NAVIGATION CHANNEL DESIGN AND TRANSIT OPERATION AT REMOTE TEMPORARY OFFLOAD FACILITY ON SAKHALIN ISLAND, RUSSIA

Aaron Porter, PE[1], Vladimir Shepsis, PhD, PE[2], and Aaron Horine, PE[3]

ABSTRACT

To deliver high value, heavy cargo (~2500 ton modules) to a purpose built temporary offload facility in a remote area of Piltun Bay on Sakhalin Island in Russia, numerous challenges were presented to provide design of a navigation channel within a dynamic natural channel. Challenges included successful delivery of 17 barges to a previously un-developed facility along a narrow tidal channel, restriction on dredging, extreme winter wave and ice conditions, variable vertical datums, Russian regulatory specifics, and an accelerated project schedule (concept to delivery <4 years). Mott McDonald optimized siting of the barge offload facility, assessed the impact of highly dynamic environmental conditions (natural waterway migration of approximately 50m per year), and provided design of a safe barge transit route with limiting depth of 2.3 meters at MSL. Designing a navigation channel meeting Russian regulatory specifics, accounting for the highly dynamic nature of bar migration, and limitations on dredging, required a multi-year analysis of channel conditions, sedimentation patterns, and numerical modeling of currents within the waterway. Mott MacDonald aided in development of cargo weight restrictions to ensure safe passage of the barges within the navigation channel by developing an operability model of the navigation channel, and determining the likelihood of transit volume per year in various conditions. To optimize throughput during optimal bar crossing conditions, barge staging areas were incorporated into the navigation channel design. To aid in timing of transit within the waterway, Mott MacDonald developed probabilistic estimates for water levels. During barge delivery Mott MacDonald optimized navigation channel waypoints to reflect changing conditions at the entrance to the channel. Despite numerous regulatory and environmental challenges, the 11 barges planned for delivery in 2016 were completed 15 days early.

Keywords: Navigation channel, dynamic environment, barge transport, design, operability, staging areas, sedimentation.

INTRODUCTION

Module marine transport is a critical element to support expanding production facilities on Sakhalin Island, Russia, at the Odoptu Stage 2 (OS2) Project Site. The project site is remote, with limited resources and infrastructure, and in an area of logistical, environmental, mariner operation, and hydro-meteorological challenges and restrictions. Work related to waterway navigation design and maintenance, presented herein, supported the safe, timely, efficient, and cost effective delivery of the modules. Modules (similar to the example shown in Figure 1) were planned for delivery to a temporary offload facility (TOF) during two seasons: summer of 2016 and 2017.

The TOF site is located within Piltun Bay at a remote area of the Russian Pacific coastline, on the Sea of Okhotsk. The waterway for the delivery of barges with modules has been aligned to begin approximately 4 km outside the Bay entrance, proceeding through the ebb tide delta (also referenced herein as "the bar"), and into the natural waterway (Figure 2), ending in the shallow bay area, approximately 22 km from the mouth of the waterway (See Figure 2). The selected waterway inside of the bay is aligned along a tidal channel thalweg with controlling depths of 2.5-3.2 m Mean Sea Level (MSL). No navigation by commercial vessels (barges) through the entrance and along the Piltun Bay had occurred previously. One of the critical restrictions on the project design and operation is limited possibilities on dredging operations. The navigation waterway must also meet Russian regulatory standards for safe navigation. Barge transit through the channel must avoid habitat areas (gray whales, seals).

[1] Coast & Harbor Engineering, A Division of Mott MacDonald, 110 James Street, Suite 102, Edmonds, WA 98020,**T** 425-977-2585 **C** 206-271-1089 E-mail: aaron.porter@mottmac.com

[2] Coast & Harbor Engineering, A Division of Mott MacDonald, 110 James Street, Suite 102, Edmonds, WA 98020, **T** 425-778-6733 **C** 425-231-2488 E-mail: vladimir.shepsis@mottmac.com

[3] Coast & Harbor Engineering, A Division of Mott MacDonald, 711 North Carancahua, Suite 1610, Corpus Christi, Texas 78401,**T** 361.661.3061 **C** 281.813.9440 E-mail: aaron.horine@mottmac.com

Figure 1 – Module Barge Transport Between Bay Entrance and TOF (2016)

The approach for the design and implementation of the Piltun Bay navigation approaches and loading operations consisted of the following steps as follows:

1. Evaluate the site’s physical conditions and develop sufficient data and knowledge for waterway design.

2. Conduct operability analysis to investigate the capability of the existing natural waterway to handle the expected barge traffic.

3. Optimize alignment and dimensions of the waterway (where required) to improve navigability and, at the same time, to minimize possible dredging requirements.

4. Design of the waterway and navigation aids and validate design with the full bridge simulation study.

5. Provide field assistance to Exxon Mobile and Marine Transportation Contractor (Foss/Teras) during delivery of barges by developing engineering solutions to assure safe navigation and success of offloading operations (where required).

SITE CONDITIONS

Piltun Bay project site conditions were investigated based on compilation and review of available historical and new field data (field data collection program of more than two years), and upon modeling and analysis of waves, tidal flows, and sediment transport. As a result of this work, a significant database on project site conditions, including winds, waves, tides, currents, coastal geomorphology was developed, some of which (tides, waves, currents, and geomorphology) are briefly described below.

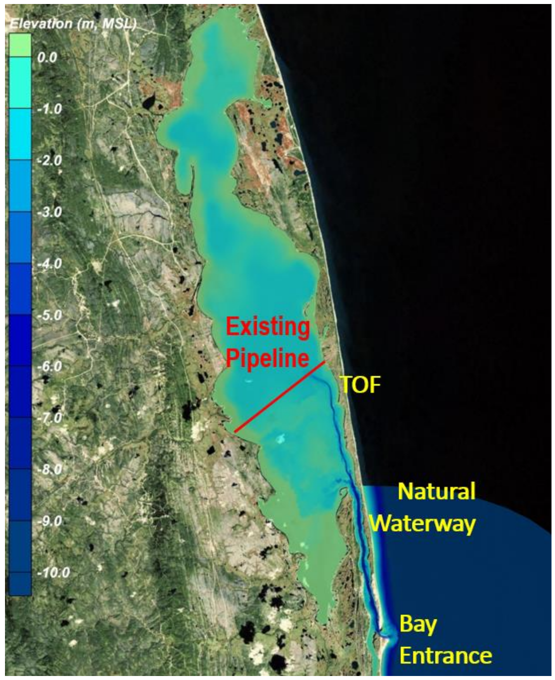


Figure 2. Piltun Bay and Key Project Locations.

