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Sultan, N.; Phillips, R.; Bermudez, H.

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N. Sultan[1], R. Phillips[2], H. Bermudez[3]

Abstract: This paper describes scour at a submerged rock structure on the coast of Washington. The SR-105 Emergency Stabilization Project was constructed in the summer of 1998 to protect a stretch of state highway from destruction because of shore erosion. The structure consists of a rubble-mound groin and dike. The rock groin extends approximately 1,600 feet from the shore. A submerged rock dike at the end of the groin functions in part as toe protection. The dike structure is 500 feet long at the crest and is built from 157,000 cubic yards of rock placed by bottom dump barge. The rock structure has induced relocation of a deep tidal channel 500 to 2000 feet further from the shore. The project performs as expected and reduces erosion along an extremely erosive shoreline northwest of the project site. Scour has developed in the vicinity of the toe of the structure. This scour was expected and the design incorporates a "launched-toe" feature to accommodate the predicted scour. Monitoring since construction shows that the structure has maintained its integrity. However, maintenance may be necessary should the scour continue and a maintenance concept design has been developed.

INTRODUCTION

The SR-105 Emergency Stabilization Project was built in the summer of 1998 to protect a state highway from destruction by a rapidly eroding shoreline. Figure 1 shows the project location. The project includes a rubble-mound dike and groin structure. The shoreline along the northern tidal channel at the inlet to Willapa Bay, Washington, has been one of the most rapidly eroding shorelines in the United States. The major causes of erosion at North Cove are northward migration of the

1) Coastal Engineer, Pacific International Engineering, P.O. Box 1599, Edmonds, Washington
2) Civil Engineer, Pacific International Engineering, P.O. Box 1599, Edmonds, Washington
3) Coastal Engineer, Pacific International Engineering, 3415 Greystone Drive, Austin, Texas

deep north tidal channel and wave action. The majority of the tidal current flows through the north channel, immediately adjacent to the shoreline. The shoreline erosion rate recently has been up to 150 feet per year. The historical rate has been observed to be greater than 250 feet per year (Figure 2). Recently, erosion threatened a 2,000-foot stretch of State Highway 105 (SR-105) near the town of North Cove, Washington. Relocation of the highway (for the second time this century) was not economically feasible.

ENVIRONMENTAL CONDITIONS

The project site is immediately north of the north entrance channel to Willapa Bay. The major causes of erosion at North Cove are northward migration of this deep north tidal channel and wave action. The entrance channel is constantly changing alignment and position and is a region of massive sediment movement. The sediment is non-cohesive fine sand. Hands and Shepsis (1999) describe cyclic behavior of the entrance channel location and associated bar. Waves offshore of Willapa Bay are regularly measured in excess of 30 feet, but are reduced as they pass through the entrance channel. The majority of the tidal current flows through the north channel, immediately adjacent to the shoreline. The depth averaged tidal current speeds in this channel frequently exceed 6 feet/second. The mean depth averaged current speeds are typically 3 feet/second for ebb tides and 2 feet/second for flood tides. The total tidal flows at the entrance to Willapa Bay are estimated to be 500,000-800,000 cfs, which exceed the discharge rate of the Mississippi River.

