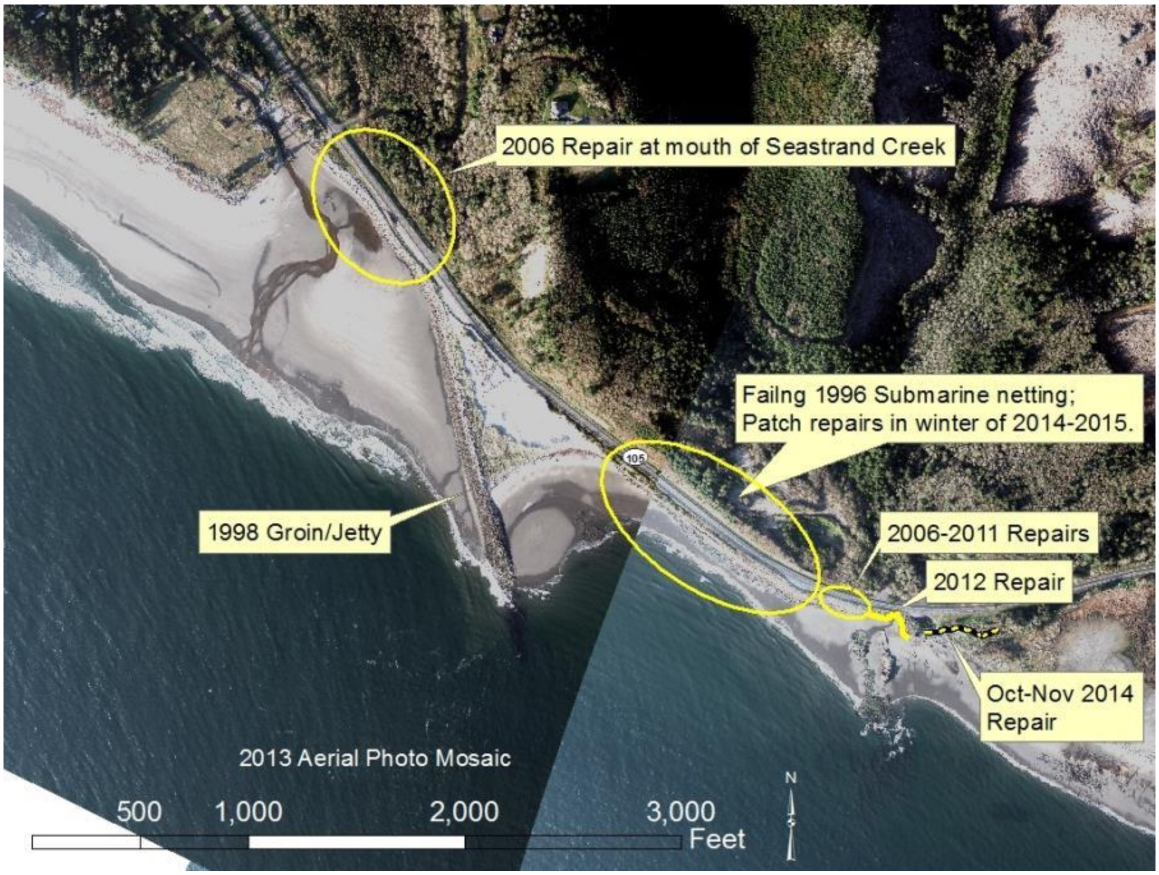


Figure 12. Historical repairs and erosion problems near SR 105 MP 20.

During the winter of 2005-06 waves eroded large sections of shoreline located to the southeast of the groin. The dune line of the backshore was breached, and destruction of SR 105 was narrowly averted by emergency action. A sloping rock revetment with buried toe logs was placed at this time, starting at the south end of the 1996 shoreline armor. These storms also undermined 600 feet of the SR 105 embankment immediately northwest of the groin near the mouth of Seastrand Creek. A revetment was installed here in the summer/fall of 2006, consisting of large rock armor fronted by energy dissipaters made up of boulder piles and large rootwads (Figure 14).

Between 2009 and 2014 erosion progressed steadily along the exposed shore southeast of the 1996 and 2006 repairs, requiring emergency repairs on at least four occasions. These have generally consisted of sloping rock revetments with buried toe logs to deflect energy

(Figure 15). Early season storms in October 2014 further eroded the shore at the point where SR 105 bends east into the North Cove embayment, necessitating a 320-foot-long emergency repair (Figure 12).

Erosion in the winter of 2013 created a scarp along the left bank of Seastrand Creek near the mouth. This is now threatening to flank the existing log and rock revetment. This erosion may have been exacerbated by removal of logs from Seastrand Creek by the local diking district in 2012. A repair to stabilize this segment is currently in design, and will be similar to adjacent revetments. The diking district has also constructed a log barrier across the mouth of Seastrand Creek, presumably to limit the progression of erosion and logs up into the creek where it drains cranberry operations (Figure 16).

Waves and high storm surge tides are now intruding into the marshes that once buffered the highway in the North Cove embayment. Maintenance was required in the winter of 2015 to clear logs that had washed up onto the highway in this area.

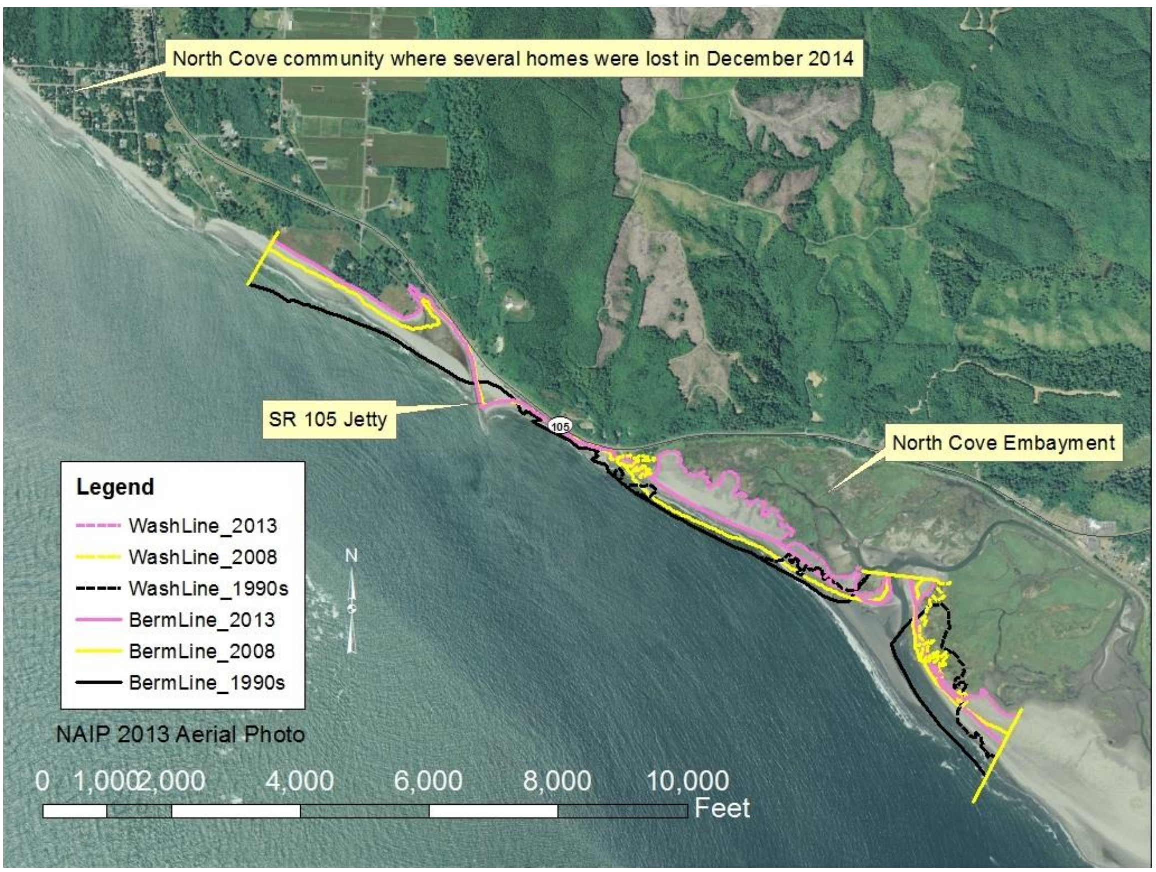


Figure 13. Shoreline retreat, 1990s through 2013.

Figure 14. Photo of the 2006 revetment with log energy dissipators northwest of the jetty along Seastrand Creek.

Figure 15. Photo of typical emergency repairs southeast of the jetty.

Figure 16. Log structure constructed by the diking district across the mouth of Seastrand Creek in 2013.

4.0 Future Trends and Threats to the Highway

4.1 Continued Migration of the Entrance Channel

The northern edge of the entrance channel is now directly entrained against the SR 105 embankment near the groin/jetty. The U.S. Army Corps of Engineers (2009a) found evidence in historical cross section data that the entrance channel has stopped migrating northward and the thalweg is starting to shift southwards. They speculated this was due to erosion-resistant marine terrace deposits that underlie the northern channel margin. In exposed locations along the shore these deposits appear to consist of poorly-consolidated marine sediments and sedimentary rock. The precise extent and location of these deposits is not fully known, so there is considerable uncertainty in these projections of entrance channel migration.

Even if the thalweg has ceased its northward migration, the channel continues to degrade and widen along its northern margin in response to wave erosion. This wave action has exposed and undermined terrace deposits that were once buried by dunes in the North Cove embayment (Figure 17). This contributes to the loss of beaches and dunes that buffer the embayment from waves, and will likely lead to a more severe wave climate on the North Cove embayment shoreline.

Figure 17. Exposed terrace and marsh deposits on the margins of the North Cove embayment.

4.2 Degradation of the 1998 Groin and Beach Nourishment

Although the 2001 “final monitoring” report (PIE, 2001) states that the SR105 project has met design expectations and “stabilized” the shoreline, erosion of the project was extensive, and the project itself may have contributed to erosion adjacent to the groin. This section reviews the performance of the two main components of the stabilization project, the groin/dike and the beach nourishment.

4.2.1 Rock groin and underwater dike

The emergency stabilization project at milepost 20.4 to 21.0 includes the groin/dike structure and the beach nourishment placed on the southeast side of the structure. The design plan view is shown in Figure 18. For the purposes of this document, we will use directional references for orientation – position relative to the groin/dike structure will be noted as either northwest (toward Grayland) or southeast (toward Tokeland).

The groin portion of the structure is that portion that was placed at an angle to the beach, and was intended as a breakwater (WSDOT 1997). The dike portion was placed at a right angle relative to the main entrance channel of Willapa Bay and was intended to prevent the channel from migrating further toward the highway. The groin is about 1600 feet in length, while the underwater dike is about 830. The as-built cross-sections are shown in Figure 19.

A large scour hole has developed on the northwest side of the dike. Figure 20 shows the latest (2013) bathymetry. The scour hole is over 142 feet deep at its deepest. The underwater dike was designed to withstand scour up to -115 feet below MLLW. In fact, the report by PIE (2001) indicates that some settling of the dike portion has occurred. The slope of the west face of the underwater dike is much steeper than in the as-built drawing. The as-built indicates a 1:7 slope (14%), when in fact it is 55% (Figure X4). The slope of the upper portion of the dike is close to the as-built slope. There does not appear to be a slump of material at the base of the dike, and there is a scour hole downstream from the dike. Therefore it appears that the dike was constructed in a manner different from what is shown in the as-built drawings (there were other, documented, design changes). However, it may have been eroded by the intense shear stress at this location. The current slope is probably at about the angle of repose underwater.

In cross-section, the as-built shows a 1:2 (50%) slope on the underwater dike (Figure 19). The 2013 bathymetry shows that the slope is 36% on the downstream side and 29% on the upstream side (Figure 22). This indicates that the slope was changed to 33% (1:3). It also indicates that there may have been some settling and/or erosion of the dike on the downstream side.

In addition, the cross-section shape appears to have changed, becoming flatter, with considerable dislodgement of rocks on the southeast side (Figure 23). The slope on the southeast side appears to be steeper than 1:7. While sand was used to fill the void spaces on the southeast side of the groin, and gravel on the northwest, neither can be observed today.

4.2.2 Beach nourishment

Another portion of the project consisted of beach nourishment, the replacement of beach sediments that have been depleted. The layout and cross-section of the beach nourishment area are shown in Figure 24 and 25.

The beach nourishment has not performed as intended. At the site of the SR105 emergency stabilization, dredged sand was placed in a rectangle, with a lower elevation (on the west side) of -7 MLLW. Within the first 3 years, almost half the placed sand was eroded (PIE, 2001), though most of this was in the first winter (a severe El Nino event). Coastal Geologic Services (2006) estimated that re-nourishment of the project, just to maintain the original area of protection, would be required every 2-4 years. This is much more frequent that either the original replenishment estimated (twice in 40 years), or the subsequent monitoring report estimate of once every 6 years (PIE, 2001). There has been no nourishment subsequent to construction.

Figure 26 shows the area of beach nourishment remaining since construction. This is based on GIS analysis. The most recent area (2009) was produced for this document, using LiDAR topography. After an initial sharp drop in area (erosion), the beach experienced some accretion, and since then has seen a slower, but steady, rate of erosion. Looking at the as-built drawing, the nourishment area went from being a rectangle 250 feet in width and 1600 feet in length to a much smaller triangle (Figure 27). The top surface of the nourishment was built to 25 feet NAVD88. In 2009, LiDAR topography showed the sand to be much lower, by 10 feet, over much of the nourishment area. Also, the shape of the nourishment area changed from a rectangle to an arc, protected by the groin on the seaward side and by the highway embankment on the landward side. Figure 27 shows the LiDAR contours as of 2009, and the 2013 aerial photograph. It is evident that even further loss of sand has taken place since 2009.

Another factor has been wind erosion. It is likely the cause of a portion of the overall decrease in elevation of the site. Wood barriers have been installed to inhibit erosion (Figure 28), and plastic mesh has been installed along the highway to prevent accumulation of sand on the highway. These measures have been partially effective as indicated by the amount of sand trapped. However, they haven't prevented a large deviation from the original configuration.

4.2.3 Effects of the emergency stabilization project on the adjacent areas

Although the final monitoring reports states that the coast northwest of the groin has been stabilized, this is not the case today. There has been significant retreat of the shore immediately west of the groin (See section 3.0), centered on the ditch that drains the cranberry bogs to the north (see Figure 27). Another emergency project was installed in 2006 to protect the highway in this location, and extension of this is being planned. Local actions, independent of WSDOT, appear to be aimed at stabilizing the creek in this location.

Additionally, the highway embankment and coastline have eroded to the east of the project. The nourishment sand that remains is in a zone protected from the refraction of waves on the highway revetment by the groin. Additional rip rap has been added to this section (Figure 29), but this also shows signs of undermining and settling (Figure 30).

Several repairs have been made, and additional rip rap has been added, in two phases during 2014 (Figure 31). The pattern of progressive erosion eastward along the highway embankment can be seen in Figure 31 by following the sequence of successive revetment installations and repairs. Foreshadowing of additional erosion can be seen by the location of the latest coastal erosion scarps and debris wracks (from late 2014). It is clear that the groin and sea dike are protecting just the portions of the highway that are located immediately behind the groin. In addition, the groin is likely impeding sediment movement along the shore, which would otherwise be replenishing at least a portion of that lost due to wave erosion.

The underwater dike appears to have created a large scour hole to the northwest (downstream) and cause accretion on the southeast (upstream). Figure 32, based on 2013 bathymetry, shows the difference in elevation adjacent to the dike on both upstream and downstream sides.

While the stabilization project was successful in diverting the thalweg of the main entrance channel, shoreline erosion appears to be happening regardless of this shift. This suggests that wave energy is primary erosive force. Especially at high and extreme tides such as during El Nino events, wave energy is unaffected by the position of the channel. The Corps of Engineers (2009a) designed their flood protection project based on wave heights alone, and concluded that the channel location did not affect flood elevations.