Water Levels

Upon data collection and analysis of tide data, it was found that oscillations of water elevations in Piltun Bay are extremely complicated and variable in time and in space. Figure 3 shows the oscillation of water surface elevations at two different locations in the bay (also shown on Figure 2) during the same period (June-October, 2015). It appears that due to the large area of the bay and the narrow and long entrance, the bay has its own and unique harmonics of water surface elevation oscillation.

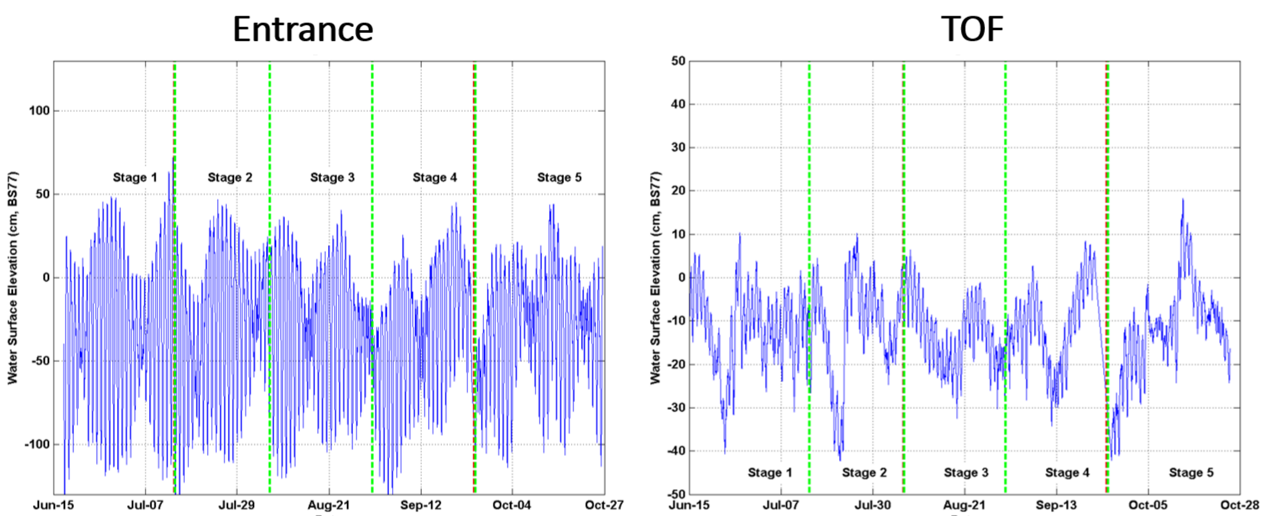


Figure 3. Example of water level collection campaign data at the Entrance (left panel) and the TOF (right panel). Also shown are the different stages of data collection (5 deployments per year).

Water levels at the entrance are tidally influenced with strong tidal signals that were predicted reasonably well by the NobleTec Tides and Currents software, once they were calibrated to measured tide data. However, water levels within the Bay do not correlate to predicted tides and differ significantly from the predictions in values and phasing. Harmonic analysis performed on the measured water levels within Piltun Bay showed a strong influence on water oscillations in the bay from factors other than tidal harmonics. The limited available data did not allow for determination of the nature of these other factors, which appear to include (but are not limited to) the following: hydraulic resistance of the narrow and long entrance (approximately 10 km) that controls water exchange between the bay and open sea, fresh water discharge into the bay, resonant oscillations of water mass in the bay, among others.

The variability of water elevations is also demonstrated by Figure 4, which shows the values of Lowest Astronomical Tide (LAT) datum along the bay. The LAT datum was developed based on available historical multi-year water level data (2009-2015) at several stations within the Bay. The figure shows that the LAT datum varies approximately 1 m along the waterway length (<25 km long). Such dramatic variability of the tidal datum, as well as instantaneous water surface elevations, has required special attention in predicting tide elevations during the navigation seasons, Summer 2016 and 2017.

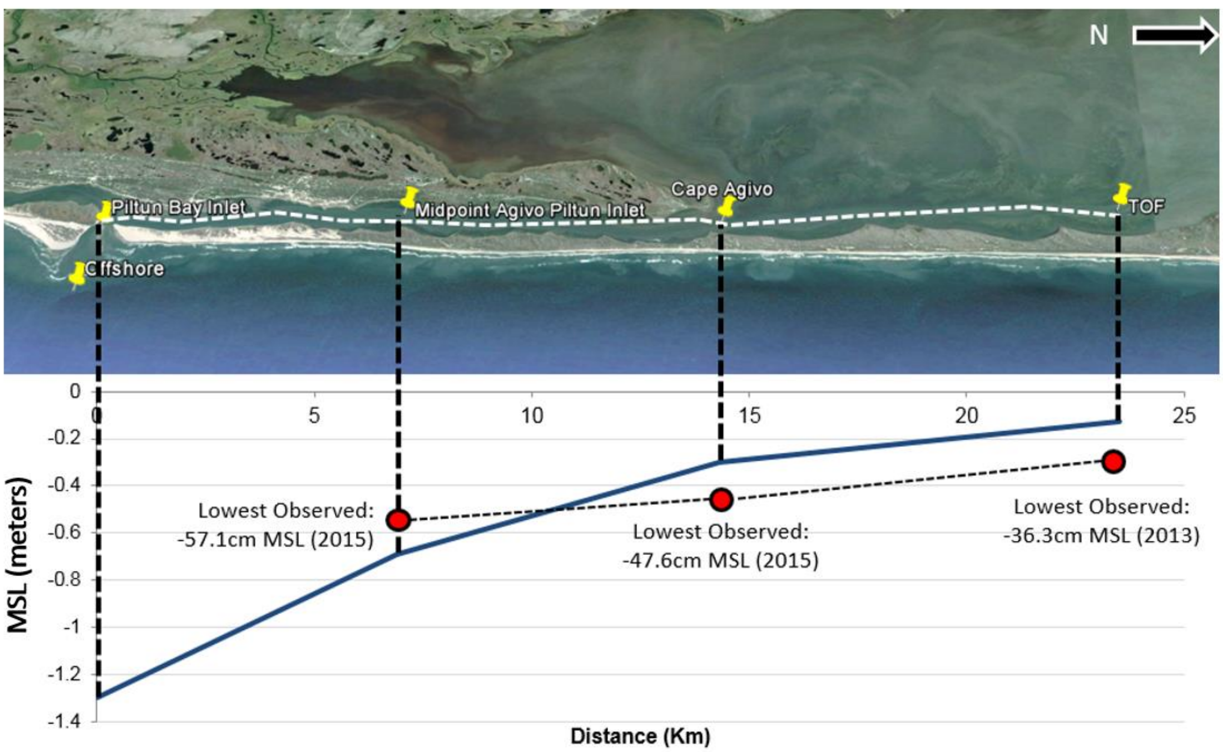


Figure 4. Variable datum conversion example along navigation channel. Note lowest observed tide is not equal to LAT.