Figure 1. Location Map

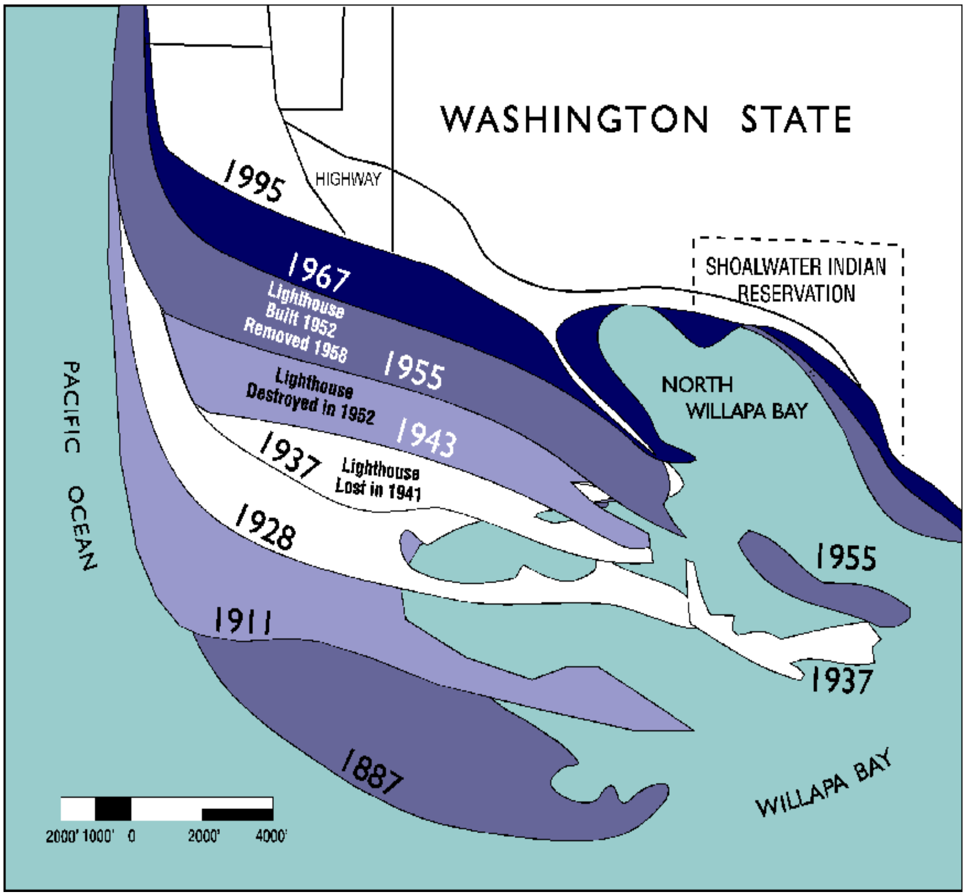

Figure 2. Erosion History at Project Area, 1887-1995

Figure 3. Aerial Photo

PROJECT DESCRIPTION

The project design consists of a rubble-mound underwater dike, a rubble-mound groin and beach nourishment. The project is shown superimposed on an aerial photo in Figure 3. Figure 4 shows in plan view the project elements. The rock groin structure extends seaward from the shoreline out to the northern edge of the North Channel. The underwater dike extends from the end of the groin across a portion of the North Channel. The beach nourishment is placed behind the dike to protect the shoreline adjacent to the highway. The project was built in the summer of 1998.