As further evidence of the erosive power of waves alone, several platforms composed of weakly consolidated sediments have eroded in recent years. There are at least three of these platforms, founded on Pleistocene sediments. These form resistant islands for a period of time, but then are leveled off by wave action. Figure 33 shows how the shoreline has retreated in spite of some resistance from the more consolidated Pleistocene sediments. The yellow polygons show the shape and location of two prominent bedrock outcrops in the surf zone as of 2013. The first panel shows these polygons with the background being aerial photography from 1999. The succeeding panels show that the bedrock is revealed over time, and eroded. The retreat of the shoreline during this period indicates that the bedrock outcrops do little to prevent shoreline erosion. They are likely not well indurated and thus succumb to the high energy waves at this location.

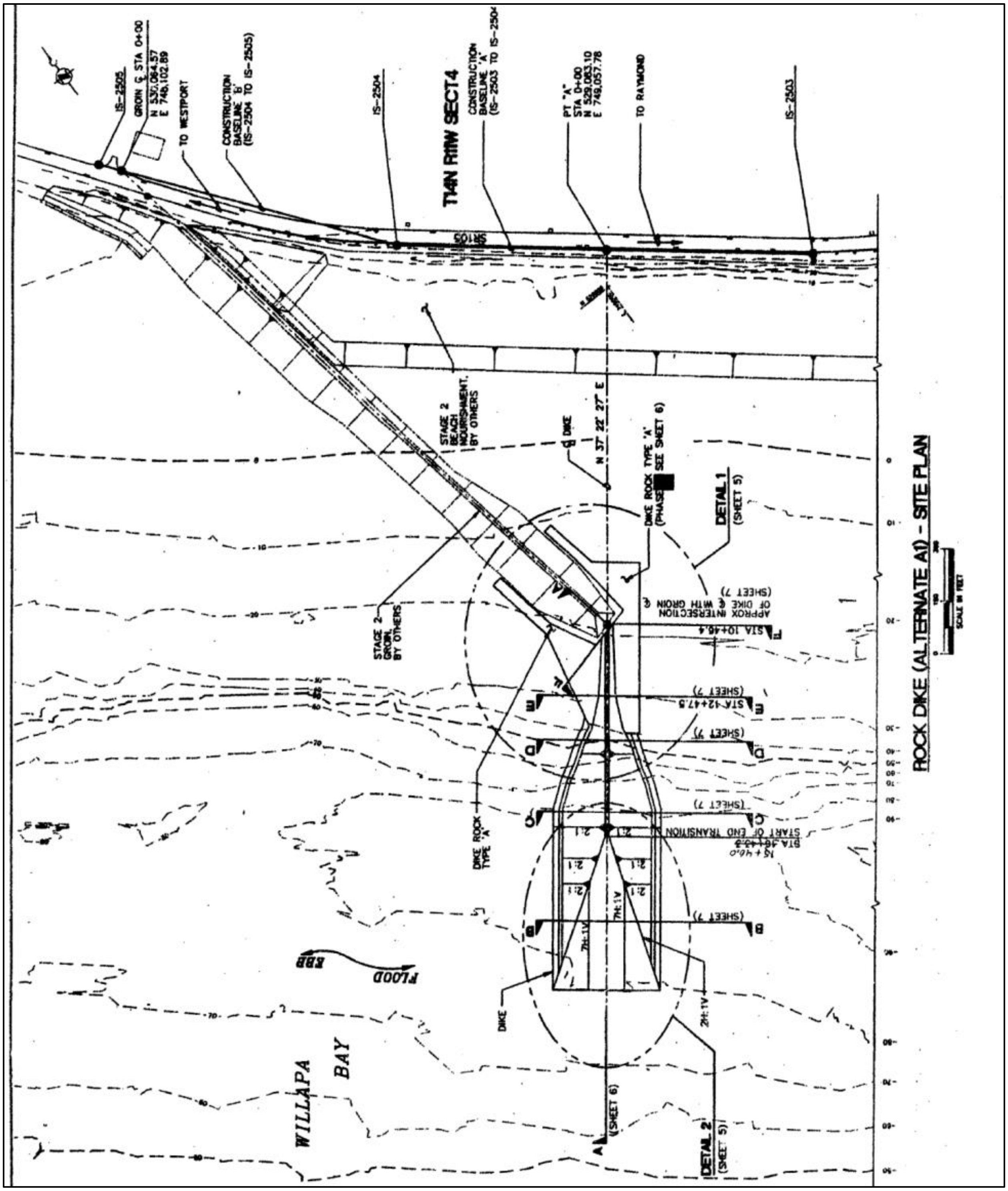


Figure 18. Plan view of emergency stabilization project.

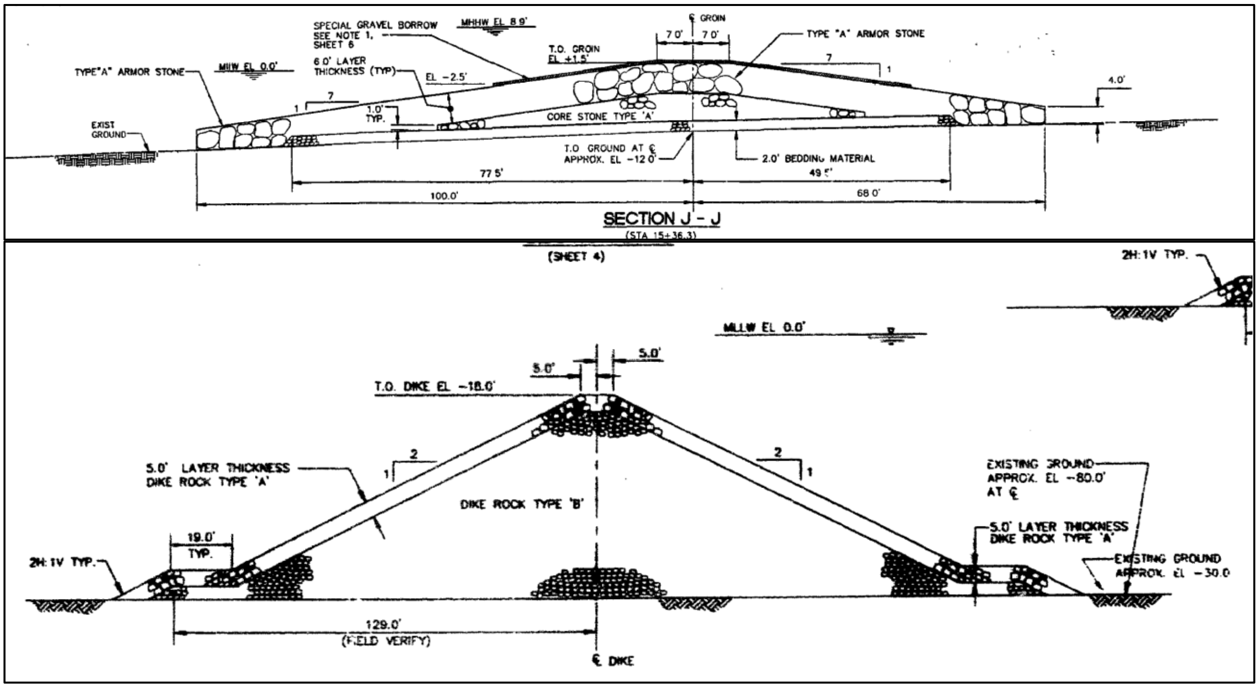


Figure 19. Cross-sections of groin and underwater dike

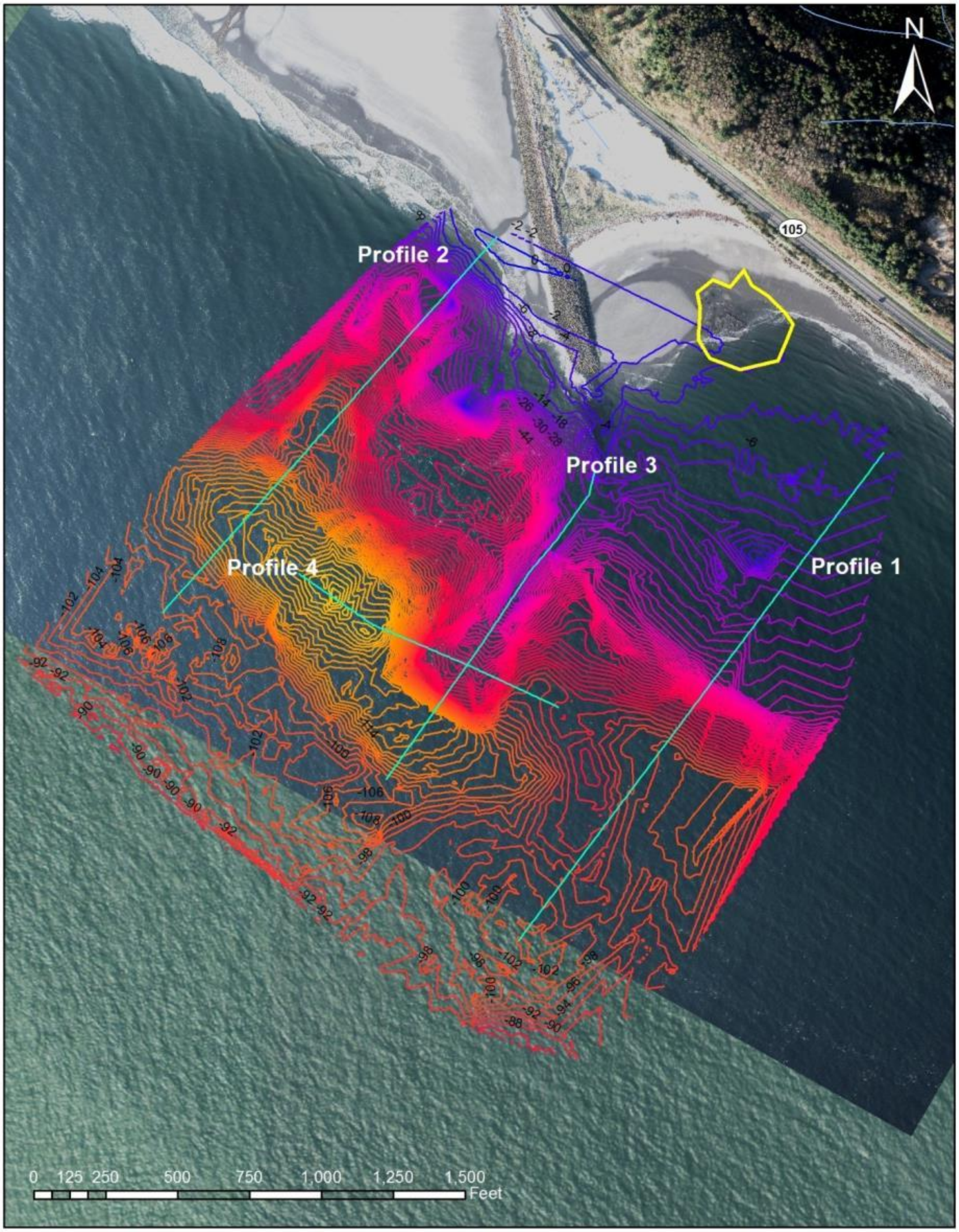


Figure 20. Bathymetry 2013. Yellow polygon indicates the size of a bedrock outcrop in 2011. Aerial photograph background is 2013.

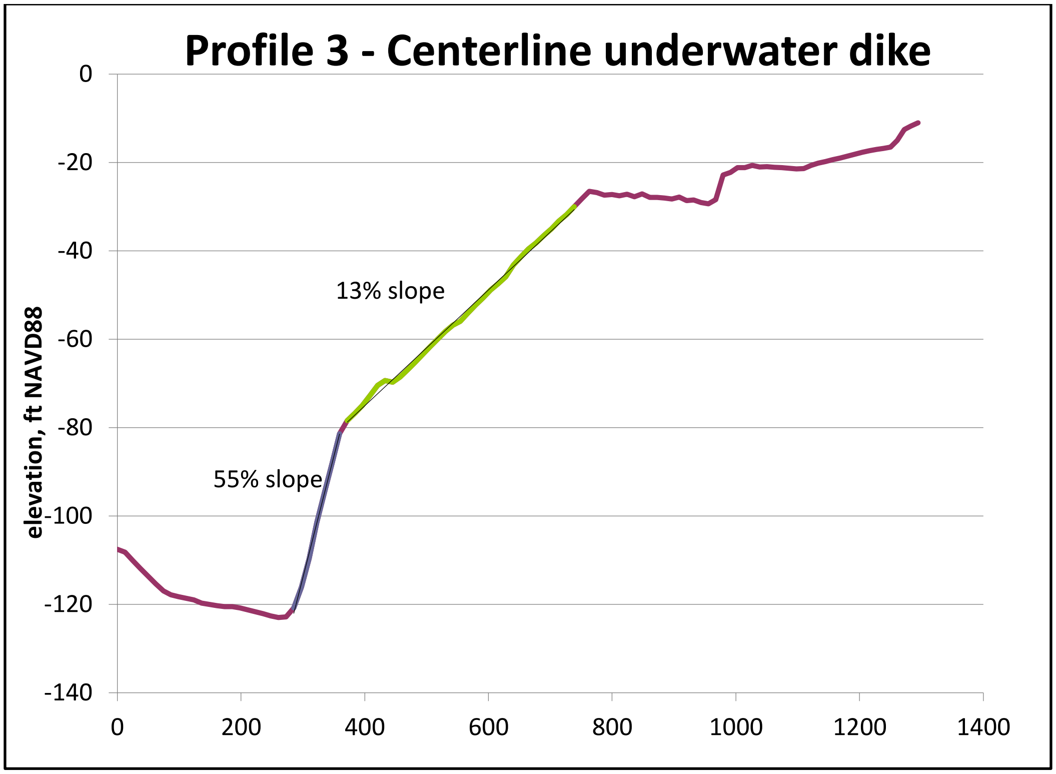


Figure 21. Profile along the dike centerline showing using 2013 Bathymetry (for location, see Figure 20).

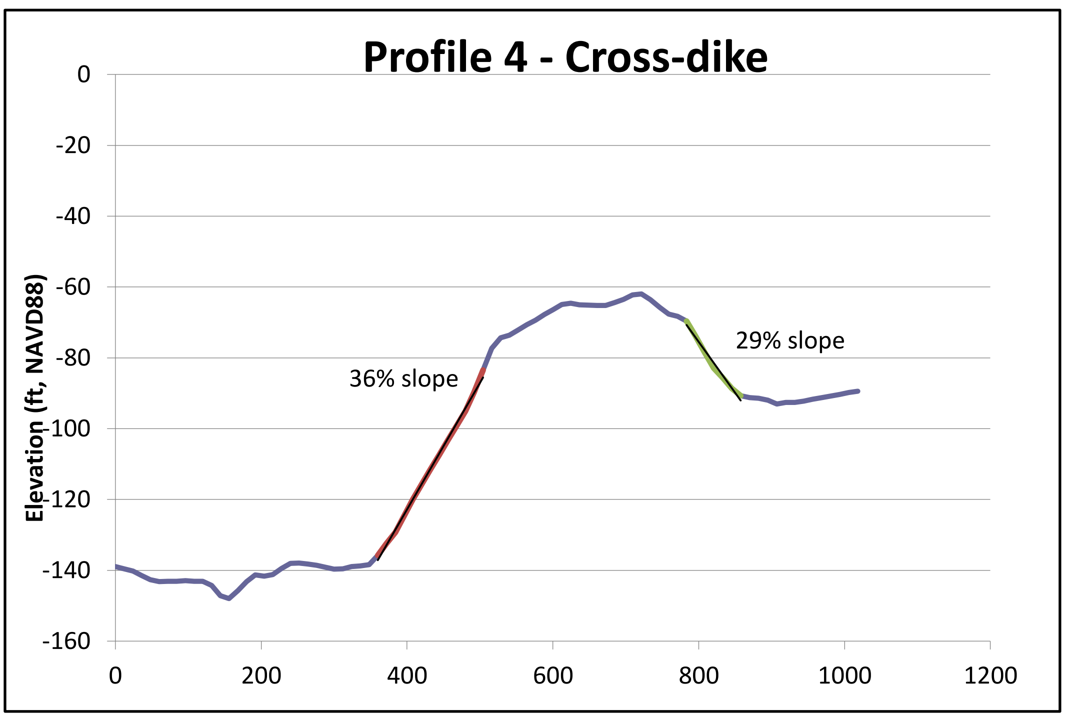


Figure 22. Cross-section of the underwater dike using 2013 Bathymetry (for location, see Figure 20).