By correlating historical and new data to the predicted tides at the open coast at the known station (from NobleTec Tides and Currents software), the empirical predictions of tide elevation in the Bay at two different locations were developed for the 2016 navigation period. The predictions were developed with 90% probability of exceedance, meaning that there is 10% probability that actual elevations may be lower. An example of these predictions is shown in Figure 5 for two stations, the entrance to the bay and at the TOF. Upon 2016 marine operations, the developed tide predictions appeared to be reasonably accurate. The predicted methodology will be further used for predicted tides during the 2017 delivery season.

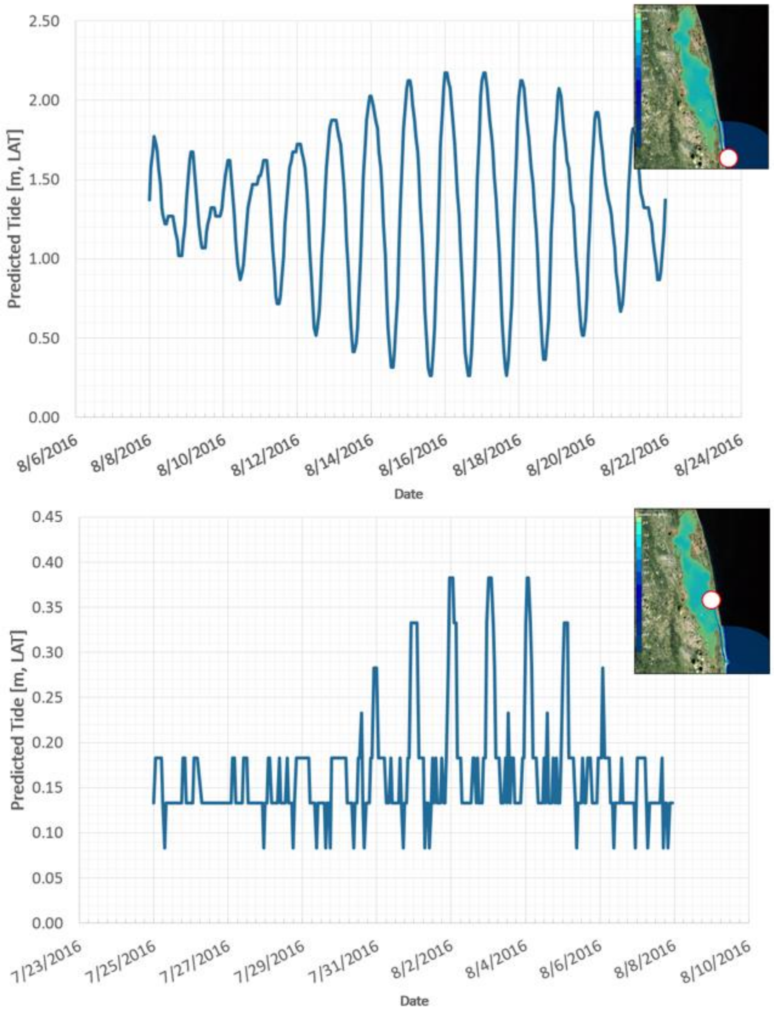


Figure 5 - Example Tide Predictions Results at the Entrance (left panel) and TOF (right panel). Note: Predicted tides are provided with 90% probability off exceedance, meaning that there is 10% probability that actual elevations may be lower.

Waves

The project site, specifically the entrance to the bay, is located along the area impacted by strong wind-wave storms and swells. Vessels navigating toward the bay and crossing the bar (ebb delta) are subject to breaking wind-waves and ocean swell even during calm summer days. As shown in Figure 6, the waves break at the bar, and dissipate as the waves move inside of the bay. Wave conditions were assessed at the entrance and the bar along the waterway through the bay, and at the TOF.

Figure 6. Entrance to Piltun Bay. Barges cross the bar and travel through the entrance up the natural waterway to the TOF located in the Bay. Note waves breaking at the Bar.

Analysis and evaluation of wave conditions at the entrance and ebb delta were conducted using the SIMOS database and the wave propagation numerical model SWAN (Holthuijsen *et al*., 2004). The model propagated wave conditions, predicted by SIMOS Grid Point #282, to the area just outside the entrance of the bay. The modeled wave heights and periods were further verified by field data collection. In general, it was found that in calm seas during the summer season significant wave heights are relatively small and do not exceed 0.5 m. However, long periods of such calm seas are relatively rare. During the summer period, significant wave heights exceed 0.5m approximately 60-65% of time and may reach as much as 3 meters just seaward from the ebb delta. Figure 7 shows an example of the time series of wave heights at the entrance to the bay (seaward from the ebb delta) at a depth of 10 m BS77 during period of approximately one month.

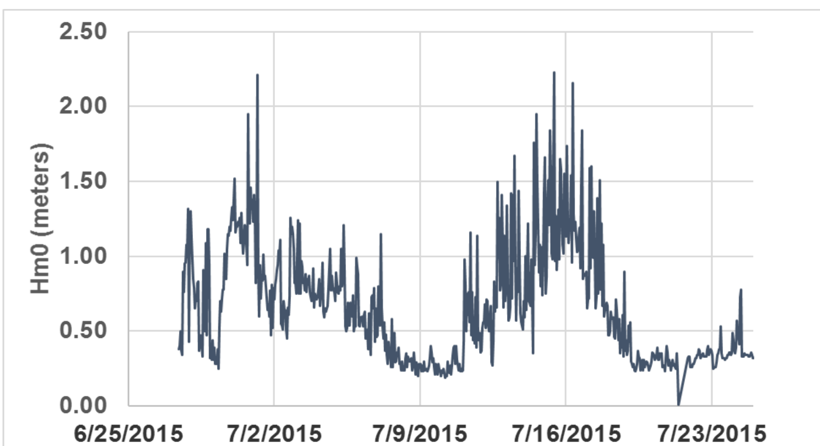


Figure 7. Example of Wave Height measured outside the bar (2015).