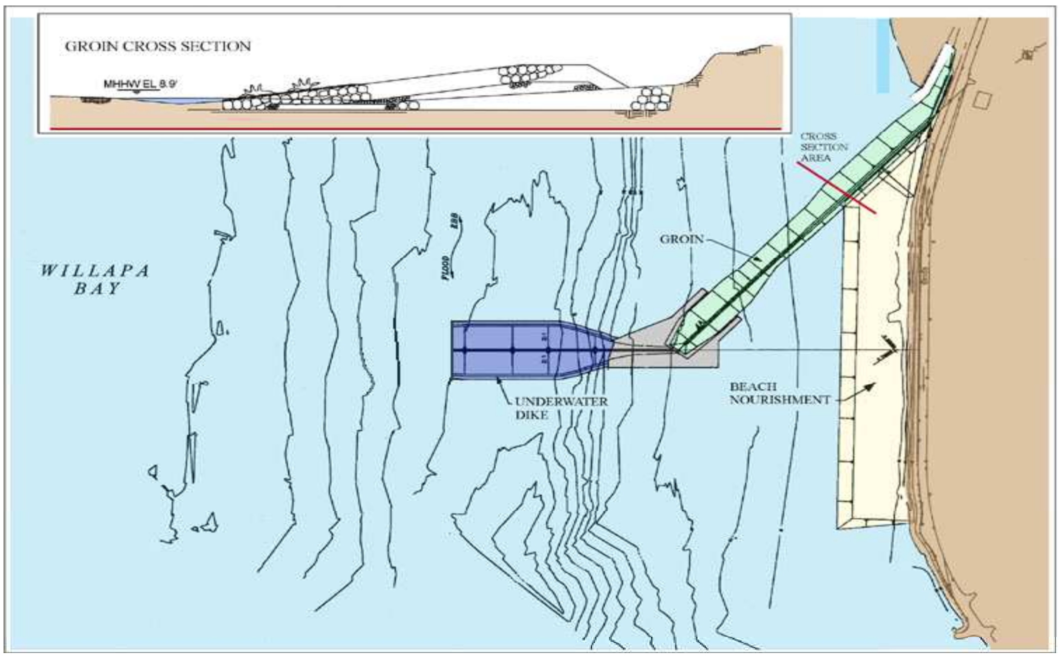

Figure 4. Project Design Features

The rock groin structure extends approximately 1,600 feet from the shoreline. The groin is aligned perpendicular to the predominant wave direction at an angle of 40 degrees to the shoreline. The seaward exposed portion of the groin was designed and built with a 7H:1V slope. The leeward side of the groin was constructed at a 7H:1V slope at locations not covered by beach nourishment material. The outermost 150 feet of the groin has a top elevation of -2.5 feet, Mean Lower Low Water (MLLW) and 3H:1V side slopes. The top of the groin varies from a maximum design elevation of +18 feet, MLLW at the groin's leeward end, to a minimum design elevation of -2.5 feet, MLLW at the offshore end (northern edge of the North Channel). The minimum height of the groin above existing ground is approximately 13.5 feet.

Different rock sizes were used to construct the groin. 8 inch minus was used as bedding material. An 8 inch to 24 inch rock gradation was used for the core. The armor stone was a 2 to 4 ton gradation. At the outer end of the groin 10 ton armor stone was used.

Approximately 350,000 cubic yards of beach fill was placed between the groin and the shoreline using a cutter-suction head dredge. The beach nourishment was constructed to a top elevation of +25.0 feet, MLLW.

The function of the dike is to deflect the tidal current away from the shoreline and reduce local current speeds, thereby protecting the steep bank adjacent to the highway from further erosion. The dike also acts as scour protection for the groin. The design and construction of the dike are described below.

UNDERWATER DIKE DESIGN

The underwater dike was designed to extend from the end of the groin seaward to the south side of the North Channel, a distance of approximately 2,500 feet. However, the length of dike approved by resource agencies was only 1,520 feet. Because of site conditions, the as-built length of dike was further reduced to a length of 500 feet along the top edge. The constructed dike extends approximately 930 feet overall from the intersection with the groin to the seaward toe of the dike. The top elevation (crest) of the dike is -18 feet (MLLW). The bottom of the dike is constructed to a depth of –80 feet, MLLW.

The dike is a rubble-mound type of structure constructed from rock with different gradations. The underwater dike cross section was constructed with a bedding layer and inner core consisting of 18 inch minus rock material. The outer armor layer of the dike was constructed using 30 inch minus rock. A cross section through the dike is included in Figure 6. The stone sizes, slope of the dike surface and overall dike configuration were designed based on consideration of a number of factors, including cost, constructibility, availability of different rock sizes, and stone stability.

The dike functions as both a tidal current deflector, and as scour protection for the toe of groin. One design issue is the stability of the outer armor stone under the influence of waves and currents. A similar design issue is the scour that can be expected in the native, granular material near the dike.

Methods for predicting the dike armor stone stability under currents can be found in the Shore Protection Manual (1984) as well as in a number of references pertaining to the design of river training structures. Formulas based on calculating a local boundary shear stress were applied. For a current velocity of 6 feet/second a stone size of 4 inches is predicted to be stable. A larger stone size was used to account for uncertainties in the methodology and the increased stress from wave action.

Analysis of scour in the adjacent granular native material is more uncertain. Scour can clearly be expected at a structure of this nature. One analysis concept that may be applicable is to treat the dike as a projection into a river. Scour at river structures has been well studied and a large number of references and design guides are available. A useful summary of a number of studies is contained in Przedwojski, et al (1995).

However, scour at the dike will also be influenced by wave action, in combination with tidal currents, and the resulting hydrodynamic regime clearly differs significantly from that of a river with a steady current. The literature concerning scour under combined waves and currents is considerably thinner than that for rivers. Recent research results on this topic are included in Sumer, et al (2001) and Whitehouse, (1998).

After review of a number of empirical equations, theory and project experience the dimensions and extent of future scour could not be predicted with an adequate level of confidence. Partly as a result, a "launched toe" feature was included in the dike design to allow for expected scour. As scour develops around the dike the rock material in the launched toe will eventually fill any scour hole that develops before it can threaten the integrity of the main structure. Also, post-construction project monitoring was included as part of the project partly in order to monitor scour and the integrity of the structure. As scour develops it would be detected and appropriate remedial/maintenance activity undertaken if necessary. With this "adaptive management" concept, scour prediction before project construction is less critical. Also, total project cost should be minimized by avoiding over-design of the scour protection before construction.