Figure 23. Current state of a portion of the groin, December 2013.

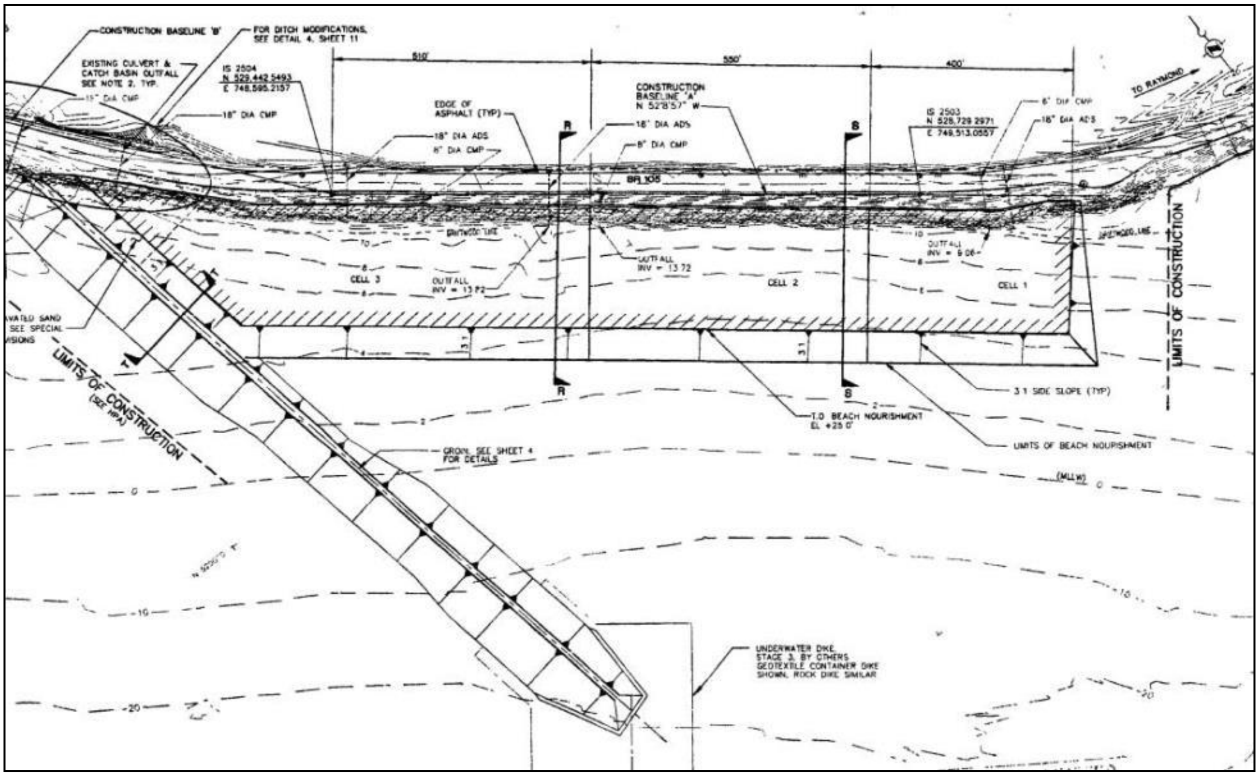


Figure 24. SR105 Emergency Stabilization Project, beach nourishment layout (WSDOT, 1998).

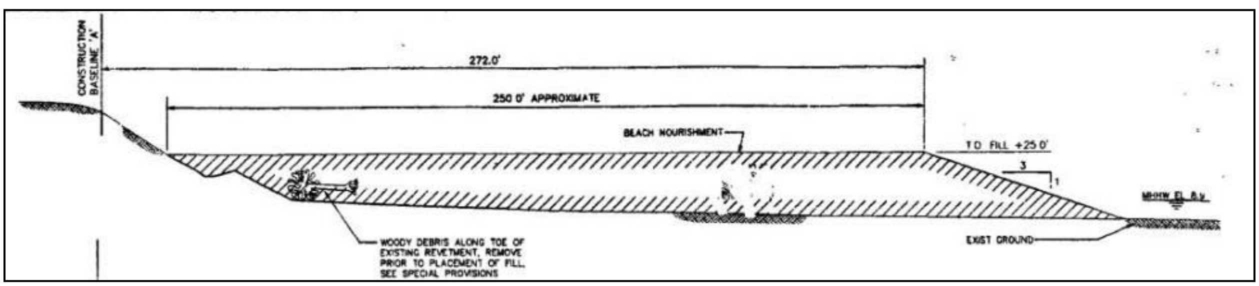


Figure 25. SR105 Emergency Stabilization Project, beach nourishment cross-section (WSDOT, 1998).

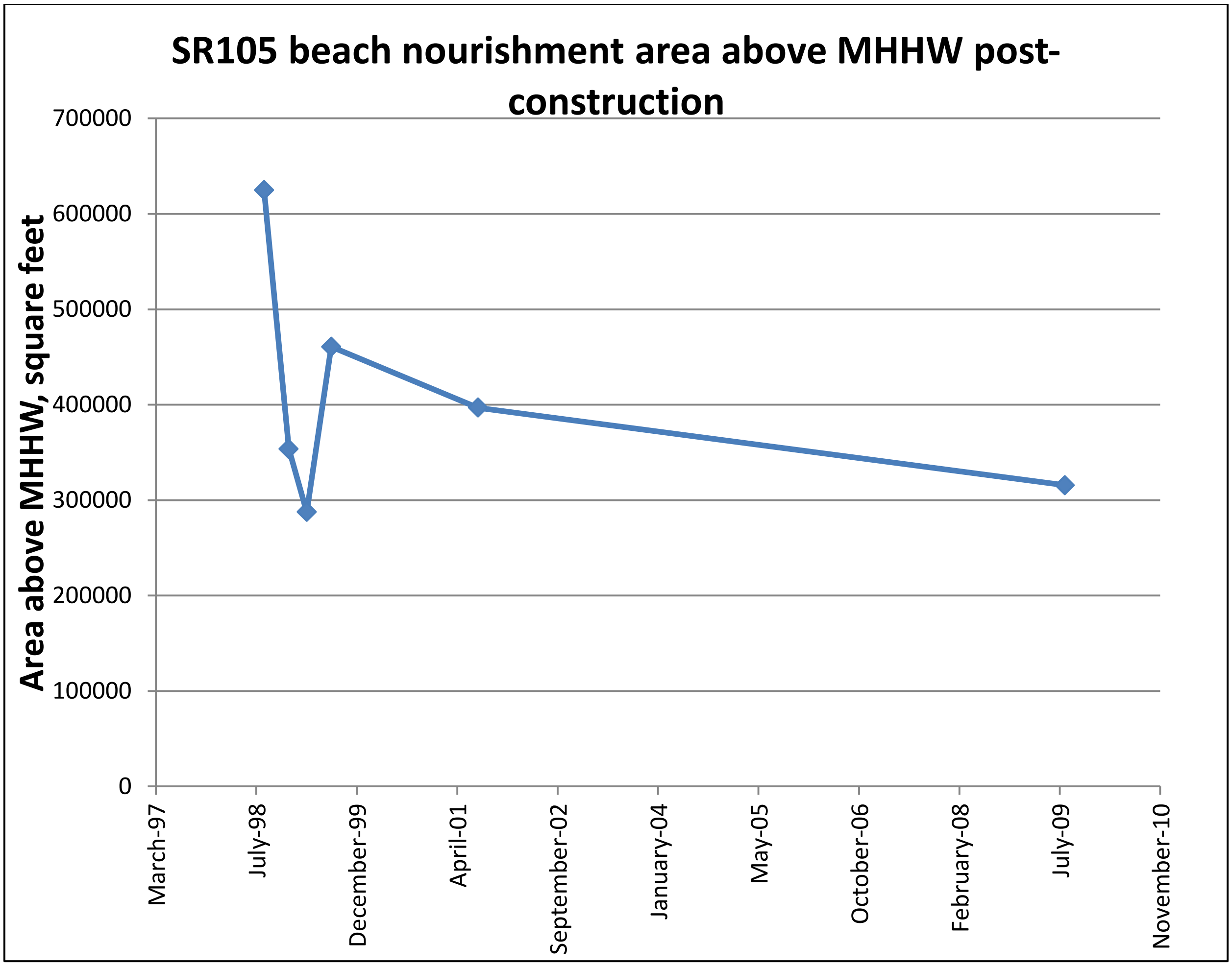


Figure 26. Graph of beach nourishment area, 1999-2009.

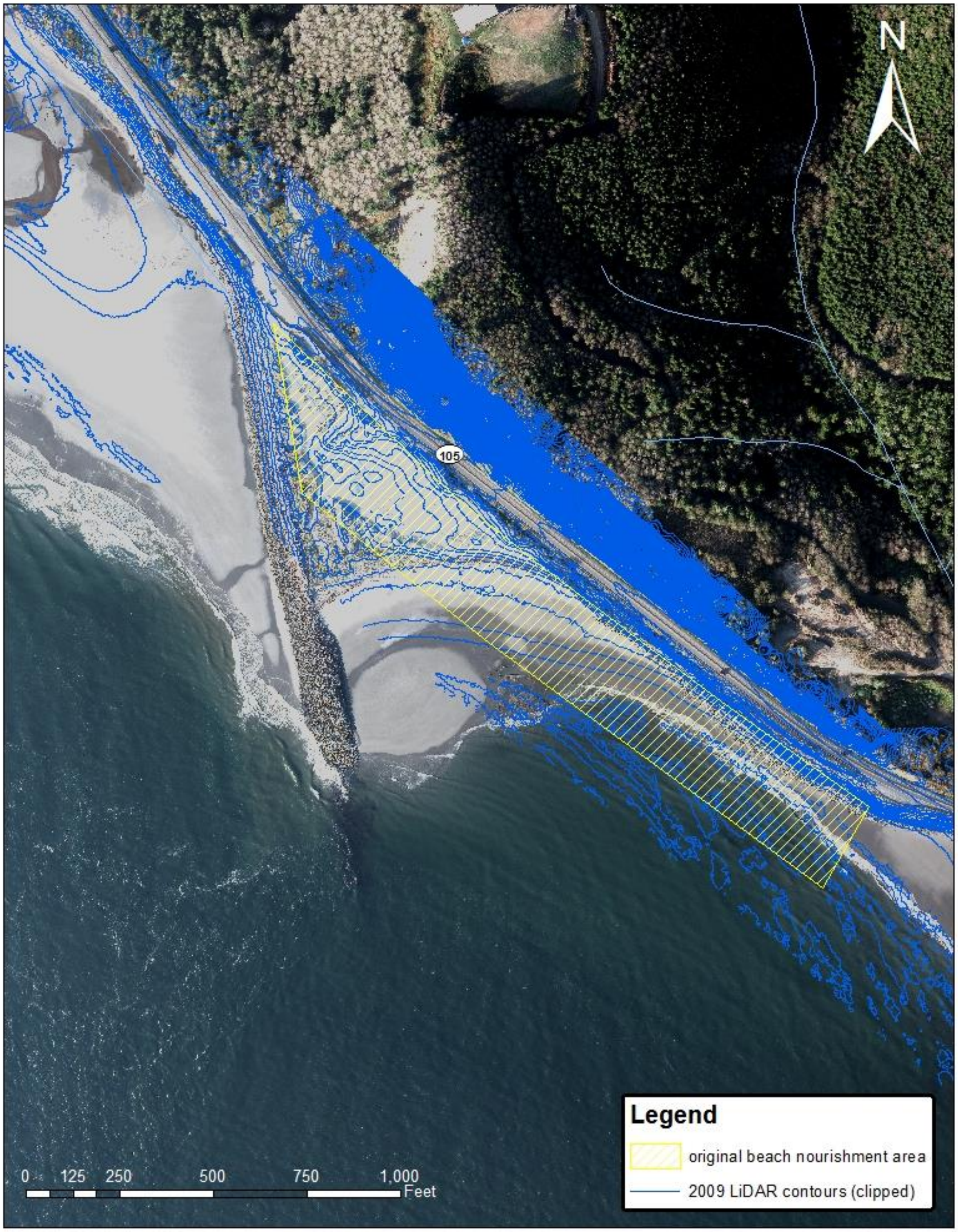


Figure 27. Aerial view of beach nourishment area with 2009 LiDAR topography.

Figure 28. Wood debris placed on beach nourishment area to slow wind erosion.

Figure 29. Section of rip rap added east of the groin/beach nourishment area.

Figure 30. Undermining of rip rap and erosion east of the emergency stabilization project.

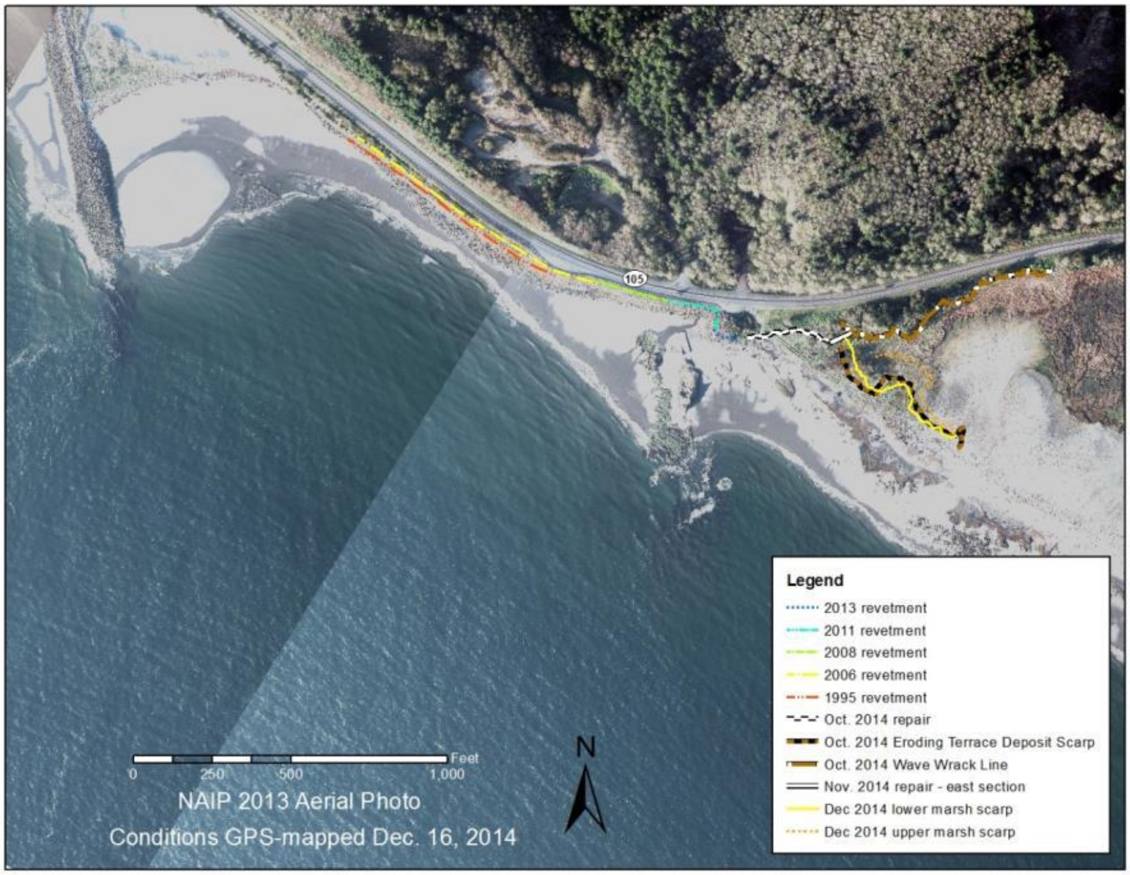


Figure 31. Rock stabilization features and selected erosion features1995-2014.