Similar to wave conditions outside the entrance, wave conditions in the bay were investigated using numerical modeling with SWAN. It was found that wave conditions in the bay along the waterway are mild and will not exceed 1 m, even during extreme events.

Currents

Analysis and evaluation of current velocity within the entire waterway and offloading facilities were performed based on field data collection and using flow circulation numerical modeling. The field current velocities data were collected at four locations: just seaward from the ebb delta, directly at the entrance to the bay, where the waterway meets the bay (also referenced as Cape Agivo), and the TOF. Measurements were conducted using Acoustic Doppler Current Profiler (ADCP) working alone or in combination with the single point measurement equipment, EMIST, for calibration and verification purposes. Measurements were conducted during the summer periods of 2014 and 2015. Figure 8 shows an example time series of measured current velocities data at two locations (Entrance and TOF) during the period of June-October 2014.

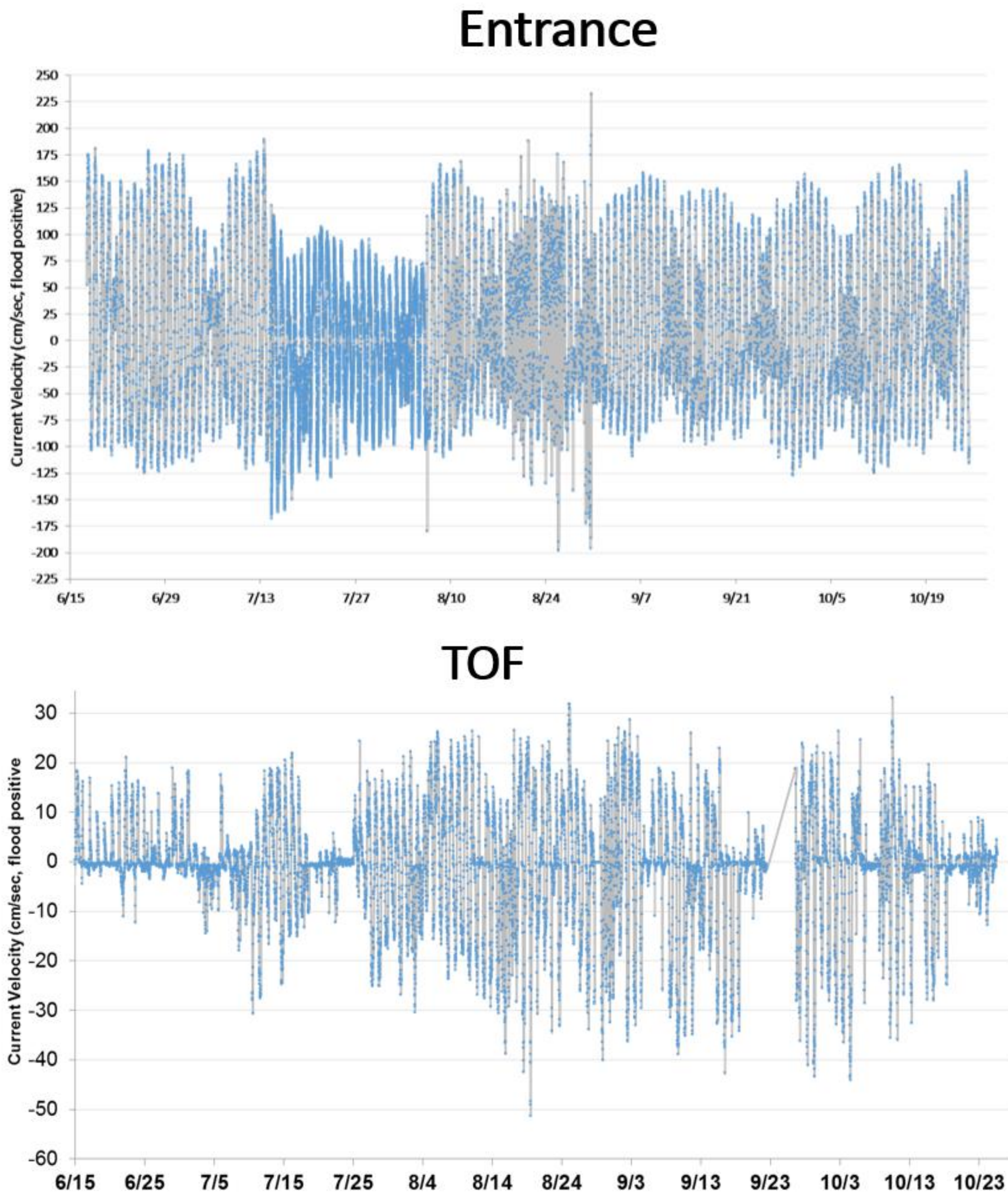


Figure 8. Example of measured near-surface currents at the Entrance (top panel) and the TOF (bottom panel) during the summer months of 2014. (Please note differences in vertical scales). Blue dots indicate data points.

Flow circulation numerical modeling was conducted with the 2-Dimensional hydrodynamic model MORPHO (Kivva *et al*., 2006). The model was calibrated and validated using the measured current velocities data collected during the field measurements campaign. Figure 9 shows an example modeling result, which is a depiction of depth averaged velocities over the modeling domain in color format. The results of the modeling showed a complicated character of current velocities along the project domain. Highest velocities are observed at the bay entrance (as shown in Figure 9). Typically, the ebb and flood tide currents in the bay entrance are about 2m/s. Flow velocities reduce upon propagation inside of the bay and typically are on the order of 0.5-1m/s within the narrow portion of the bay, i.e., the first 10 km from the entrance. Currents near the TOF are relatively small and typically are around 0.25-0.5 m/s.