UNDERWATER DIKE CONSTRUCTION

The project was bid in April 1998 as two separate contracts, a first contract for the beach nourishment and groin/breakwater features and a second contract for the underwater dike feature. Two contracts were let to ensure the project was completed prior to the 1998 winter season and completion within the in-water work windows specified by natural resource agency permits. In May 1998, a unit price contract was awarded to Quigg Brothers Construction Inc. of Aberdeen, Washington for a low total bid of $8,260,000. Miller Contracting of Vancouver, British Columbia provided the rock source, transport barges and ocean tugs as a subcontractor. Figure 5 shows rock placement during project construction.

Construction of the underwater dike began on July 6, 1998 and was completed September 15, 1998. Approximately 299,000 tons of rock (175,000 CY) was placed to construct the underwater dike. Rock for the underwater dike was supplied by Miller Contracting from a source on the west coast of Vancouver Island, Canada. Rock from this source was primarily limestone and metamorphic. Rock was loaded onto flat deck and split hull barges and transported from Vancouver Island to the project site, a 20-hour one-way trip. Delivery of rock to the project site was scheduled to coincide with "slack" high tide to ensure navigation across the shallow, un-maintained Willapa Bay entrance bar and to time placement of rock when tidal currents were a minimum.

Prior to the start of construction, the contractor requested a change to the specifications to provide additional armor stone and bedding stone in lieu of the core stone material at no additional cost to the owner. The contractor proposed to construct the bedding stone per plan at the outer edges of the dike and twice the specified thickness at the center of the dike. Additionally, they proposed to construct the remainder of the dike with armor stone instead of core stone. The request was granted with the requirement that the minimum bedding and armor stone thickness be maintained at all locations.

Equipment used to construct the dike consisted of a floating crane with clamshell and skiff buckets, four ocean tugs, one harbor tug, four split hull barges, two flat deck barges and a survey boat. The contract documents specified daily pre and post placement surveys be conducted by the contractor and submitted to the owner for review. The contractor provided a dedicated survey crew consisting of two survey boats fitted with differential GPS and echo-sounder equipment for quality control. Surveying was conducted daily before and after each individual placement of stone. Periodically, the owner's representative conducted independent hydrographic check surveys using single and multi-beam echo-sounder and side-scan sonar.

Three methods of rock installation were used to construct the dike, and are illustrated in Figure 6:

- Direct placement by side dumping off flat deck barges and by a floating crane with skiff bucket,
- fixed location split hull barge placement, and
- split hull barge "fly" spreading.

The first method (direct placement) was used to construct the dike in the shallows in and around the end of the breakwater/groin, between existing bottom elevation -12 and –20 feet, MLLW. The floating crane and flat deck barges were used for this construction method. The contractor developed a placement grid based on the contract drawings to determine the quantity of material to be installed within each cell of the grid. Flat deck barges were then tied to the crane barge and positioned over placement grid cells. A front-end loader located on the flat deck barge was used to place a pre-determined quantity of rock within each grid cell. Current velocities within this area were measured and did not have a significant impact on installation procedures. Daily quality control surveys were conducted to determine the adequacy of the installed rock. Areas outside the placement limits were "trimmed" using the floating crane with clamshell bucket.

The second method of placement used split hull barges tied to the floating crane. This method was primarily used for the installation of the interior dike material. The floating crane was anchored with four lines and then positioned using GPS to the appropriate location within the placement grid. The floating crane was then used as a tie-up for the spilt hull barges while unloading. Current velocity magnitude and direction was measured to predict the trajectory of the rock being dumped. Current velocities within the middle portions of the channel were measured as high as 8 feet/sec during mid ebb/flood tides. Each barge load of rock was dumped at a predetermined location within the established grid cells at slack high tide. Hydrographic surveys were conducted to determine the location of each load of dumped rock. Areas determined to be out of tolerance were identified and delineated within the defined placement grids for trimming work. Final trimming to the specified lines and grades was conducted with the floating crane clamshell. GPS was installed on the floating crane boom to provide the operator control over the location of each bucket load of material removed and reinstalled within each grid cell.