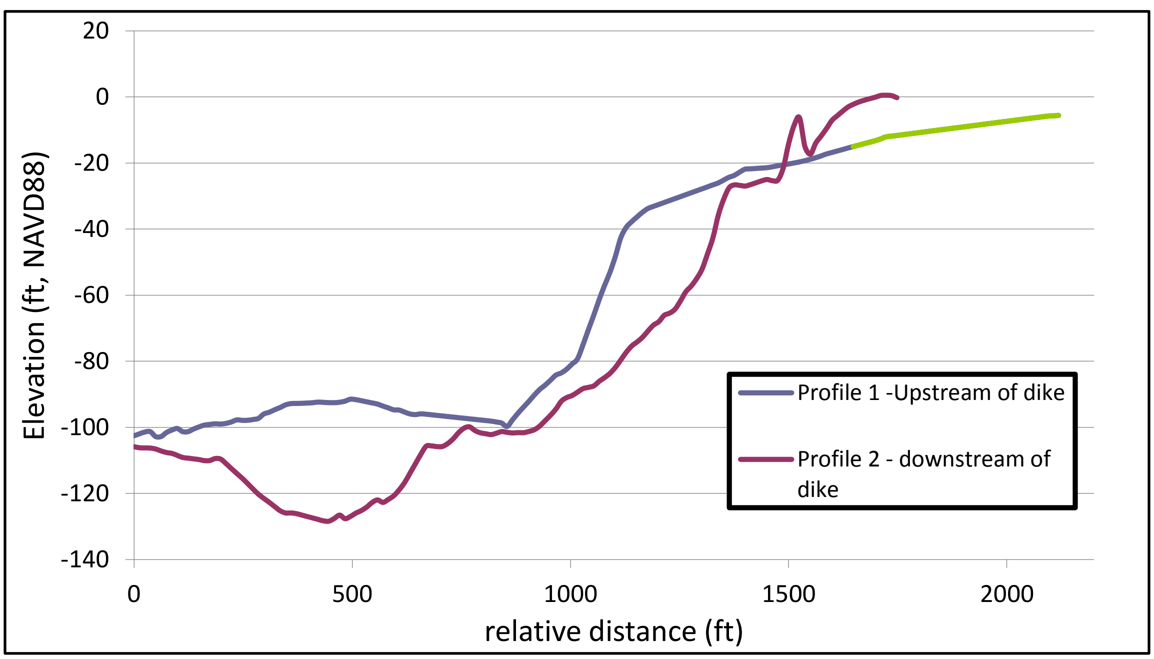


Figure 32. Profiles of right bank of entrance channel, upstream and downstream of the underwater dike. Based on 2013 bathymetry.

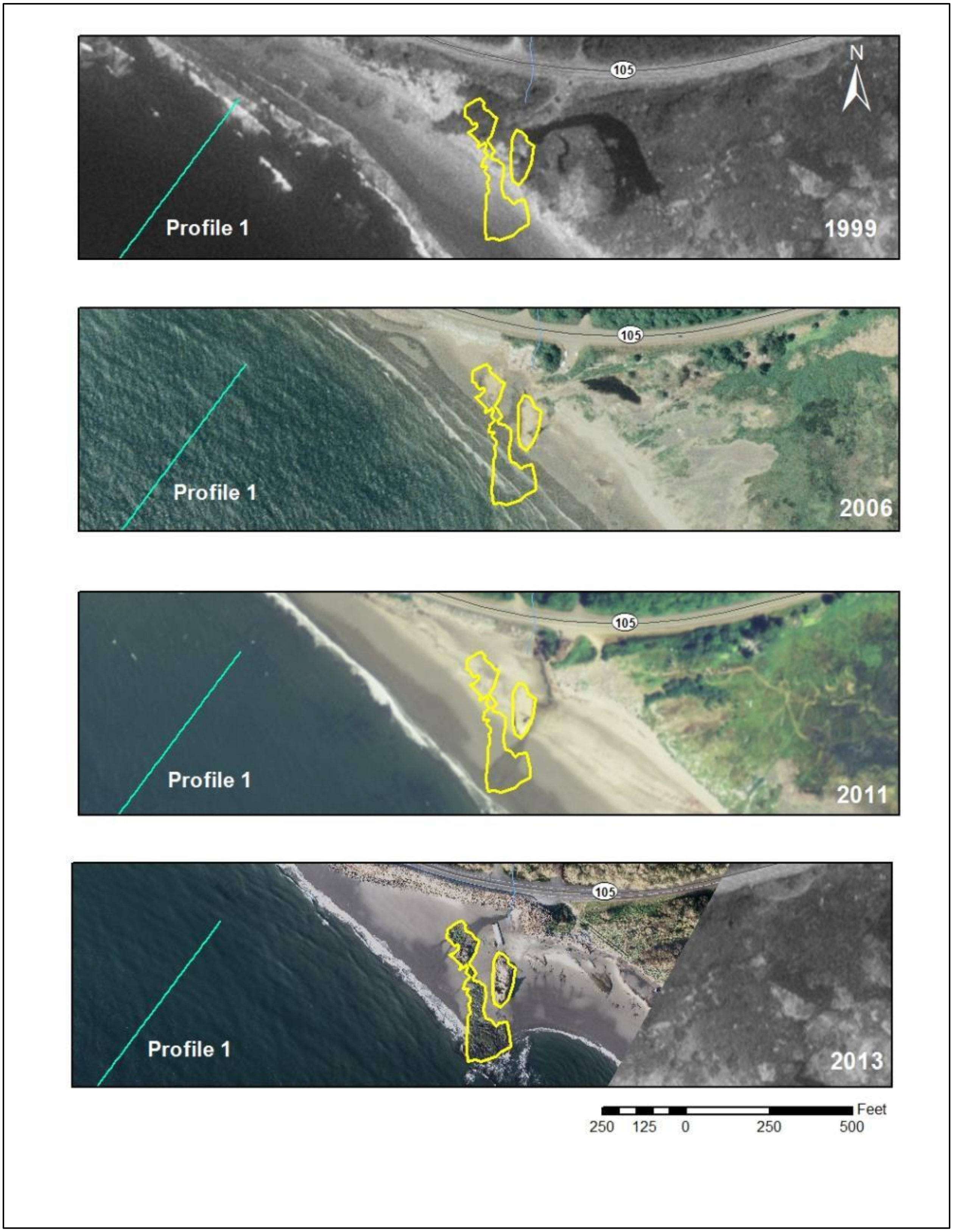


Figure 33. Progressive erosion of exposed marine sediment "islands".

4.3 Loss of Dunes and Increased Wave Action in the North Cove Embayment

Dunes on Graveyard and Empire spits shelter the Tokeland Peninsula and segments of SR 105 from wave action, and were once fed by sand from beaches to the northwest. Recent shoreline erosion has severely reduced this supply of sand. Continued undermining of marine terrace deposits along the northern margin of the entrance channel has also increased wave erosion of the dunes. The result has been severe intrusion of waves and loss of vegetation in the North Cove embayment (Figure 13). The rate of overwash has increased rapidly since 2011. The U.S. Army Corps of Engineers (2009a) projects wave heights in the North Cove embayment will double if the dunes disappear. The Corps' dune restoration project on Empire Spit is intended to replace dunes fronting Tokeland Peninsula, but does not shelter SR 105 on much of the North Cove shoreline.

This threat is most severe where SR 105 transitions out of the North Cove embayment towards the jetty (Figure 34). Dunes are now absent here, and the marine terrace deposits that underlie the cove are exposed and rapidly eroding. Wave overwash has destroyed large areas of marsh vegetation, and a small back channel is forming along the toe of the vegetated SR 105 embankment. The brunt of this wave overwash is now aimed at a 315-foot segment of highway embankment with only a narrow vegetated upland buffer.

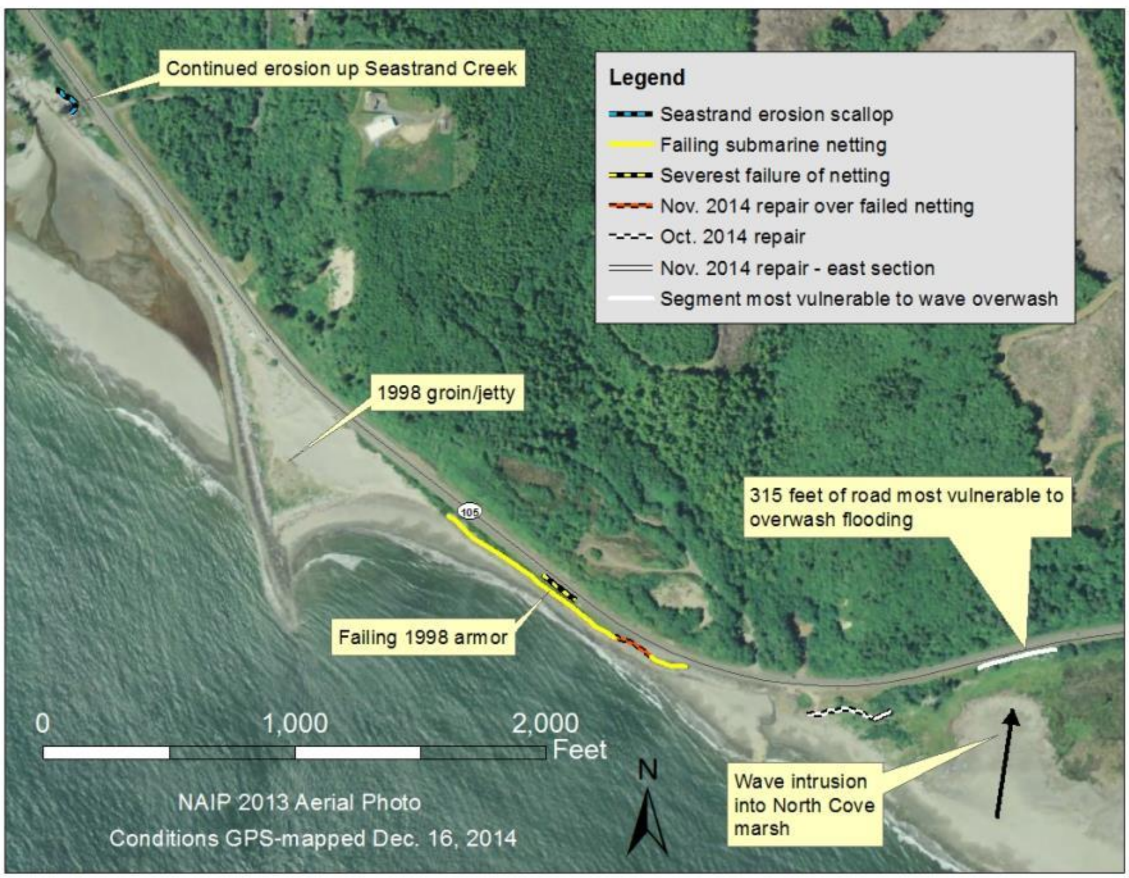


Figure 34. Failed armor and vulnerable highway segments, December 2014.

Figures 35 and 36 show 2009 LiDAR elevations in the project area. Much of the highway along the North Cove embayment shoreline lies at elevations between 15 and 16 feet

NAVD. The USGS (2004) estimates a total flood level with no dunes of 19.5 feet NAVD during major storms along the Tokeland Peninsula. This segment of the highway is therefore highly vulnerable to inundation by the more severe wave climate that will occur with the loss of the dunes.

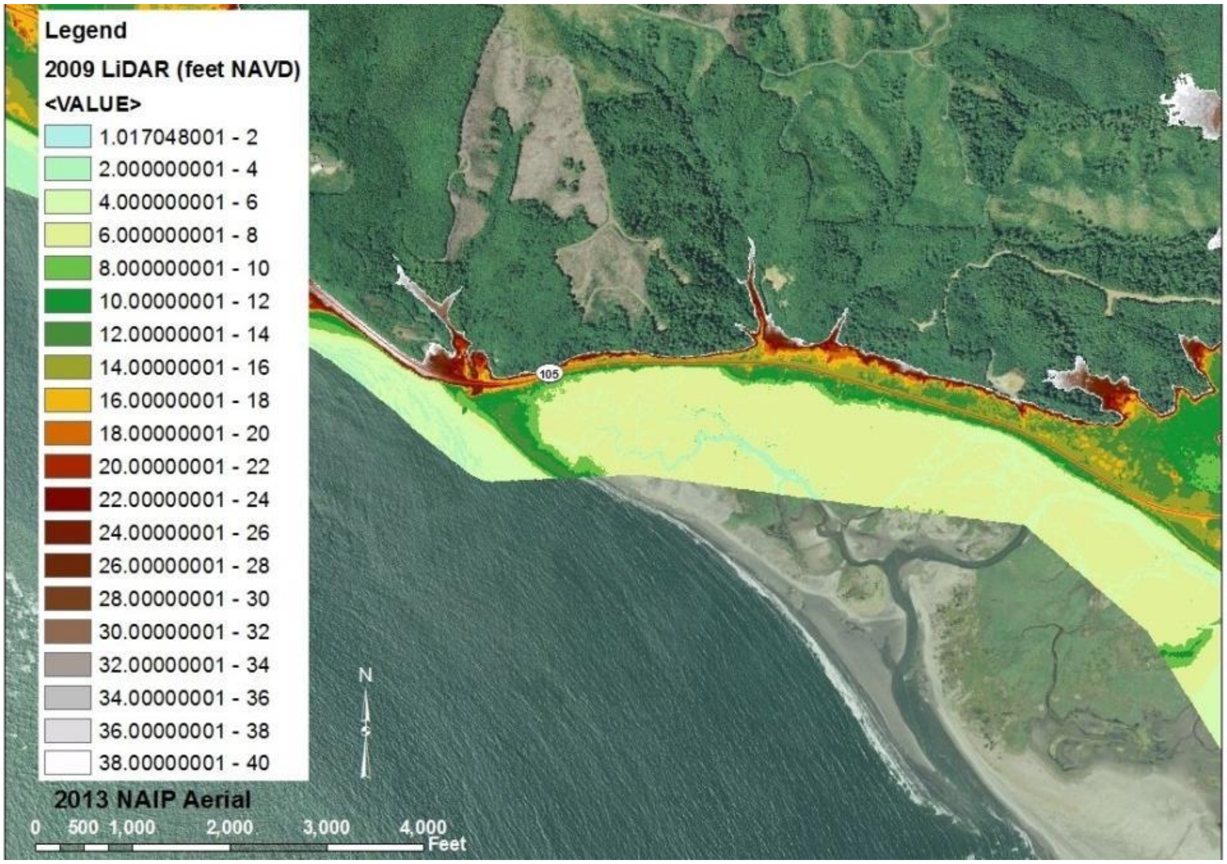


Figure 35. 2009 LiDAR elevations in the project area.