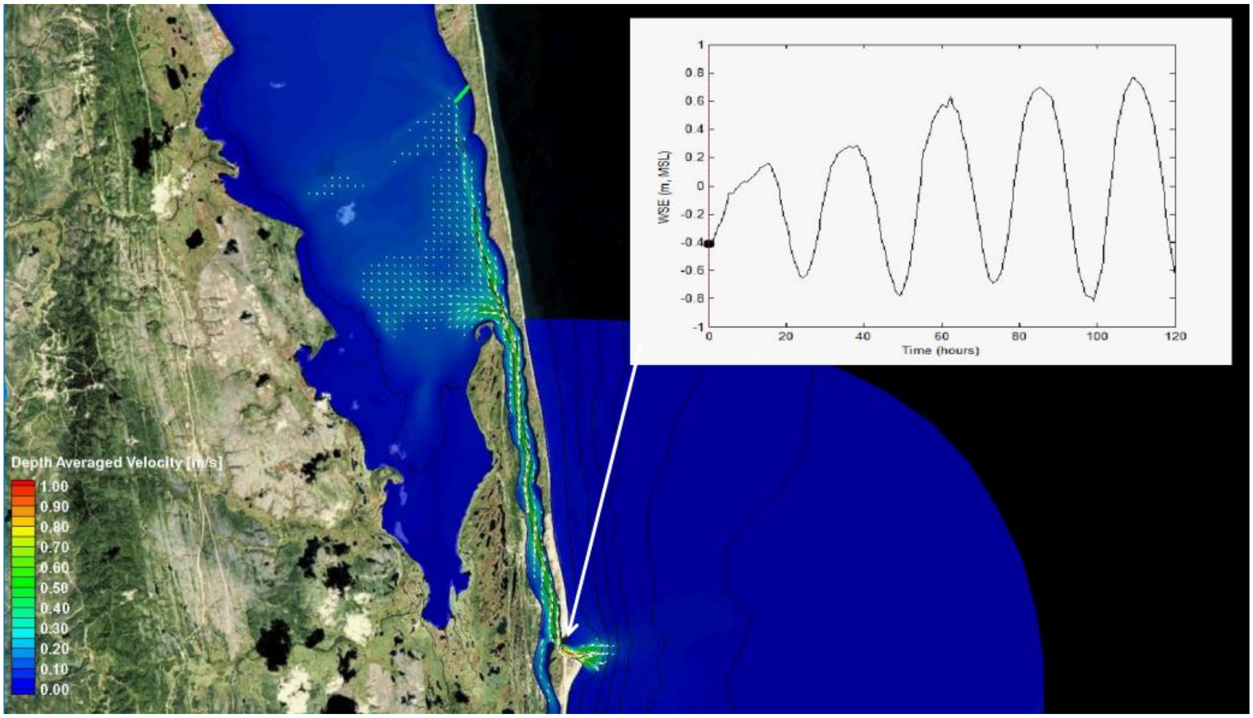


Figure 9. Depiction of Numerical Circulation Modeling Results for Piltun Bay (redder colors indicate higher velocities)

Geomorphology

The data collection program and analysis has identified unique phenomena in geomorphology at the entrance to the bay. It was found that the entrance, including the offshore sand bar system (ebb delta), are in a permanent dynamic condition, migrating to the south with an approximate annual rate exceeding 30 meters per year. Figure 10 shows the channel bottom profile evolution between the years 2012 and 2015, which verifies the historical knowledge that the natural channel at the entrance is migrating to the south at an approximate rate of 30-50 meters per year. Over the past 3-4 years, the tidal channel thalweg over the bar appears to be rotating to the south at a more accelerated rate than at the primary entrance between spit features.

Geomorphic analysis was conducted for planned navigation areas within the waterway in Piltun Bay. Bathymetry within the bay was found to be more stable than the dynamic region outside the entrance. A comparison of bottom elevations was conducted and depth changes were found to be insignificant, as shown in Figure 11.

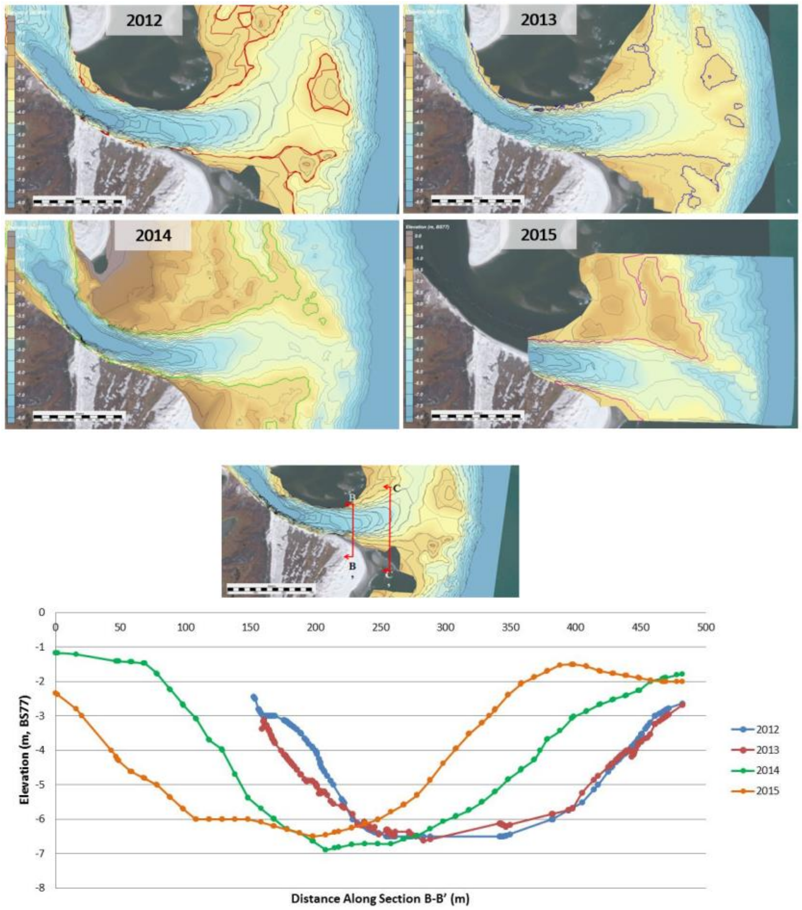


Figure 10. Tidal Channel Thalweg Migration (2012-2015). Plan view (top panel), with 3.0m depth contour highlighted relative to BS77, and cross section view (bottom panel)