The third method of placement used split hull barges to "fly" spread rock at specific dike locations. This method was primarily used for installing armor stone in the interior and at the top of the dike and for installing bedding stone. Using GPS, the incoming loads of rock were positioned over the desired placement cell, either unassisted or adjacent to the crane barge. The split hull barge was then opened at a slow rate and moved over the placement cells to spread the rock over a large area rather than an entire load dropped instantly at one location. This method was used to minimize trimming work by spreading each barge load over a greater area rather than installing large individual piles. Current velocity magnitude and direction was measured to predict the trajectory of the rock being spread. Rock was placed at slack high tide in order to work around the extremely high velocities encountered at the site during mid ebb and flood tides. The floating crane was positioned with GPS and securely anchored for use as a tie-up barge for each incoming bottom dump barge load of rock.

For both the "fly" spreading and moored barge placement methods, the initial barge dumps onto existing sand resulted in the material fanning out along the footprint to a 4H:1V to 5H:1V side slope. Once a foundation of rock existed, the dike began to rise up a 1.5H:1V to 1.25H:1V side slope; slightly steeper than the 2H:1V specified slope. Rock continued to be placed with split hull barges up to the specified side slope and top elevation tolerances.

Figure 5. Project During Construction

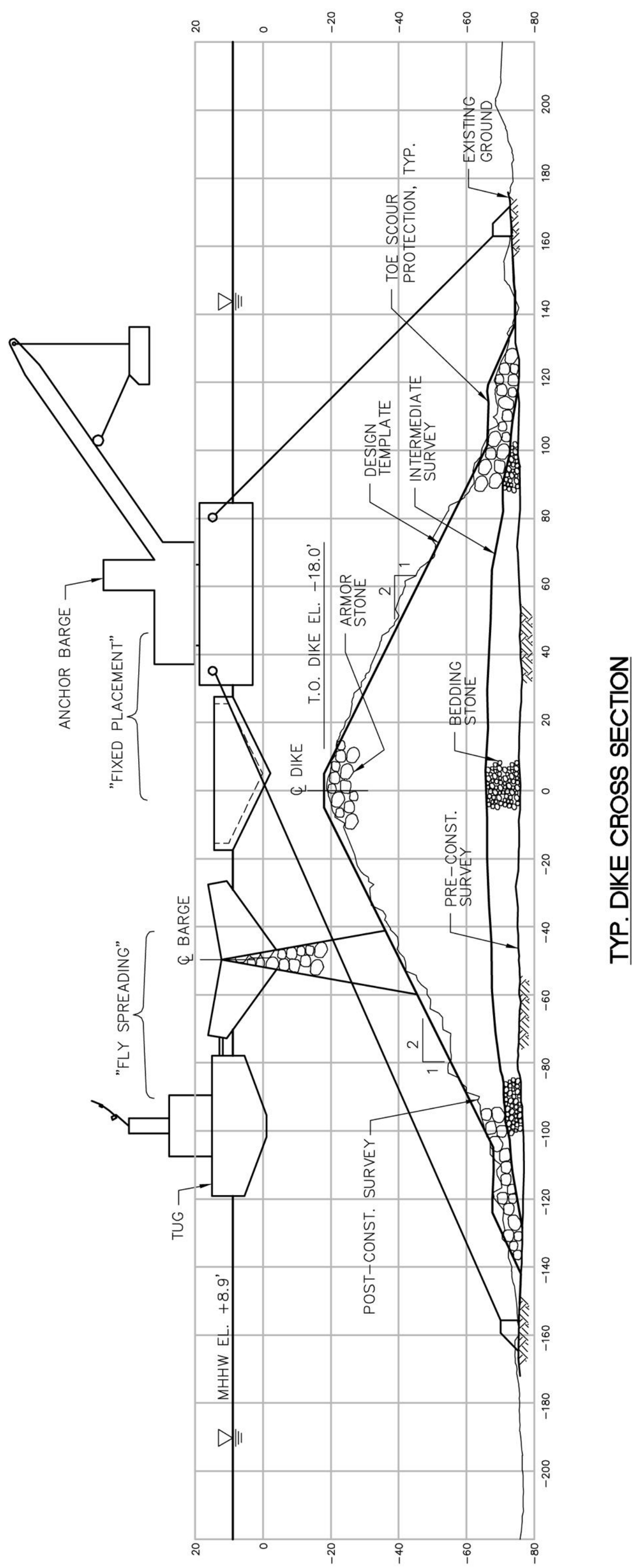

Figure 6. Underwater Dike Rock Placement

PROJECT MONITORING AND SCOUR HOLE ANALYSIS

Project monitoring included aerial photography, hydrographic and topographic surveys, water surface elevation (wave height) measurement and current velocity measurements. Currents and wave heights were measured from a tripod deployed on the seafloor and serviced at monthly intervals. Currents were also measured using Acoustic Doppler Current Profilers (ADCP) on a survey vessel moving along transects across the north tidal channel. In this manner, current velocities along a "slice" of the channel were measured. The monitoring program is described in Sultan (2002).