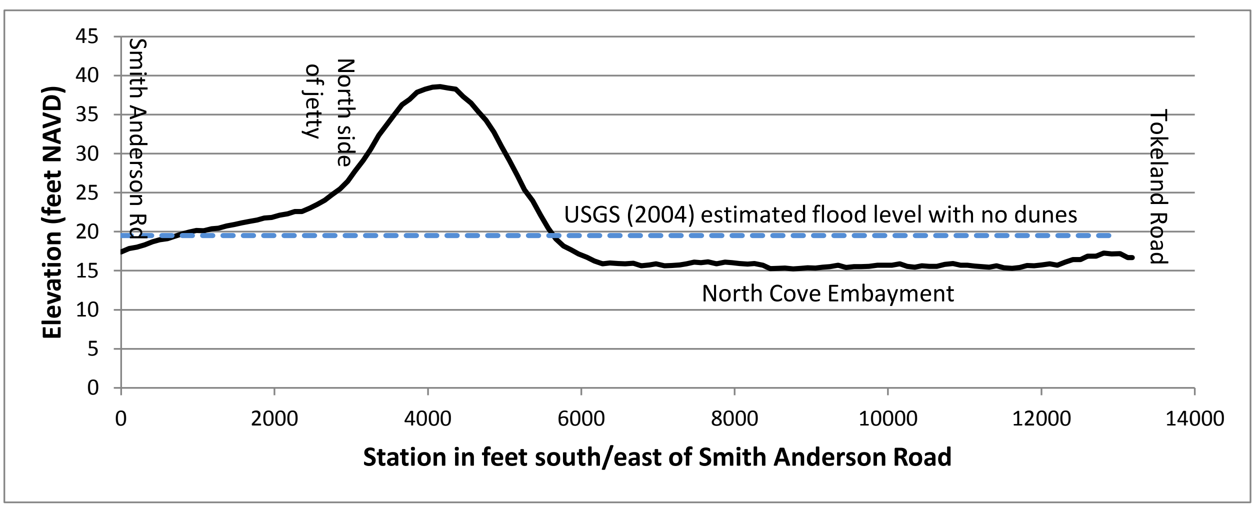


Figure 36. Centerline profile of SR 105 derived from LiDAR data.

4.4 Failure of Existing Shoreline Armor.

Older portions of shoreline armor constructed just south of the groin/jetty are beginning to fail as they are exposed to more severe wave action (Figures 34 and 37). These segments were constructed in 1996 with rolls of rock wrapped in steel submarine netting supported by a rock toe. Wave action has undermined the rock toe, causing large segments of the submarine netting to rotate downslope. This has created an exposed scarp where the netting has pulled away from the top of the slope. An emergency rock repair was placed in November 2014 on one 165-foot segment of the net-wrapped armor, and another 200-foot segment will be repaired in 2015. Another 800 feet of this armor is still vulnerable but has not yet warranted an emergency repair. All of the armored shoreline faces a severe wave climate and will require continual maintenance to protect the highway.

Figure 37. Failure of submarine netting and armor just south of the jetty.

4.5 Severe Shoreline Erosion North of the Project Area.

The shoreline continues to retreat rapidly north of the project area from high waves and tidal surges during winter storms (Figure 13). This erosion is particularly damaging to the community of North Cove, where several homes were most recently lost during storms in December 2014.

4.6 Sea Level Rise

Direct and indirect effects of changes in sea level must be considered in any long-range coastal planning project. This is especially true in an area like North Cove, where there is a lot of low-lying terrain. Portions of SR105 on the North Cove are currently below the extreme high tide.

The Washington Department of Ecology predicts the range of sea level rise on the coast of +6.5 inches, with a potential range of between -1 and +19 inches by 2050 (WDOE website 2014). This includes estimates of the offsetting effect of tectonic uplift in the area.

In addition, climate change may be contributing to increasing frequency of El Nino events. These events spawn major storms. Storm surges and waves have both been higher in the last 25 years of record than ever before (Allan and Komar 2000; Coast Geologic Services, 2005). El Nino events result in temporary sea level rise. Evidence has been found of repeated increases in monthly sea level on the order of 0.7 to 1.0 feet for several months during El Niño events (Corps of Engineers, 2009c).

One of the strongest El Nino events on record (1997-1998) increased monthly mean water levels 0.4 meters (1.25 feet) higher than typical, monthly mean winter wave heights were up to 1.0 meter (3.25 feet) higher than usual, and wave directions had a more southwest approach (Kaminsky et al. 1998, Komar et al. 2000, Sallenger et. al, 2002).

Any future projects along the coast should plan for the high end of the range of sea level rise, +19 inches, and the more frequent El Nino storm surges, of 3.3 feet. Design should use mean lower low water plus an additional 4.9 feet as a vertical datum.

5.0 Treatment Options

5.1 Option 1 – Armor and Elevate SR 105 to Maintain the Current Alignment

Description: This option assumes the highway remains on the current alignment, and no offshore structures or other measures will be constructed to reduce the increasingly severe wave climate. The highway would be maintained in this alignment through a combination of shoreline armoring and road elevation projects that are implemented over time in response to erosion and inundation problems.

Figure 38 shows a likely combination of treatments that would be needed for different highway segments. Most of the shoreline immediately north and south of the jetty (MP 20.0 to MP 20.8) has no remaining shoreline buffer and is already exposed to a severe wave climate. The elevation of the road is generally sufficient to limit inundation, but the shore embankment has experienced severe erosion and has been armored with rock and log toes through a series of emergency maintenance projects. A project is currently being designed to protect the last unarmored portion near the mouth of Seastrand Creek. Future actions will therefore likely focus on repairs to maintain the existing armor.

Segments along the North Cove embayment (MP 18.7 to MP 20.0) are less exposed but will experience an increasingly severe wave climate as offshore dunes erode. The road embankment is only partially armored and the road lies well below projected coastal flood elevations. The road will therefore eventually need to be either elevated (Option 1A) or protected with a shoreline berm (Option 1B).

North Cove Option 1A: Elevate SR 105 above flood level and armor the most vulnerable shorelines. SR 105 would be raised an average of about 4.5 feet along the North Cove embayment to an elevation of 20.2 feet NAVD. This is the design elevation used by the COE for their revetment alternative, and includes flooding by tides, storm surges, and wave runup during severe storm such as the record March 3, 1999 event. Figure 39 shows typical highway cross sections, assuming a total roadway width of 36 feet and 3:1 side slopes to accommodate stormwater treatment. WSDOT should consider increasing the road elevation to 21.8 feet NAVD to account for projected sea level rise of 19 inches in the next 50 years (as described in Section 4.5).

Shoreline armor will also be needed on some segments of the new embankment, particularly where there is only a narrow and steep existing shoreline buffer. The armor would be configured similar to shoreline protection projects used near the jetty, with a slope of about 1.5:1 to minimize wetland impacts. The shoreline in other segments currently has a substantial vegetated buffer that may not immediately need armor. Shoreline armor could be buried proactively along these segments to anticipate future erosion, but this would disturb a substantial portion of the existing vegetated buffer.

North Cove Option 1B: Protect SR 105 with an armored berm. This option is similar to the COE's revetment alternative, and we have used design parameters developed by the COE to describe potential impacts. A berm of armor stone would be constructed parallel to SR 105 along the entire North Cove shoreline with a top elevation of 20.2 feet NAVD. WSDOT should consider raising the berm elevation to 21.8 feet NAVD to account for projected sea level rise of 19 inches in the next 50 years (as described in Section 4.5).

Figure 40 shows a typical berm cross section. The berm would begin at least eight feet from the edge of the shoulder to provide room for stormwater treatment, and would have an 8-foot top width and 1.5:1 side slopes. In segments that are most vulnerable to erosion the armored shore face of the berm would extend down to a buried toe at +6.2 feet NAVD, and would land on the North Cove marsh surface. In segments with a wide vegetated buffer the berm could initially be constructed without additional shoreline armor at the toe, but armor may need to be added in the future as the buffer is eroded by wave action. Proactively armoring the toe of the berm would anticipate future erosion but would disturb a large portion of the existing vegetated buffer. Culverts with tide gates would be needed at various locations on the berm for stormwater drainage.

Benefits: Options 1A and 1B maintain highway access for all properties in the existing corridor, and would require minimal acquisition of new right-of-way. Environmental impacts would be limited to resources and areas that line the existing highway corridor.

Shoreline and Wetland Impacts: Protecting the highway from inundation and shoreline erosion will result in substantial permanent impacts to shoreline and wetland habitats along about 6950 feet of the North Cove embayment. Option 1A (Elevate SR 105) would have a new fill footprint beyond the existing highway of about 2.3 acres on the landward side of the highway and 3.2 acres on the bayward side. Most of this fill would be above MHHW, but freshwater and transitional estuarine wetlands are common on both the shoreline embankment above the log wrack line and in low areas fed by hillslope seepage on the inland side of SR 105 (U.S. Army COE, 2009a). Option 1B (Armored Berm) would only impact wetlands on the bayward side of the highway, with a total new fill footprint of about 5.6 acres.

New shoreline armor will likely be needed along 1200 linear feet of shoreline in the North Cove where there is insufficient vegetative buffer to protect the embankment from waves. This will eliminate the shoreline vegetation on these embankments, and will likely involve excavation and fill below MHHW. The remaining 5750 linear feet of North Cove shoreline could be proactively armored with a buried revetment that would involve temporary impacts to wetlands and shoreline vegetation. These segments have a substantial existing vegetated buffer, so an alternative strategy would be to leave this buffer undisturbed and only armor as needed when erosion threatens the highway. The extent of shoreline impacts will generally be greater for Option 1B (Shoreline Berm) because this alternative extends further out into the North Cove embayment.

Existing and new shoreline armor will require continuous maintenance, especially as the wave climate becomes more severe in response to entrance channel widening, jetty degradation, and loss of beach/vegetative buffer. The U.S. Army COE (2009a) estimates that about 25% of shoreline armor stone in the North Cove would need to be replaced every 25 years. These repairs will typically involve work below MHHW and may require mitigation for aquatic habitat impacts.

Elevating the highway or constructing the berm will likely require substantial detours and interruptions to traffic flow. Traffic interruptions are also likely during large storms that damage armor or inundate the highway.

Risks: The behavior of the entrance channel and waves in this area are poorly understood, adding considerable uncertainty to the design and expected performance of shoreline protection structures. Key risks include:

- Northward migration of the entrance channel: If the entrance channel migrates more rapidly than expected it could undermine the footings of shoreline armor to the point where WSDOT is unable to stabilize the embankment.
- Sea level rise and climate change: The frequency and severity of major storms has increased in recent years, and projections of rates of climate change vary considerably. There is substantial risk that sea level rise and storm severity could increase more rapidly than anticipated, overtopping berms or elevated highway segments and undermining shoreline armor to a point where the highway alignment becomes unsustainable.
- Loss of the Shoalwater protective dune: The artificial dune constructed by the COE protects the eastern end of the threatened highway segment, but has already experienced significant erosion in its first year after construction in 2013.
- Continued shoreline retreat north of the project area: This could flank the project area and significantly extend the threatened segment of highway, particularly near the community of North Cove.

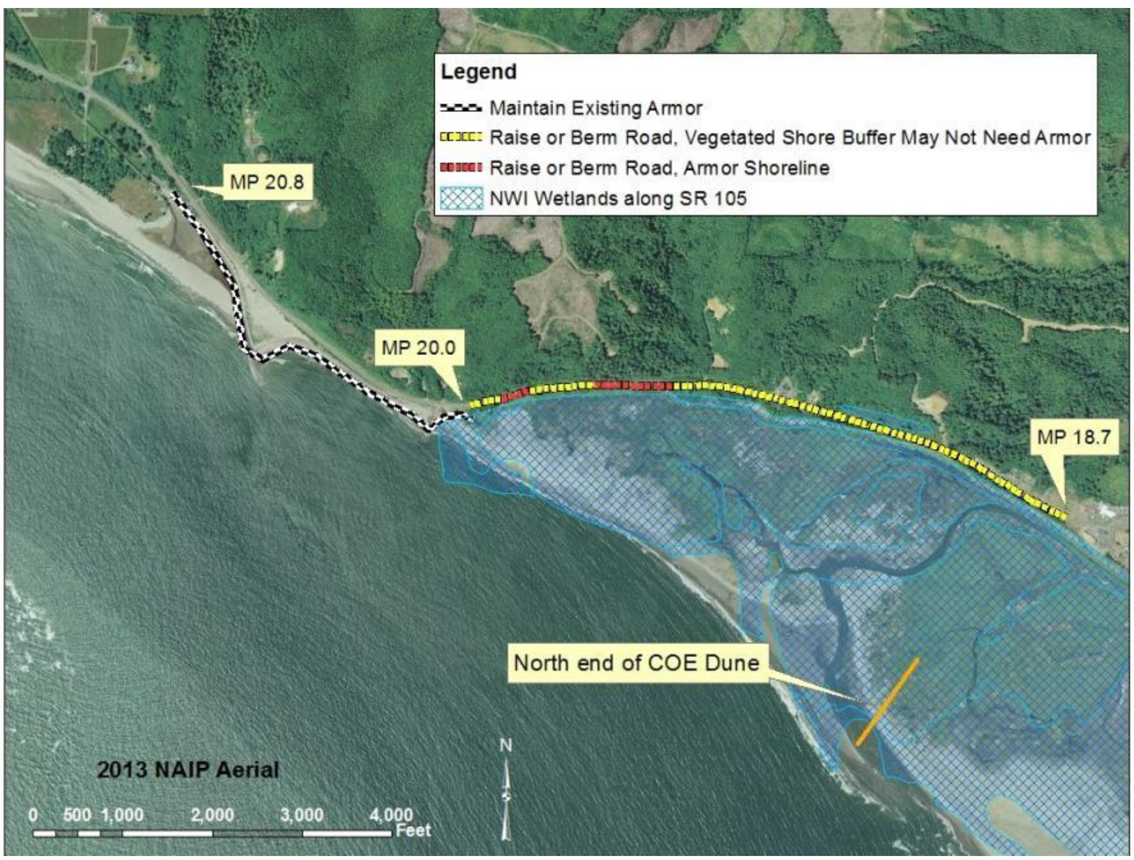
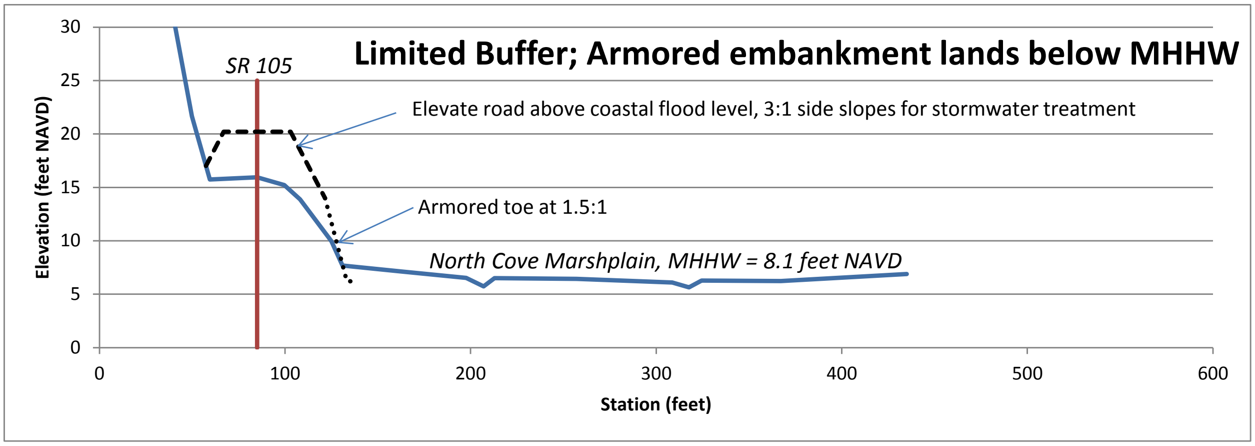


Figure 38. Shoreline treatments for maintaining existing alignment (Option 1).