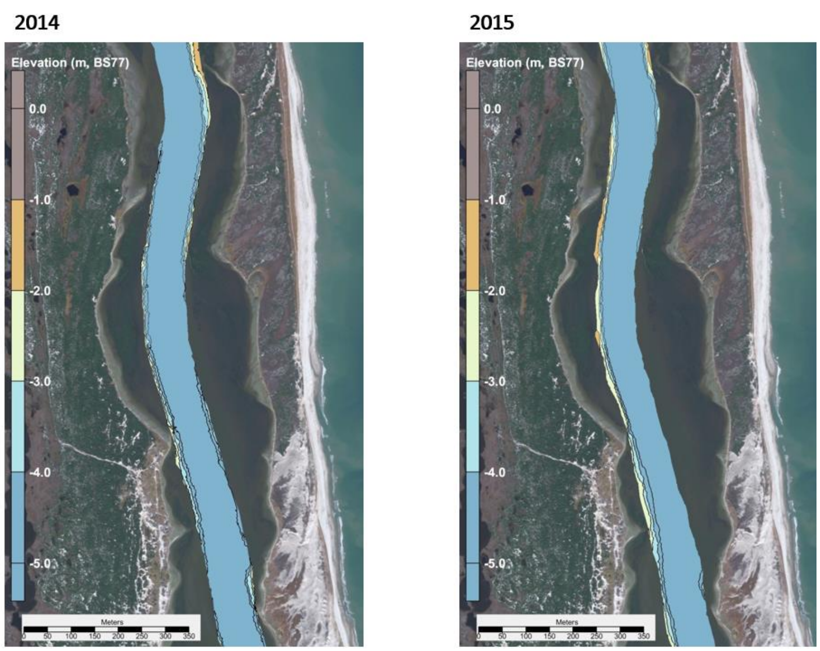


Figure 11. Depths in protected Natural Waterway. 2014 (left panel) and 2015 (right panel)

OPERABILITY ANALYSIS

The operability analysis was conducted to determine if the natural waterway can support the barge traffic needed to satisfy the schedule of the OS2 project by delivering and offloading 15 barges loaded with modules from South Korea and from Brownsville, TX. Due to ice and severe wave conditions, the window for delivery of barges with modules to Piltun Bay TOF is limited to 2-4 months in the summer period. Therefore, for planning purposes, the objective of operability study was also to identify if a single summer period would be sufficient to complete the delivery operations of 15 loaded barges. Otherwise, if the window is determined not be sufficient, the delivery operations should be conducted over several summer seasons. The analytical operability model, Piltun Bay Operability (PBO), was developed in probabilistic mode and was used for the conditions of the Piltun Bay barge delivery project to estimate the probability of a one-year (2016) modules delivery operation. If indeed this probability is low, then the 2-year duration delivery operation would occur.

The PBO model is a logistical Monte-Carlo type simulator which makes probabilistic estimates of the likelihood of successful barge delivery given different scenarios, input conditions, and assumptions. The model inputs incorporate both deterministic time-series data (tides, currents) and statistically-driven parameters (waves, winds, bottom depth conditions, visibility, and a manmade factor during delivery process). Winds, waves, and visibility are randomized based on measured statistical distributions at each applicable checkpoint in the model. Tides and currents are predicted hourly in the model, and are assumed to be known for each model hour at each checkpoint. A wide-range of input parameters is required to run the PBO model and to provide reliable information on barge delivery operability in Piltun Bay in 2016. These include Metocean input parameters, module dimensions, sequence of delivery, barge specifications, operational conditions, and operational constraints. Metocean input parameters were developed as described in the Site Conditions section of this paper, results from a navigation study conducted by The Glosten Associates, and input from Exxon-Neftegas Limited (ENL). Underkeel clearance at the Piltun Bay mouth is a major limiting factor, and is assumed to be characterized by the combination of barge draft, depths at the sandbar outside the mouth, wave action, and tide elevations.

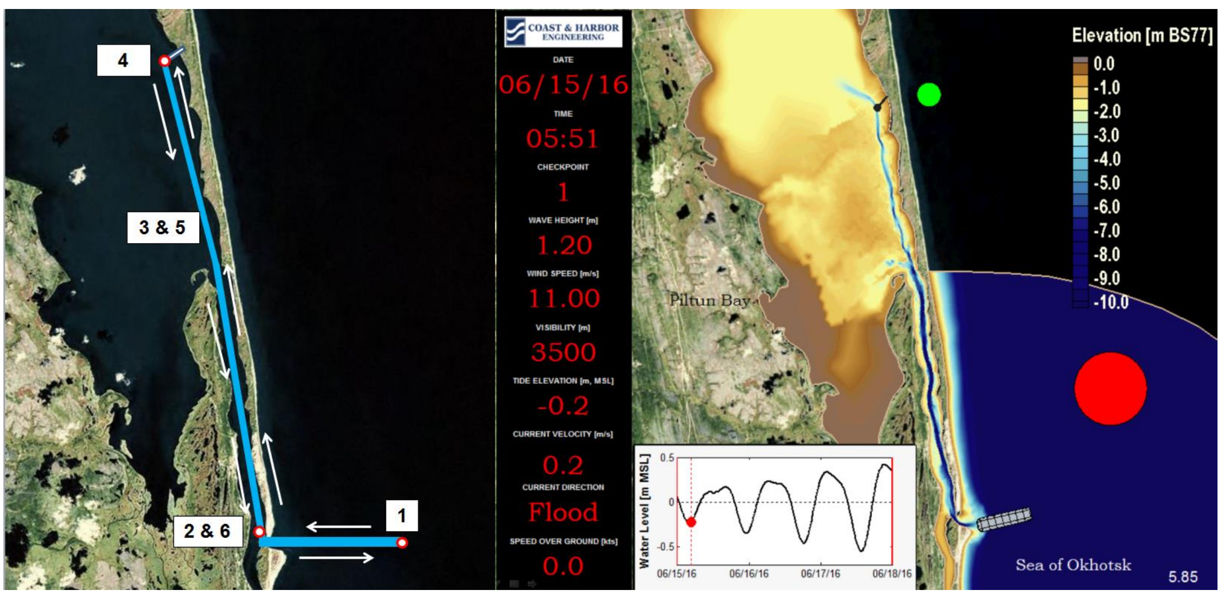
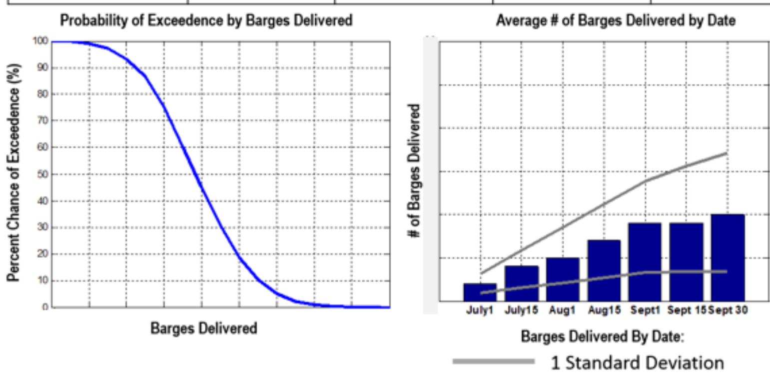


Figure 12. PBO modeling domain consisting of five (5) checkpoints: 1 – Transfer point; 2 and 6 – Staging area; 3 and 4 – Channel through the bay; and 5 –TOF (Left Panel). Example PBO simulation snapshot (right panel).