Hydrographic survey results show that the North Channel has moved south, 500 to 2000 feet, in response to project construction. The dike and groin have acted as a tidal current deflector and prevented further northward migration of the channel. North bank slopes in the vicinity of the project have generally accreted and moved southward. Figure 7 shows before and after hydrographic surveys taken across the north tidal channel.

Local scour in the vicinity of the structure is shown in Figure 7-Transect C. Also, the scour is shown in plan view in Figure 8, and in a section through the dike in Figure 9. The local scour induced by the groin appears overlapped, or superimposed, on a larger channel migration. The channel movement away from the north slope is caused by deflection of the tidal current by the groin. Some of the scour is likely due to a general channel migration away from the north bank. Figure 7-Transect C shows that the cross sectional area of the channel has increased more than the cross-sectional area of the dike and groin extending into the channel. The overall cross-sectional area of the north channel in the vicinity of the project has increased, as shown in Figure 7. This is consistent with velocity measurements showing a decrease in tidal current speeds near the shoreline along the north channel.

The scour hole immediately adjacent to the dike is approximately 40 feet deeper compared to pre-construction bathymetry. The scour hole forms a classic kidney shaped depression around the toe of the rock dike. The scour on the seaward side of the structure is deeper than the landward side. This may reflect the fact that ebb tide currents are stronger than the flood current. It may also be a consequence of the seaward side of the dike being generally more exposed to wave action than the landward side.

Comparisons have been made been the measured scour dimensions and predictions based on methodologies in Przedwojsk et al. (1995). The predicted scour hole dimensions are larger than that predicted from analysis based on sediment size and a steady current speed. One possible reason is the influence of waves combined with a steady current. Another possible reason is that the scour hole is reacting in part to the overall migration of the tidal channel away from the dike and groin. It is probable that the scour hole is caused in part by large eddies generated in the vicinity of the dike, including eddies about a horizontal axis formed over the top of the dike. However, the current meters deployed in the field do not have sufficient temporal or spatial resolution to measure macro-turbulent eddies.