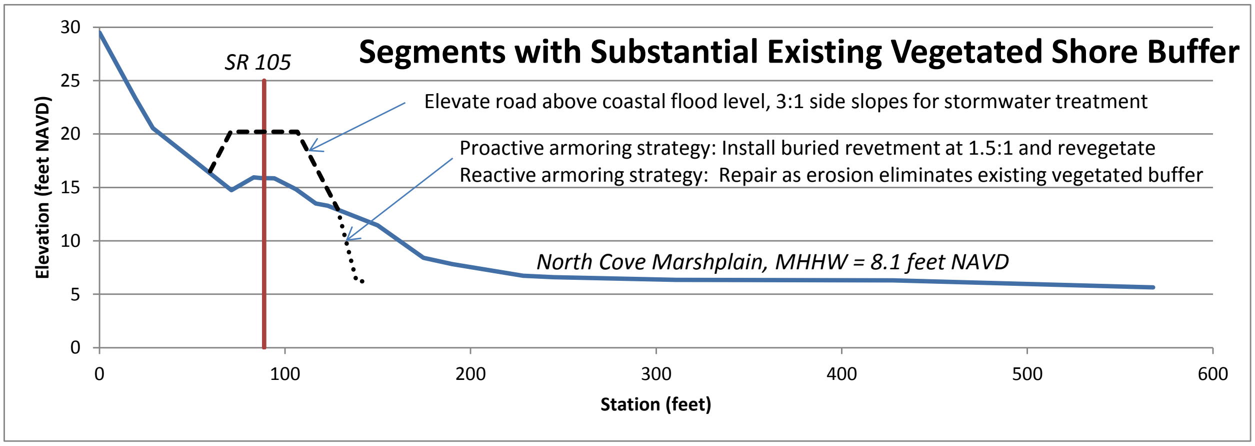
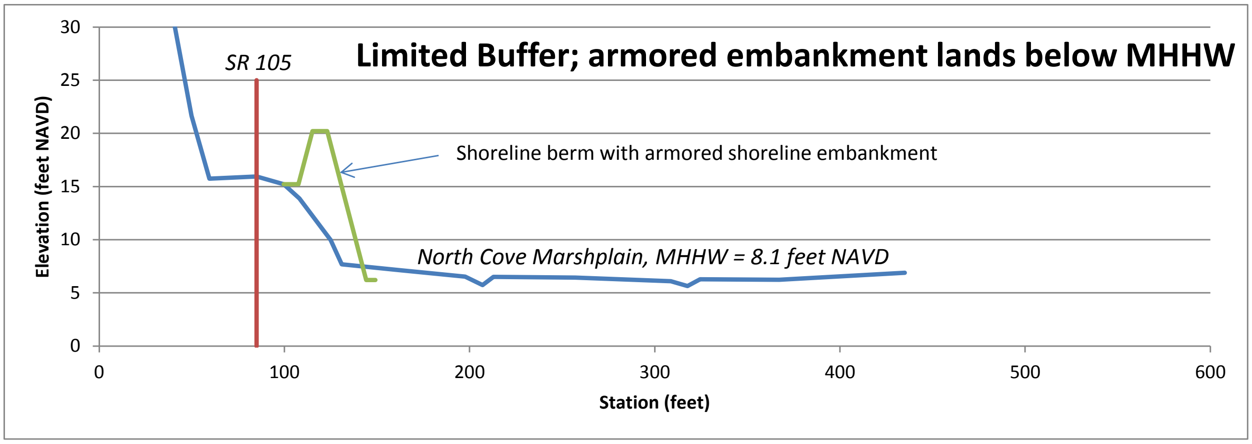


Figure 39. Typical sections for Option 1A (Elevate SR 105).



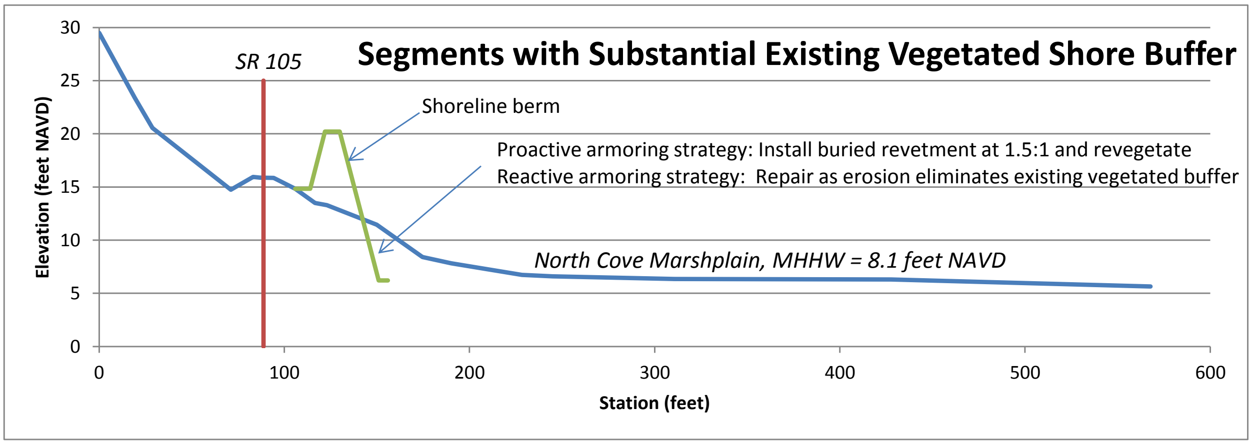


Figure 40. Typical sections for Option 1B (Shoreline berm).

5.2 Option 2 - Groins

This option would involve adding more groins along the highway to deflect wave energy and retain beach sands. The use of groins has been considered previously at this site (WSDOT 1997) and at the Empire Spit by the Corps of Engineers (2009).

The alternative considered at SR105 consisted of groins along the shore with articulated concrete mats at the toe, to protect them from erosion from the main entrance channel (Figure 41). A typical cross-section from the environmental assessment is shown in Figure 42.

Since the groin option was considered, the location of the shore has changed considerably. The groin option was rejected due to the prediction of inability to control erosion of the main entrance channel. However, the wave erosion occurring along Washaway beach and the Empire Spit is not dependent on further eastward migration of the entrance channel. The Corps of Engineers rejected various groin options due to a relatively high environmental impact.

The primary way that groins could be used to protect the highway along North Cove/Washaway Beach would be to retain the sediment and road embankment currently in place. A possible configuration is shown in Figure 43. Beach nourishment would be needed in the space between the three groins on the northwest side, as the shoreline has eroded already.

Design of groin length and spacing would be based on wave direction and shoreline orientation, as well as wave height and runup. Geometry of the groins would be similar to that shown in Figure 42, although these would not need to be as long as those proposed in the EA, since they would not be attempting to deflect the entrance channel's migration.

The locations of any additional groins would need to be modeled to achieve the most effective combination of shear stress reduction (by deflecting current) and least environmental impact. The groins described in the 1997 environmental assessment had an aerial impact of 28 acres of subtidal area, and 2 acres of intertidal habitat. The groins shown in Figure 43 would directly impact 8.6 acres. Beach nourishment and indirect and temporary impacts could total an additional 15 acres. Note however that this option would not address the potential flooding of the lower elevation portions of SR105, but would redirect flow away from the highway embankment. East of the existing groin, the new groins would be installed in anticipation of continued shoreline retreat into North Cove.

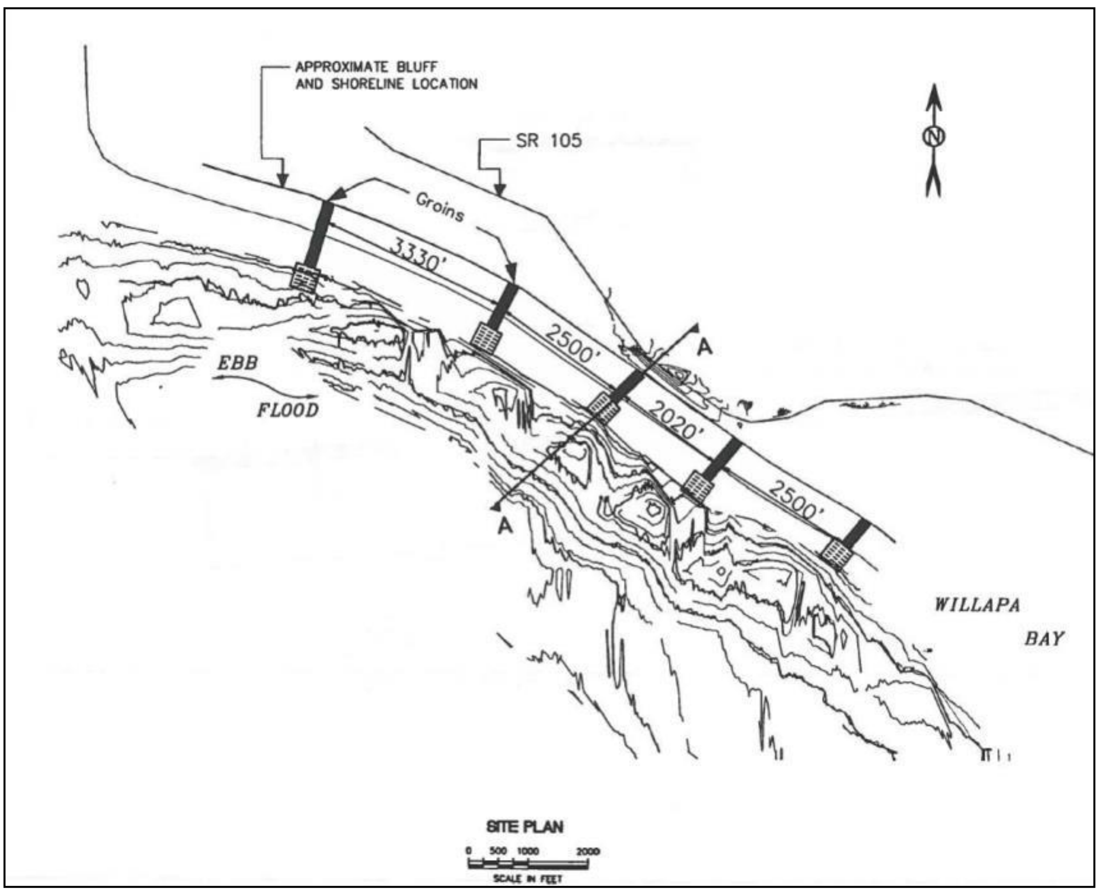


Figure 41. Site plan from 1997 environmental assessment, Alternative 6 (WSDOT, 1997).

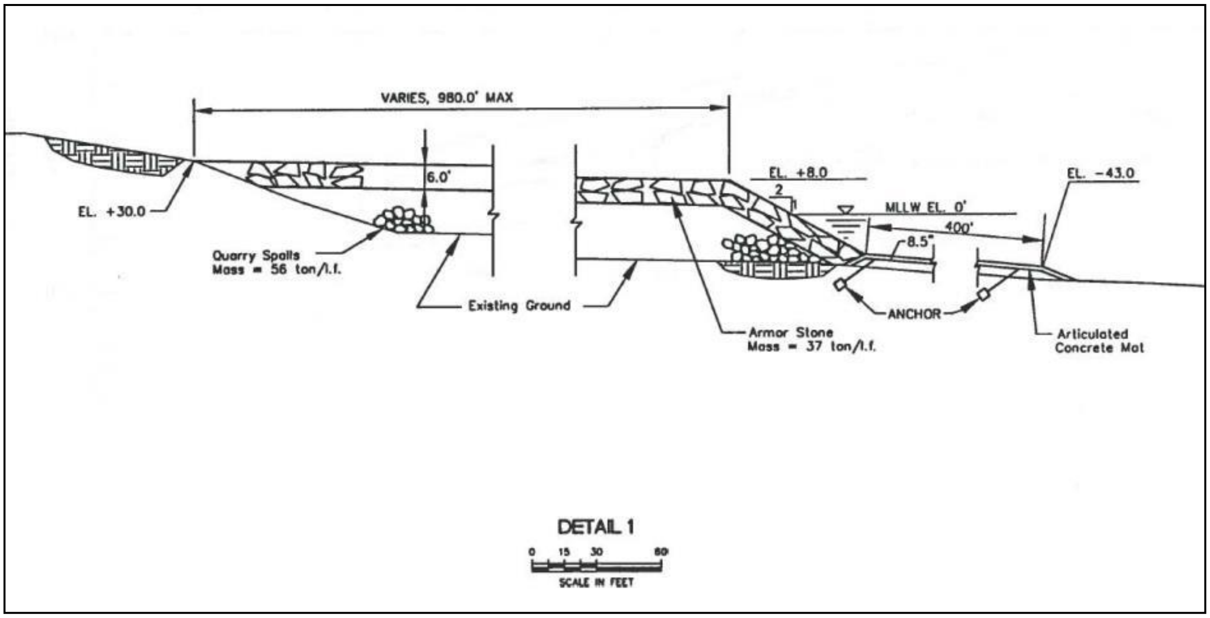


Figure 42. Cross-section, Alternative 6, from 1997 environmental assessment (WSDOT, 1997).

Figure 43. Possible groin configuration for SR105 at North Cove/Washaway Beach.

5.3 Option 3 - Beach Nourishment

"Beach nourishment" is an alternative considered due to its relatively low impact nature. In practice, beach nourishment encompasses a variety of applications with various objectives. In Washington state, beach nourishment has been conducted on gravel beaches, at a much smaller scale than on the east coast or Gulf coast of the U.S. The main purpose has been for property protection in an environmentally acceptable or beneficial manner. Bibliographies on beach nourishment in Puget Sound have been compiled by Terich and others (1994) and Shipman (2002). These mostly describe the coarser, gravel nourishment in coastal settings much more quiescent than at Cape Shoalwater.

Along the eastern seaboard, nourishment is conducted by pumping sand from off the coast directly onto the shore, and reshaping. This is done for both beach preservation and recreation. Along the Gulf Coast, beach nourishment using sand is used to maintain artificial beaches. (see Trembanis and Pilkey, 1999). As a result of these efforts, there is a considerable body of research done to date on beach nourishment in sandy, high energy coastal environments – more like along SR105.

A summary of beach nourishment guidelines and methodology was developed as part of an assessment of the SR105 emergency stabilization project (Coast Geologic Services, 2006). The summary highlights parameters that should be considered when planning a beach nourishment project: sediment compatibility, background erosion; wave climate; site geometry; volume density; location of placement on beach profile; and the presence and/or use of engineered beach structures.

Sediment for any potential beach nourishment along SR105 would be derived locally, and thus match the existing sediment distribution. Local sources were used in both the SR105 Emergency Stabilization Project, and in the dune restoration project on Empire Spit.

Background erosion rates must be understood to plan for the design and maintenance of a potential beach nourishment project. In the case of Washaway Beach, since nourishment would entail seaward placement of material, in would be advisable to assume a rate of erosion higher than the background rate (Verhagen 1996). The erosion rate at the project site has been estimated at 115 feet per year, averaged over the 1870-1970 (Corps of Engineers, 2009a). The erosion rate since 1980 has been much slower. It would be prudent to plan on the higher long term average erosion rate when planning beach nourishment.

Wave climate has been discussion section 2.5. The wave heights for planning purposes would be 20 feet NAVD88.

Site geometry for the SR105 includes the area behind North Cove, from MP to 20.5. At the seaward edge of the Empire Spit, conditions are dynamic and unstable – this is well-demonstrated but also consistent with the literature (Pompe and Rinehart, 2000). The potential platform for dune restoration/beach nourishment at this site is limited. There is about 500 feet of beach platform that slopes at average of 1.8%.

Density of nourishment (mass per unit volume) should be as high as possible at the project site, given the intense wave climate, erosion history, and dynamic location.