The model simulates loaded barges (with the OS2 modules) traveling from the Ocean Transfer Point (OTP) 4km offshore through the bar, bay entrance, waterway, bay, offloading modules at the TOF, and returning light drafted barges back to the OTP, represented by point 1 in Figure 12. For this purpose, the modeling domain consists of five (5) legs (or check points), as shown in the left panel of Figure 12. The PBO model analyzes conditions at each checkpoint (starting from the OTP) at various specified frequencies, and provides information for a go or no go decision. For example, for the barge with a module at the OTP and ready for travelling toward the entrance, the model analyzes and resets the predicted parameters: depth, winds, waves, tide elevation, current velocities, and visibility at a model interval of 1 hour. Then, the model compares the predicted parameters to the navigable criteria at the entrance to Piltun Bay (criteria agreed upon by the project team). If all the above predicted parameters are within the navigable criteria, the PBO model outputs a "go" decision. The barge then proceeds to the next checkpoint, and the analysis resets and repeats. If any parameter from the above exceeds the navigable criterion, the model outputs with a "no go" decision. The barge waits at the OTP, or its current checkpoint location, until the next check occurs.

The PBO model tracks movements of each barge throughout the operational period, marking the day and hour that each barge is at each checkpoint. For example, the model knows what day of the year, and what hour a given barge would be exiting the bay for a given model scenario test (e.g. varied staging area location, barge draft, etc.). For a single year, it then tracks when each barge has made its delivery, and the total number of modules that have been delivered between June 15 and September 30. This process is repeated 10,000 times for each model scenario. The outcome of each simulation was considered as a sample of the statistical dataset that was further used to determine probability of successful delivery barges during a one-year (2016) period, for any number of barges selected (e.g. 11 or 15).

Time Frame	# of Barges per Delivery	Operational Conditions	Barges Required	% Chance of Delivery
June 15 – September 30	1	Lower Bound	15	2%
June 15 – September 30	1	Upper Bound	15	6%



Time Frame	# of Barges per Delivery	Operational Conditions	Barges Required	% Chance of Delivery
June 15 – September 30	2	Lower Bound	15	58%
June 15 – September 30	2	Upper Bound	15	73%

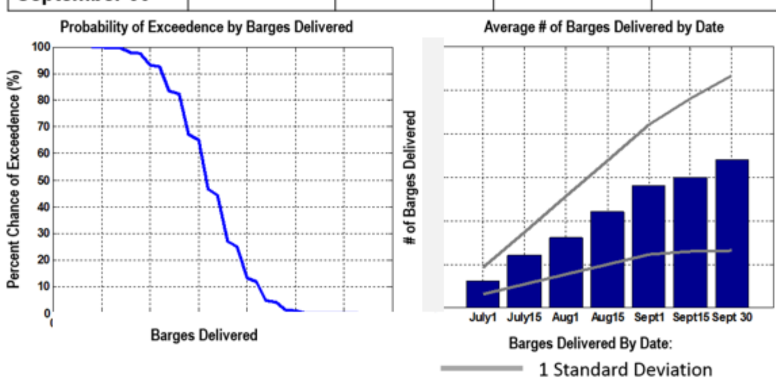


Figure 13 - Operability Analysis Results Example. Top panel shows results without a staging area. Bottom panel shows results with a staging area (some information shaded to preserve confidentiality).

Figure 13 is an example of model output and shows modeling summary for two different scenarios of the input operational conditions. The tables within the figure indicate several example operational conditions[4], including the delivery window (June 15-September 30), number of barges per delivery, and total barges that are required to be delivered per one 2016 season. A “2” in the number of barges per delivery column indicates that 2 barges shall be crossing in each favorable weather window (should the window be wide enough for two tug/barge combinations to enter), where one of them shall be staged just inside the entrance as the other is delivered to the TOF. A “1” in this column indicates no staging area would be used, and one barge crosses per favorable weather window. The operational conditions, referenced in the figure also include upper and lower bounds. The upper bound reflects the most optimistic conditions for barge movements, and greater speed crossing the bar, while the lower bound assumes possible complications with delivery due to human and other unexpected natural factors. The righthand column in the tables in Figure 13 show the computed probability of success estimated by the model. As shown by Figure 13, the likelihood of successful delivery of the barges is much greater with a staging area inside of the Piltun Bay. But even with the staging area the probability for success of delivery all 15 barges was estimated to be in the range between 58% (lower bound) and 73% (upper bound), which was found to be a high risk to the project.

As result of the operability analysis, the Project Management Team had decided to perform 2-years delivery operations: 11 barges to be delivered during Summer 2016 and remaining 4 barges[5] during Summer 2017. In addition, it was decided to incorporate into the waterway design two barge staging areas in Piltun Bay.

WATERWAY DESIGN

The Piltun Bay waterway design was completed to provide safe navigation and module delivery operations while accounting for the complicated natural conditions and restrictions on dredging dictated by Russian Regulatory rules. The limiting depth of the bar crossing was determined to be 2.9 meters BS77, or 2.6 meters MSL. The typical width of the waterway at this depth was determined to be approximately 130 meters.

To perform the emergency removal of sediment that may encroach into the waterway in a form of sand waves and to comply with regulatory restriction of “no dredging”, a special “screeding” barge was designed and built by Manson Construction and delivered to the site by the marine contractor. The screeding barge includes a leveling beam suspended from barge that grades the subsurface seabed to the design depth, if needed.

Design of navigation aids was complicated by the compliance with Russian Coastguard regulatory requirements. It was found that some statutes of this regulatory code are not completely applicable to the project’s physical and operational conditions. If navigation aids were designed to follow strict Russian regulatory conditions, the number and types of ocean buoys and markers to be delivered and deployed along the waterway would have made the project infeasible to complete at the time required for barge delivery. At the same time, the installation of such number of buoys and markers would have conflicted with the rules imposed by the other Russian regulations- such as Russian environmental regulatory requirements. To find a compromise with the Russian Coastguard Regulatory requirements, a full bridge simulation was conducted and results of the simulations were incorporated into the design. At the end the design of navigation aids was completed using combined standards, defined by International Association of Lighthouse Authorities (IALA, 1990) in combination with most applicable stipulations from Russian Coastguard Regulatory requirements.

Two staging areas were incorporated into the design of the navigation waterway, following the results of the operability study. Locations of these staging areas were coordinated with the Marine Transport Contractor, and were based on the most recent available survey data. A depiction of the final geometric design for a part of the navigation waterway is shown in Figure 14. Note that some text included in this figure is in Russian.