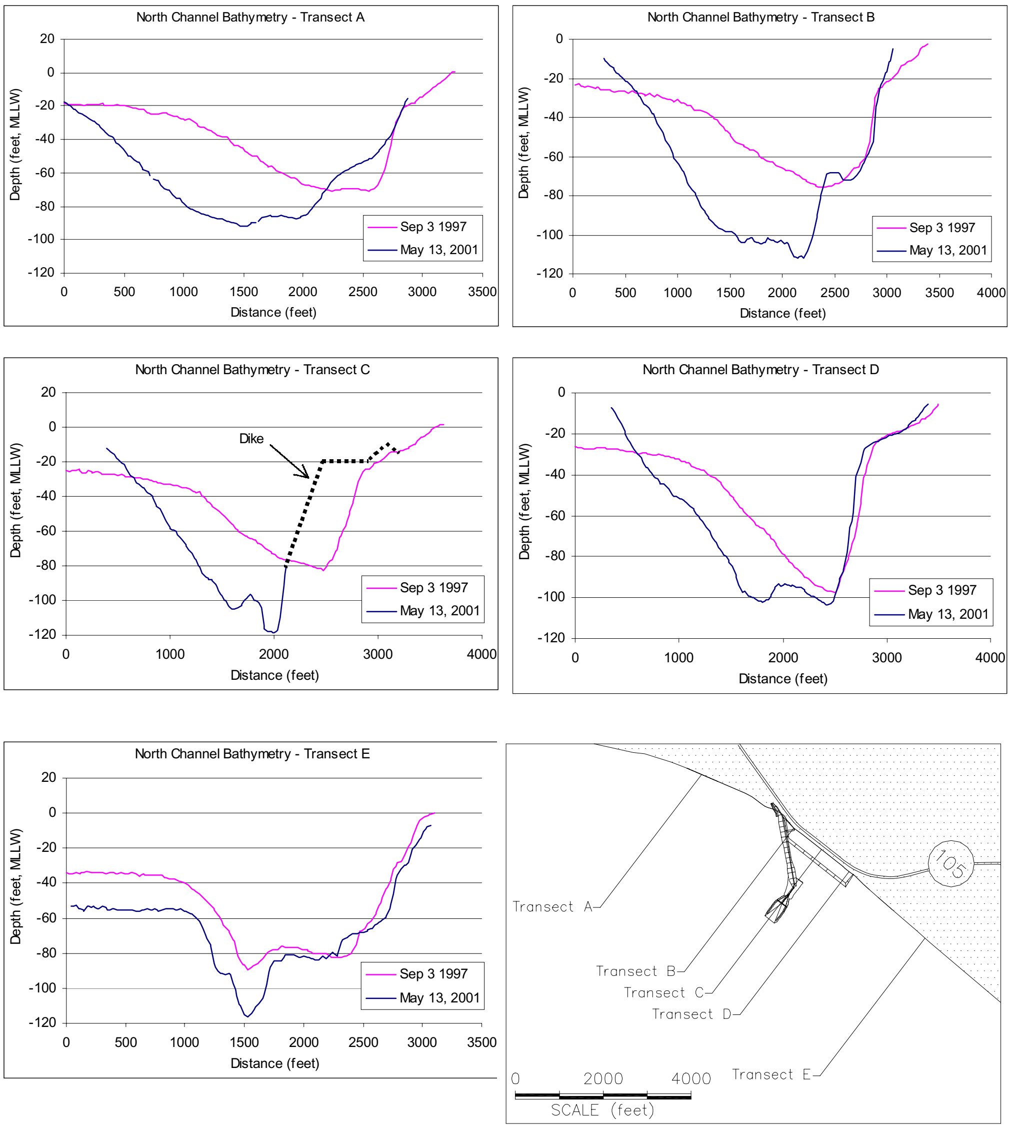

Figure 7. Hydrographic Survey Data

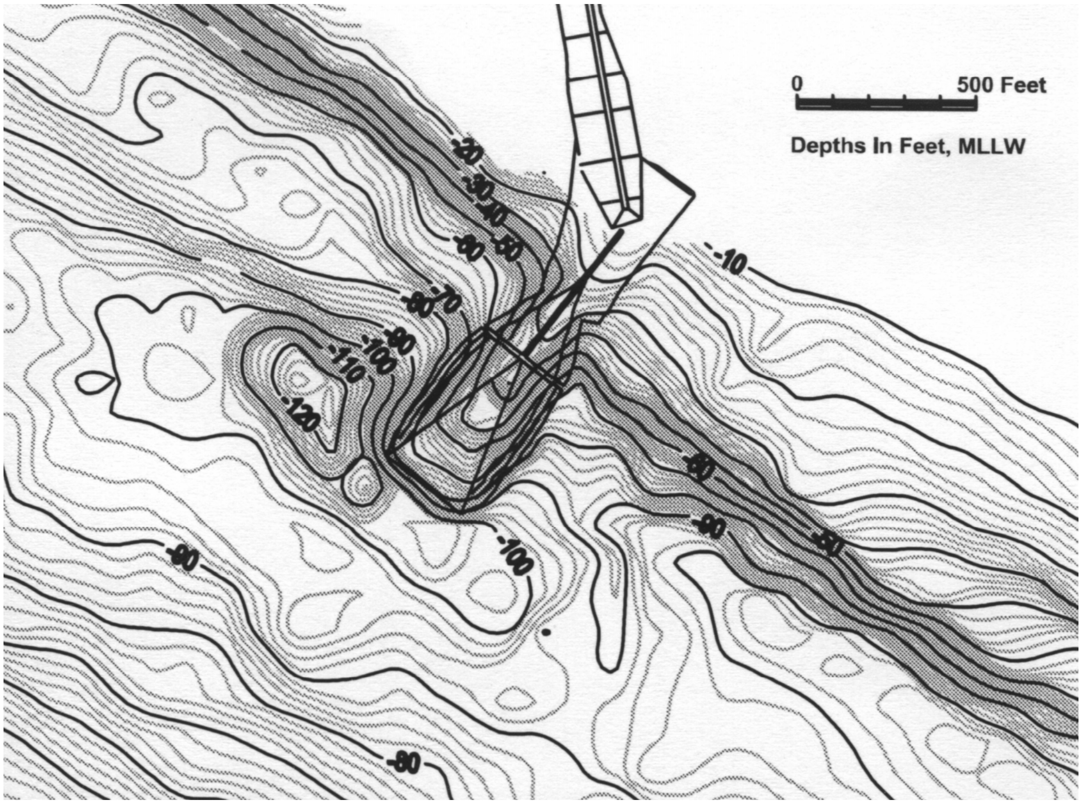

Figure 8. Scour Hole Bathymetry, April 2000

DIKE MAINTENANCE CONCEPT DESIGN

Figure 9 shows a maintenance concept design to address scour at the dike. If the deepening continues, scour may endanger the stability of this part of the structure and performance of the project. The design includes placement of rock at the toe of dike to protect from further scour. The rock is placed in the scour hole to form a "blanket".

The Coastal Engineering Manual (2001) provides design guidance for scour protection blankets. Application of a Shield's parameter type equation predicts that a stone size of 2 inches will be able to resist a depth averaged current speed of 6 feet/second at the scour hole. However, considering the additional influence of wave action and to account for other uncertainties, a larger stone size is recommended.

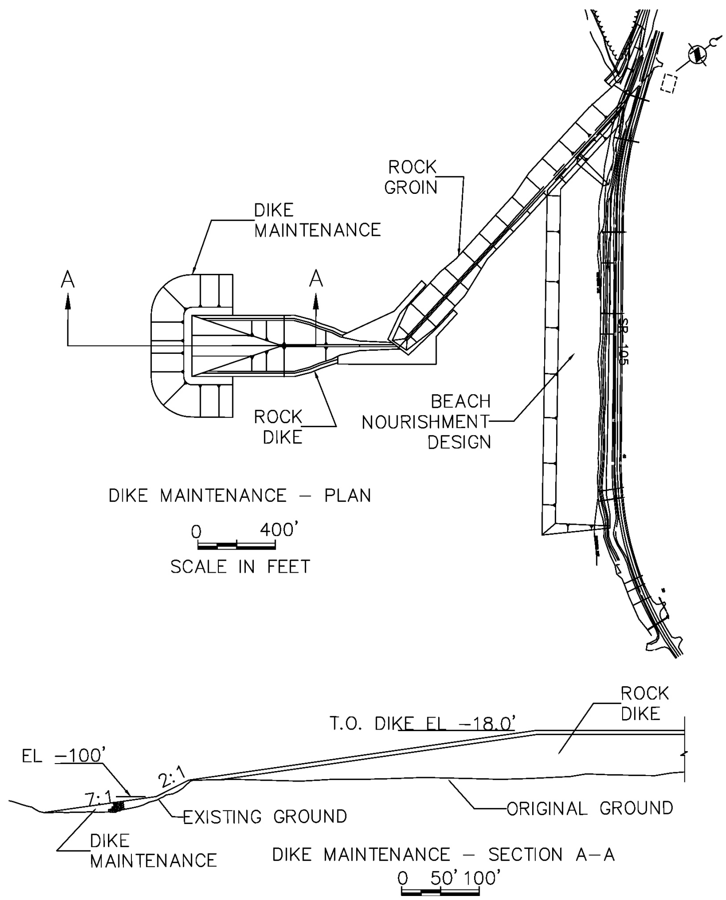

Figure 9. Dike Maintenance Concept Design

CONCLUSIONS

A rubble-mound rock groin and dike and beach nourishment was constructed to protect a highway from erosion. Monitoring since construction shows the project was constructed as designed and has performed as expected. Measurements of the groin and dike showed no signs of structural deterioration. Erosion has been greatly reduced and the shoreline has stabilized.

Scouring has occurred near the end of the underwater dike. If the scour continues this may endanger the stability of the dike part of the structure. A concept design involving the placement of rock scour protection has been developed.

A number of scour prediction methods have been applied and compared to the measured scour hole. The scour hole is deeper than predictions based on a steady current, such as occurs at river training structures. This may be a result of the combined effect of waves and currents.

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