Nourishment can occur over the entire beach profile from the backshore area down to the depth of closure (as deep as –20 m NGVD), to just over a small portion of the beach profile. The term "equilibrium profile" refers to the generally accepted understanding that a beach, with an unchanged sediment size, will have a dynamically stable beach profile. Sand nourishment projects that only nourish the dune area or the upper foreshore tend to experience relatively rapid erosion following placement (Bruun 1988). Many smaller sand nourishment projects have occurred on just the subaerial (upper) portion of the profile, such that they should be expected to lose substantial volumes from the upper beach to the lower foreshore and subaqueous portions of the profile, and potentially alongshore (Bruun 1988; Finkl and Walker 2005). This has been the case with the 1998 beach nourishment at MP 20.5.

When considering beach nourishment as a form of protection for the highway corridor, two examples are readily applicable – the beach nourishment undertaken as part of the emergency stabilization in 1998, and the dune restoration conducted nearby in 2009, both of which have been described in previous sections. They each represent very different types of beach nourishment.

At the dune restoration site, the modeled velocity of the Willapa channel reaches a maximum of 8 feet per second during the 100-year storm. At the SR105 site, it reaches 7 feet per second just offshore (WSDOT 1997; USACE, 2009). Close to shore, peak ebb tide velocity is 4.3 feet per second.

The intense La Nina winter of 1998-99 had 17-22 major windstorms and substantially elevated sea level (Allan and Komar 2002). Seven El Nino events have occurred over the 20 years leading up to the 1997-98 event. Therefore El Nino and La Nina winters should be expected to occur with a frequency on the order of every 3-5 years with varying intensity such that any renourishment sediment placed at the site in the future may or may not be subjected to these highly erosive winter seasons soon after placement. In addition, climatologists and oceanographers project an increased frequency of El Nino events due to climate change.

It must be noted that any determination must be prefaced with the fact that the study area experiences highly variable winter storm intensity. This is caused by the El Nino-La Nina cycle, which has varied both in frequency and intensity in the past, and will undoubtedly continue to do in the future. In recent decades it has been shown that the storm intensity has increased in the North Pacific adjacent to the Pacific Northwest (Allan and Komar 2002). As outlined above, deepwater wave heights have increased on the order of 3.25 feet, and intensity of El Nino winds and waves also appears to have increased. This leads to heightened variability in project performance and makes the nourishment sediment vulnerable to erosion (Dean 2002). In general, it appears that relatively frequent renourishment would be required to maintain toe protection along the eastern half of the threatened road revetment. Renourishment would be needed on a 2-4 year cycle to maintain adequate toe protection of the complete length of the revetment. The PIE Design Memo stated that renourishment requirements were expected to be every 6 years, which appears optimistic.

The first renourishment could occur at very low cost by moving sand from the high elevation backshore (that extends up to +25 feet MLLW) to the active beach system. There is a very large volume of sand well above the elevation of the active beach immediately east of the groin that could be bulldozed down to the active beach. This volume could be determined by topographic surveying for planning purposes. For rough planning purposes, a rough estimate of 70,000-100,000 cubic yards of "available" sediment was made using the GIS work and examination of monitoring profiles.

Option 3b - Renourishment With New Down-Drift Groin – The addition of a large rock groin at the down-drift (east) end of the threatened road revetment would prolong residence of renourishment sediment. A new shore-normal structure would act to trap eastward transport of nourishment sand and maintain better toe protection at the revetment. However, a large groin would likely exacerbate flanking erosion some distance to the east, along the beginning of the large spit complex that protects the (very large) saltmarsh complex. In addition the base of barrier spits is often the most subject to erosion and breaching, and thus would be a potential danger.

A second groin was briefly considered by PIE (1997b) but its exact location was not explained. It appeared that the groin would angle offshore similar to the existing groin such that it would not be as effective in holding sediment on the up-drift side. It would likely be more effective in acting as a wave attenuator relative to a shore-normal structure. A large groin in this environment would be quite expensive and would cause the additional loss of intertidal habitat.

5.4 Option 4 – Highway Relocation

5.4.1 Description

This section relies heavily on the relocation alternative developed in the Revised Environmental Assessment SR 105 Emergency Stabilization Project, North Cove, Washington prepared by the Federal Highways administration and WSDOT dated 7/25/97. This option would involve the northward realignment of SR 105 from its present location to a route along the North Fork of the Cedar River (Figure 44). The new route would parallel the Cedar River for approximately 5 miles, climb out of the drainage, and then traverse the tops of the ridges east of the community of Grayland before merging with the existing SR 105 north of Grayland. This option would require the acquisition of a new right-of-way and construction of approximately 9 miles of new roadway.

The proposed alignment of the new highway was chosen to protect the highway from future erosion impacts and to avoid impacts to cranberry bogs. WSDOT held a public meeting in 1995 to present the potential proposal of relocating the highway, and at that meeting the public stated their desire that the highway relocation should be considered only as a last resort. In addition, the option of relocating the highway through tunnels in the hillside adjacent to the north of the existing highway was looked at and rejected because it would require constructing two one-lane tunnels and would be prohibitively expensive.

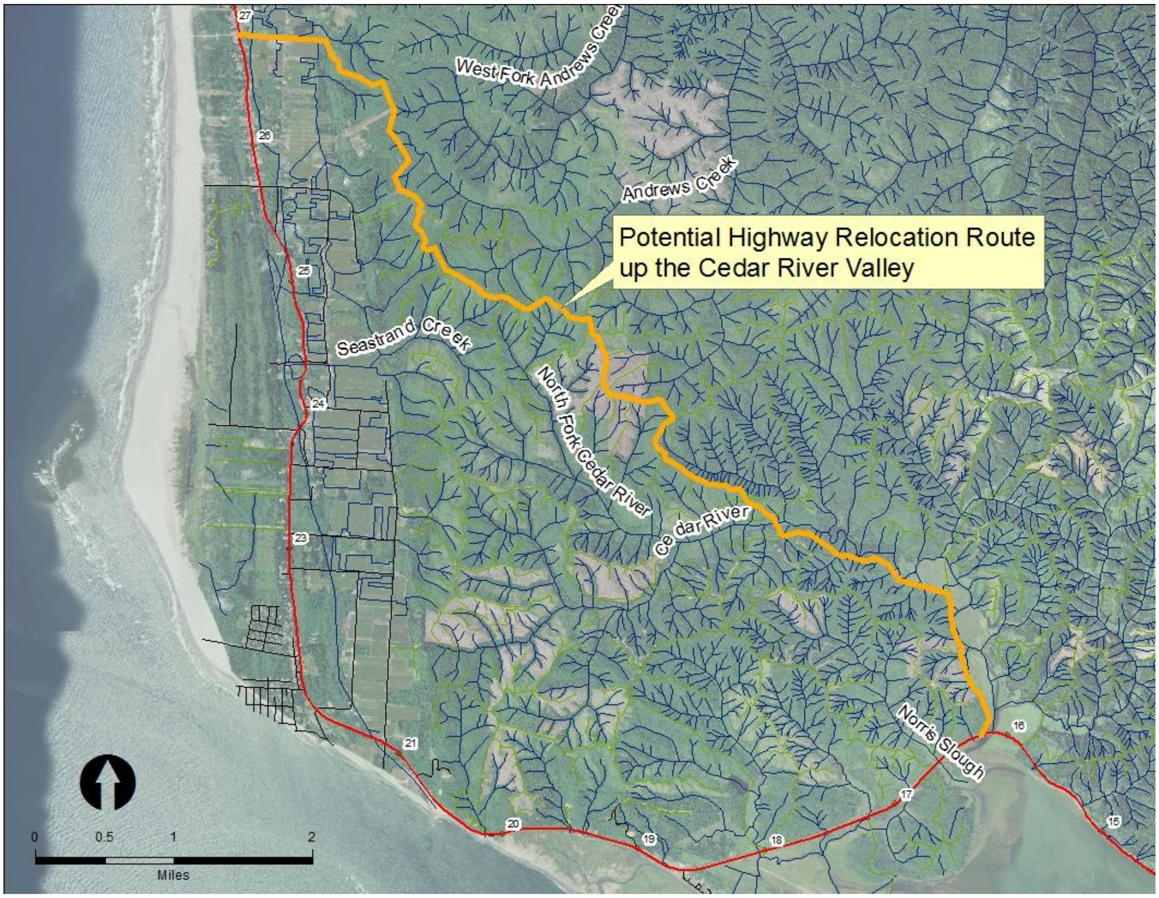


Figure 44. Potential Realignment Routes

5.4.2 Potential Impacts

Relocation of the highway would result in impacts to transportation which could translate into adverse impacts to socioeconomics. Secondary impacts to land use would include elimination of use of land for cranberry production. In addition, this option has the potential to adversely affect water quality, fish resources, wildlife and botanical resources. There would be substantial impacts to wetlands which would require mitigation.

Potential Transportation Impacts: The communities of Tokeland, North Cove, and The Shoalwater Indian Reservation would be bypassed by the new route. It is estimated that the relocated highway would add approximately 20 minutes to the trip from Tokeland to Aberdeen, Westport, Grayland and North Cove. The trip from Tokeland to North Cove would double in time required.

It is estimated, however, that a period of eight years could elapse between the closure of SR 105 and the completion of the new highway.

Potential Socioeconomic Impacts: Relocating the highway will have socioeconomic impacts associated with the increase in driving time. An average of 20 extra minutes of driving time will be added to the trip from Tokeland to Aberdeen, Westport, Grayland and North Cove. It is assumed that at least one-third of the 1500 average daily trips which

SR 105 experiences are trips from Tokeland to Aberdeen, Westport, Grayland or North Cove.

Impacts to the cranberry industry would not be prevented under this option. In addition, the towns of Tokeland, North Cove, and the Shoalwater Indian Reservation would be off the main route between Raymond and Aberdeen as a result of this option, possibly resulting in an adverse impact to the amount of tourist business experienced in these communities.

Potential Land Use Impacts: Construction of approximately nine miles of new roadway would require the acquisition of between 105 and 118 acres of new right-of-way. This land is currently undeveloped land in a natural setting. If this option is implemented the natural erosive processes will continue to cause changes in land use along the existing SR 105 alignment. Residential and recreational property would continue to be washed away, and the cranberry bogs located north of the highway would not be able to be used for cranberry farming due to saltwater inundation.

Current use of the properties for recreation in the project area and south to Tokeland may also be affected if this option is implemented. Additionally. there is the potential that erosion of the landfill located behind the highway could result in significant leaching of pollutants into the Bay, potentially affecting fish and wildlife, thereby affecting use of the area for recreational and commercial fishing.

Potential Water Quality Impacts: The proposed route would likely involve four main stream crossings requiring construction of four bridges. Two of these would be located on tributaries of the Cedar River, and two would cross the main stem of the Cedar River. Additional stream crossings over small streams would require the placement of culverts. Impacts associated with the construction of stream crossings would include temporary increases in turbidity, alteration of streambed substrates if rip rap is used for scour protection, and the permanent loss of vegetation and aquatic habitat at bridge pier and culvert locations.

There would be temporary increases in transport of sediment to the stream during highway construction. These short-term increases would diminish over time as vegetation establishes and stabilizes soils on cut and fill slopes. Over the long term, water quality may be affected as runoff from the roadway could introduce grease, oil, sediment, and other contaminants into the stream. The addition of new impervious surface may affect both the quantity and quality of runoff to the lower volume streams within the project area In order to minimize these impacts, best management practices (retention ponds, water quality treatment BMPs, erosion an sediment control requirements pursuant to WSDOT's Highway Runoff Manual) would be implemented.

Potential Fish and Wildlife Impacts: Approximately 105 acres of riparian, wetland, and upland habitat would be directly lost as a result of highway construction. The removal of riparian vegetation would result in temporary (1 to 10 years) increases in stream temperatures until woody vegetation is reestablished along the streambanks. Sections of the roadway that closely parallel the stream would involve the permanent loss of riparian vegetation, which could result in long term (> 10 years) increases in stream temperatures. There would be a long term (40 - 60 years) decline in potential woody debris recruitment before young stands of trees would be mature enough to contribute substantial amounts of woody material to the stream (Grette 1985).

Table 2 presents an estimate of the number of acres of 'riparian, wetland, and forested habitat that would be directly disturbed by construction of the highway along the Cedar River route. The total area of disturbance would depend on the width of the right-of-way, which would likely be 96 to 108 feet. These estimates were made by overlaying the route shown on Exhibit 14 on National Wetland Inventory (NWI) and topographic maps.

The suitability of habitat for wildlife would be reduced in areas adjacent to the highway. A decline in habitat value would occur as a result of noise and human presence, both during and after Habitat use by big game may decline up to 0.5 mile from roads (Perry and Overly 1977). Encounters between vehicles and animals would result in wildlife mortalities.

Table 2. Acreage of riparian, wetland, and upland habitat directly affected by road construction.

Right-of-way width, feet	Riparian habitat, acres	Wetland habitat, acres	Upland
96	29.1	17.5	46.5
108	32.7	19.6	52.4

Up to 20 acres of wetlands could be directly affected by highway construction. Of this, approximately two acres of saltmarsh habitat and 18 acres of freshwater wetland habitat would be affected. In addition, wetland functions, including wildlife habitat and hydrologic support, would be affected in areas adjacent to the highway. Mitigation for direct fill impacts and loss of wetland functions would be required as a condition of local, state, and federal construction permits. Mitigation ratios are likely to be high because of the high quality of affected wetlands.

5.5 Option 5 - Dynamic Revetment

A recent development in shoreline protection is the advent of cobble berms, also called "dynamic revetments." The goal of these structures is to protect infrastructure in a way that is more natural looking. The strategy is to mimic naturally occurring cobble beaches (Komar and Allen, 2010). The cobble berm protects the vulnerable shore from erosion from wave run-up. This technique has been used in Oregon in three locations, starting in 2005, with the most recent having just been completed in 2013 (Allan and other, 2004; Boehlert, 2012; U.S. Army Corps of Engineers, 2013b).

The cobble berm must have sufficient width, and thus pore space, to absorb wave run-up (U.S. Army Corps of Engineers, 2013b). As the berm is deformed by waves, the cross-section equilibrates, until a configuration stabilizes. The gradation of cobble can vary, depending on exposure to wave action. Cobble gradation may also vary along the cross-shore aspect of the berm, with smaller material being located along the lower part of the berm cross-section and larger material being located along the upper slope area and on the berm crest. Gradation range for cobble material generally would be within a range of

1-inch to 8-inches. The cross-section of the dynamic revetment is expected to deform from the initial, as-built, shape.

The advantages of a dynamic revetment include lower cost, simpler construction, accommodation of shore-face recession, and reduction in adverse impacts to shoreline. Nearby examples can be examined to understand the components of a dynamic revetment (Figures 45 and 46). The dynamic revetment planned for the South Jetty foredune protection (U.S. Army Corps of Engineers, 2013b) features a 1:5 slope with a 4-foot thick top layer of coarse cobble, resting on a "core" cobble layer (Figure 46). The top width of the revetment is planned to be 65 feet, though the equilibrium profile will be much narrower on top. The fill volume for a 1,100 foot long revetment was estimated to be 43,000 cubic yards. The expected minimum project life was 30 years, with maintenance at 10-15 year intervals and 10-25% cobble replacement.

An analogous area in Washington, useful for use as a reference reach is Kalaloch Beach, north of Grays Harbor. A series of beach profiles was surveyed to help inform the design of potential dynamic revetment in the Washaway Beach area. The survey results are presented in Appendix A. The typical slope of the cobble berm is about 19%. The height of the cobble berm is about 15 feet. The crest of the cobble berms averaged about 25 feet above mean lower low water.

For the section of SR105 between milepost 18.8 to 20.4, there are three general options for dynamic revetment, depending on where and how much is treated. One option is to protect the entire section of highway subject to flooding and future erosion, approximately 8,300 feet. This would require a volume of approximately 325,000 cubic yards of material. The initial cross-section of the dynamic revetment would be somewhat like that shown in the example in Figure 46. Although the sites vary somewhat, the wave climate is similar between the South Jetty and Cape Shoalwater. Instead of the foredune, the highway embankment would serve as the anchor for the cobble berm. The footprint of this potential project is shown in Figure 47. This option could protect against flooding to storm waves as well as due to extreme tides. We would expect a project life of 30 years, with some maintenance – addition of cobbles – every 10-15 years.