[4] Please note that there are other operational conditions that are required to run the model, such as: module dimensions, sequence of delivery, barge specifications, MetOcean parameters, etc. For the sake of space all other parameters not discussed herein are not shown

[5] Furthermore, it was determined that additional 4 barges with modules are required for OSC2. Thus 2017 delivery will consist of delivery of total 8 barges.

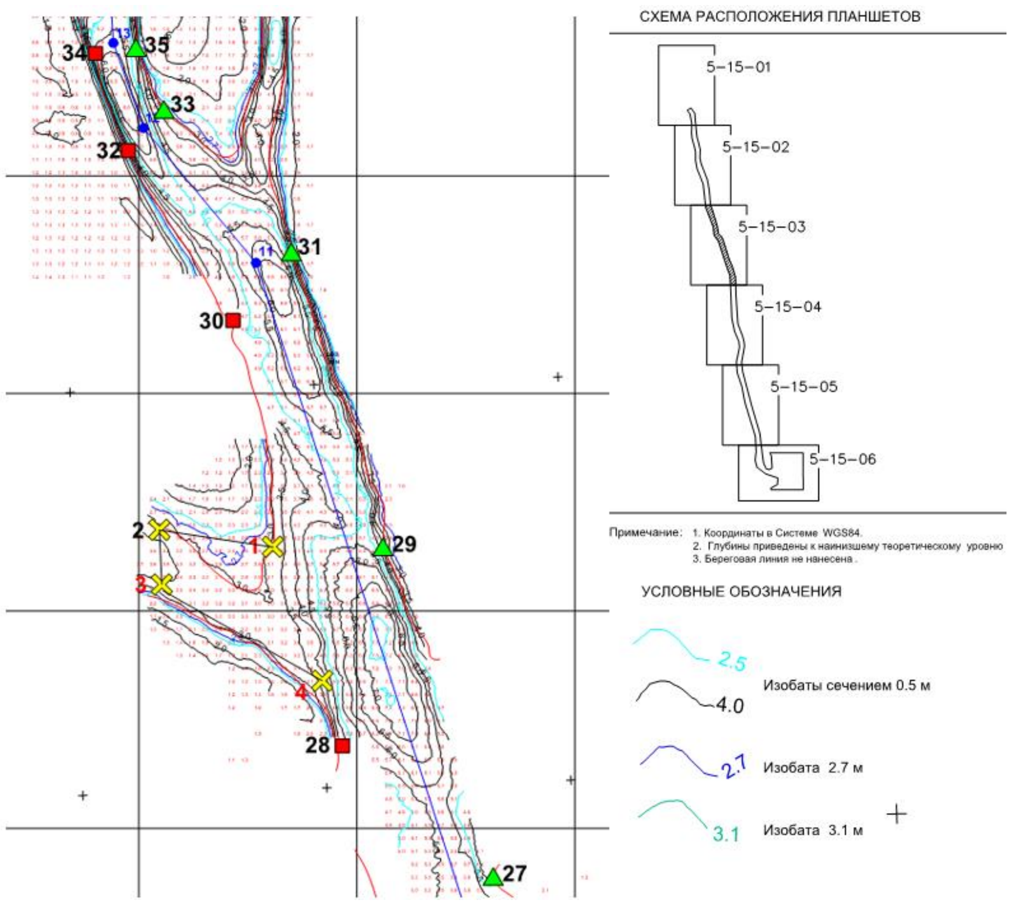


Figure 14 – Excerpt of Final Navigation Channel Centerline Alignment (blue line), Navigation Aid Locations, and Staging Area (yellow "X" symbols). Gridlines are on 500m spacing.

2016 DELIVERY SEASON

As discussed above, the decision was made to conduct barge delivery operations over two summer seasons (2 years). Eleven module barges were scheduled to be delivered during period June 15-September 30 of 2016. In anticipation of this first year's delivery operations, the hydrographic survey crew and equipment were mobilized on site at the end of May 2016, standing by for ice clearing and acceptable weather conditions on the bar. Upon obtaining survey data, navigation aids were installed and barges with modules were given clearance to approach Ocean Transfer Point on June 14.

Due to the high skills and careful training of the Marine Transportation Contractor, all further operations with delivery 11 barges went smoothly and were completed ahead of schedule. The last (11^{th}) barge was delivered in mid-August, prior to the fall storms arriving to Piltun Bay.

During the summer of 2016, depth conditions at the entrance were highly dynamic, as expected. A thalweg of the natural waterway shifted to the south by approximately 75 m during a two-month period (June 1-August 2). Because of the dynamic nature of the thalweg across the bar, the project team anticipated the need to be adaptive in navigation aid location during the delivery season, which required re-alignment of the navigation aid location.

Re-alignment of the waterway and appropriate relocation of navigation aids was sufficient for the first year of operations (2016) and the need for screeding barge at the project site to maintain navigable conditions at the entrance to Piltun Bay was not required. However, to control risks related to safety conditions, the screeding barge is still scheduled to be part of the 2017 barge delivery (Sealift) operations. The experience with monitoring depth conditions at the entrance and timely repositioning of navigation aids is now well documented and will be further utilized for the 2017 barge delivery operations.

SUMMARY

A navigation waterway, consisting of bar, entrance, waterway, bay, and TOF elements was designed to provide safe navigation and offloading operations for the barges loaded with modules. Significant amounts of historical and new field data were collected, and extensive numerical modeling efforts were undertaken to assess specifics of natural conditions and develop waterway design criteria.

The analytical operability model, Piltun Bay Operability (PBO), was developed and used to determine the feasibility of safe navigation and offloading of the loaded barges and estimate probability of success for various barge delivery scenarios. The PBO model appears to be a reasonable tool for the planning level and design. If the PBO model is used in the future, special attention should be given to data collection and data quality to properly define the project physical conditions.

In combination with input from the project team (tug captains, Russian regulation experts), the navigation waterway design provided the framework for successful delivery even if conditions had been significantly worse than experienced in 2016.

The delivery of 11 barges was completed on August 2, 15 days ahead of schedule. There were several outstanding factors that worked well in support of delivery operations in 2016. Based on lessons learned, it appeared that constant monitoring of depth conditions and timely repositioning of navigation aids was the most reasonable method to provide navigable conditions for such complex physical conditions and restrictions that exists along Piltun Bay. This method was recommended and will be intensively used for the 2017 barge delivery season.

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