Alternatively, the dynamic revetment could be built along the existing shoreline, preventing further retreat of the coastline. In this case, the cobble berm would need a "root", since the existing shore has very little vertical relief and has eroded recently. The combination of dynamic revetment and artificial dune could be built in this case. This was used in the Cape Lookout project (Komar and Allan, 2010). The cross-section is shown in Figure 48. The artificial dune was constructed with a core of sand filled geotextile bags, each about 1 cubic meter. The core was then covered with loose sand and shaped to grade, with a dune crest at 7-9 m elevation (NAVD898). The footprint of this potential project is also shown in Figure 46. We would expect a project life of 30 years, with some maintenance – addition of cobbles and sand – every 10-15 years.

As a smaller project, a dynamic revetment could be constructed that protects the highway from near term erosion, but not long term erosion or flooding. This option would have the cobble berm extend from the eastern end of the beach nourishment area (remaining), to the old highway pullout, about 1800 feet long. This option is shown in Figure 47. The advantage of this option would be a cost savings and less wetland and nearshore habitat impact. We would expect a project life of 30 years, with some maintenance – addition of cobbles – every 10-15 years. This option would not protect the lower areas of the highway from occasional flooding during extreme high tide events. However, based on the performance, the dynamic revetment could be extended farther southeast along the highway.

Figure 45. Cobble berm (dynamic revetment) with artificial dune, Cape Lookout State Park, Oregon (2009).

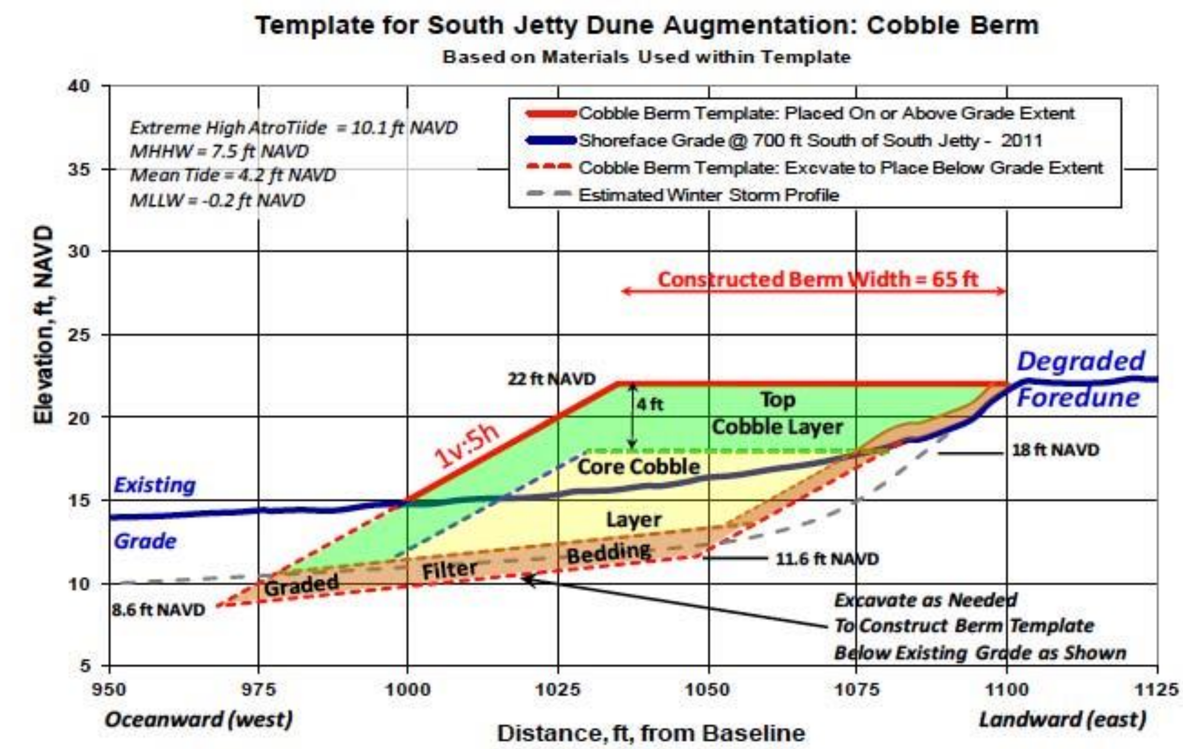


Figure 7: Cross-section for dynamic revetment featuring a 65 ft wide cobble berm.

Figure 46. Cross-section from the South Jetty foredune augmentation project (Corps of Engineers, 2009).

Figure 47. Options for highway protection incorporating dynamic revetments.

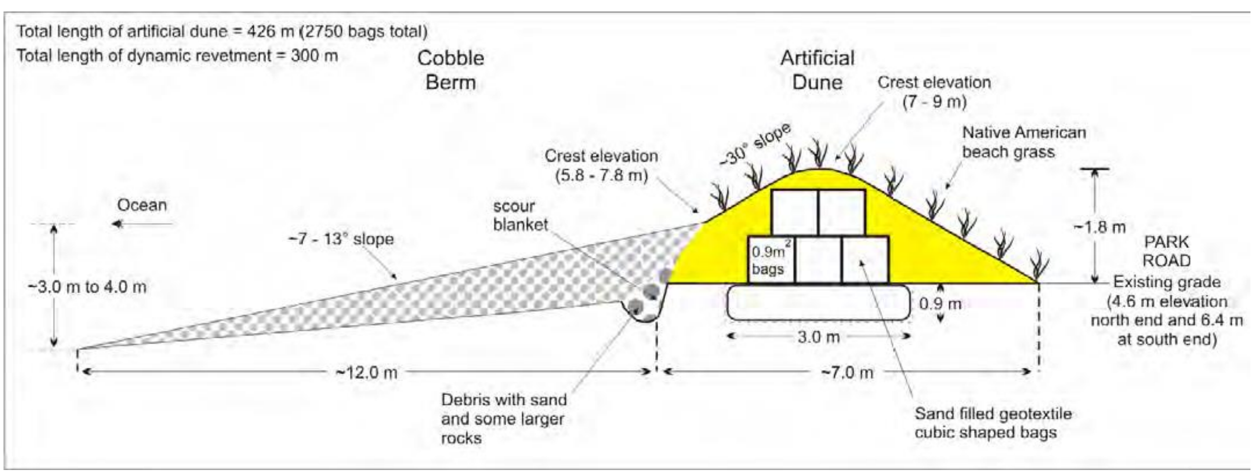


Figure 48. Cross-section diagram of cobble berm and artificial dune (Komar and Allan, 2009).

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Appendix A: Natural cobble berm study

We wanted to find a reference site for dynamic revetments in Washington State, to better characterize this potential alternative. In Olympic National Park's coastal section lies Kalaloch Beach, a long, mostly undisturbed section of beach, with extensive cobble berms. The aerial photographs of this area show no measurable bluff retreat during the last six years (since 2009, the oldest aerial photograph layer readily available on the WSDOT GIS). We chose two sites to survey, one at "Beach 1" and the other at South Beach Campground (Figure A1).

We surveyed the Beach 1 site using a total station. We noted the time when we surveyed the elevation of the water, and later tied that into the tide elevation using tide data from La Push. Heavy rain precluded the use of the total station at South Beach, and we used the tape and clinometer method instead. This survey could not be tied into absolute elevation, but was useful for general berm geometry.

The results of surveying at Beach 1 are shown in Figure A2. There was a distinct slope break on each profile that coincided with a significant change in substrate size, from gravel to sand. The average berm face slope was 18%, and the material was cobble and coarse gravel. Below this, the substrate was sand, and the average slope was 3%. The crest of the cobble berm was about 25 feet above mean lower low water (MLLW). The height of the berm relative to the break in slope/substrate change was about 15 feet, while the total distance between the backside of the berm and the slope break was about 100 feet.

At South Beach, only 2 profiles were surveyed. The profiles are not tied to a vertical datum. Similar to Beach 1, the profiles here showed a distinct slope break that coincided with the change in substrate from coarse to finer. The average cobble/gravel slope was 21%, while the average sand slope, at the base of the profile, was 7%. Overall this indicates a somewhat steeper profile than at Beach 1. We don't view the profiles taken at South Beach to be as reliable as those at Beach 1, owing to the survey method.

In conclusion, the beach profiles at Beach 1 and South Beach can be used to develop conceptual geometry of a dynamic revetment in an environment with similar wave energy. These profiles represent a dynamic equilibrium slope. They suggest that a dynamic revetment with similar orientation should reach an equilibrium profile with a crest that is 25 feet above MLLW. A cobble berm with a minimum height of 15 feet and width of at least 50 feet should be sufficient to provide a base for reaching an equilibrium profile.

Figure A1. Reference site locations.

Photo points shown in green dots.

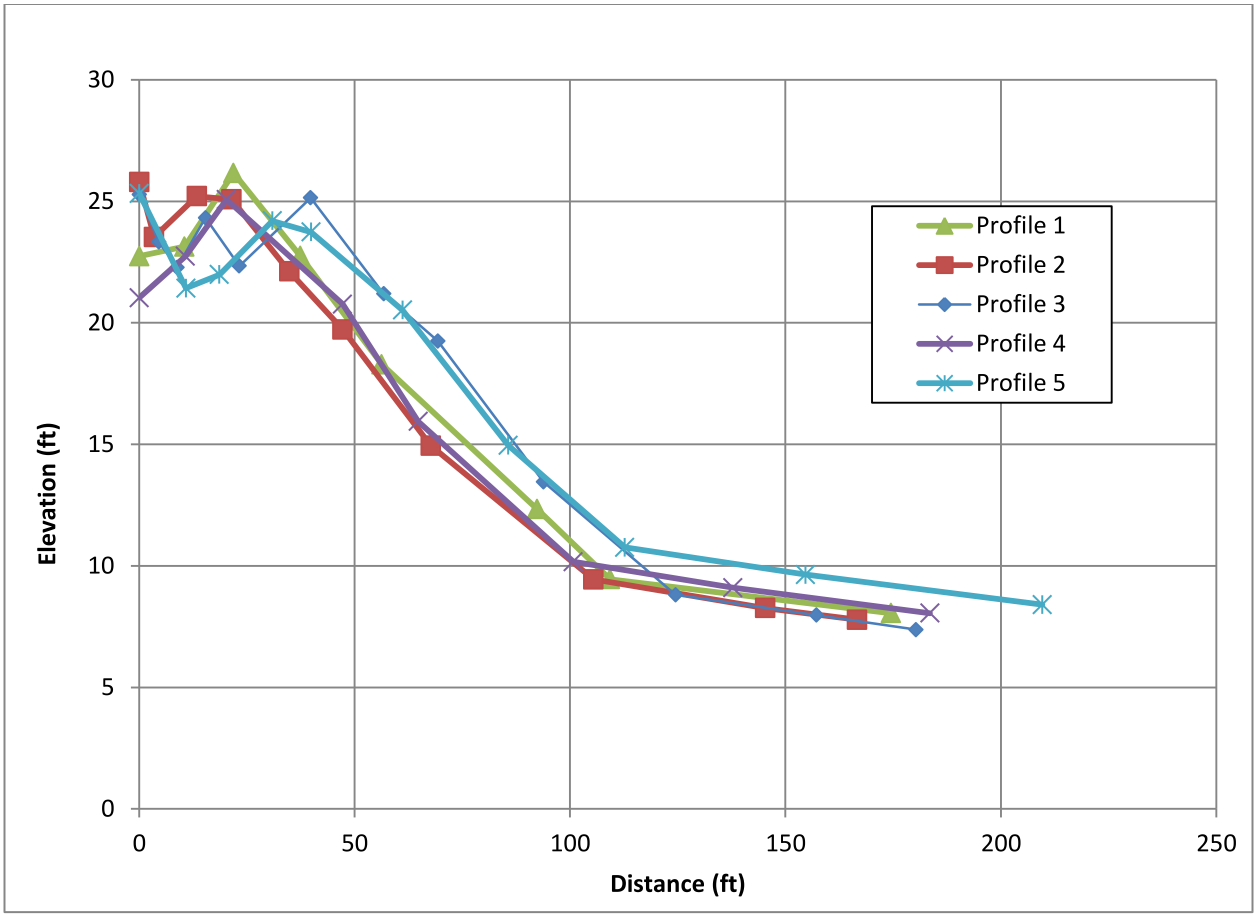

Figure A2. Beach 1 reference profiles.

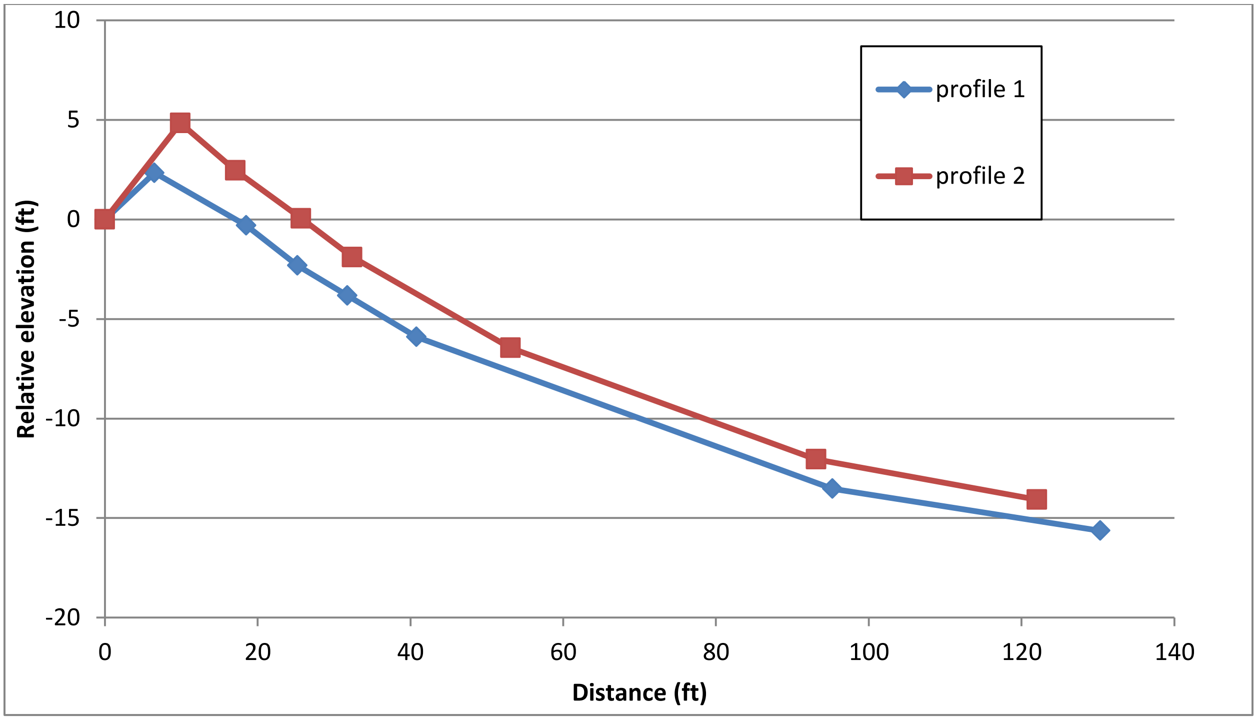

Figure A3. South Beach reference profiles.

Figure A4. Beach 1 reference site photo 1.

Figure A5. Beach 1 reference site photo 2.

Figure A6. Beach 1 reference site photo 3.

Figure A7. Beach 1 reference site photo 4.

Figure A8. South Beach reference site photo 1.

Figure A9. South Beach reference site photo 2.

Figure A10. South Beach reference site photo 3.