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Environmental Statement

Appendix D.3 - Sediment Re-Suspension by Cruise Ships

September 15, 2015

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Innovation, Excellence & Service

Proposed Cruise Berthing Facility, Grand Cayman

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Appendix D.3 - Sediment Re-Suspension by Cruise Ships

Prepared for

Ministry of District Administration Tourism & Transport and The Port Authority of the Cayman Islands

Prepared by

Baird

W.F. Baird & Associates Coastal Engineers Ltd.

For further information please contact
Dave Anglin at 1-608-273-0592

12214.101

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1.0 INTRODUCTION

Operation of the proposed cruise berthing facility will involve the berthing and de-berthing of large cruise ships at the piers. These operations, specifically, the hydrodynamic flows generated by vessel propulsion systems (propellers, Azipods and thrusters) during berthing and de-berthing, may result in "re-suspension" of sediments from the seabed, with the potential for increased turbidity and sedimentation levels in the surrounding areas and associated impacts on the marine environment, including corals and fish. For example, Figure 1.1 presents a photograph of a turbidity plume generated by a cruise ship departing from The Royal Naval Dockyard in Bermuda.

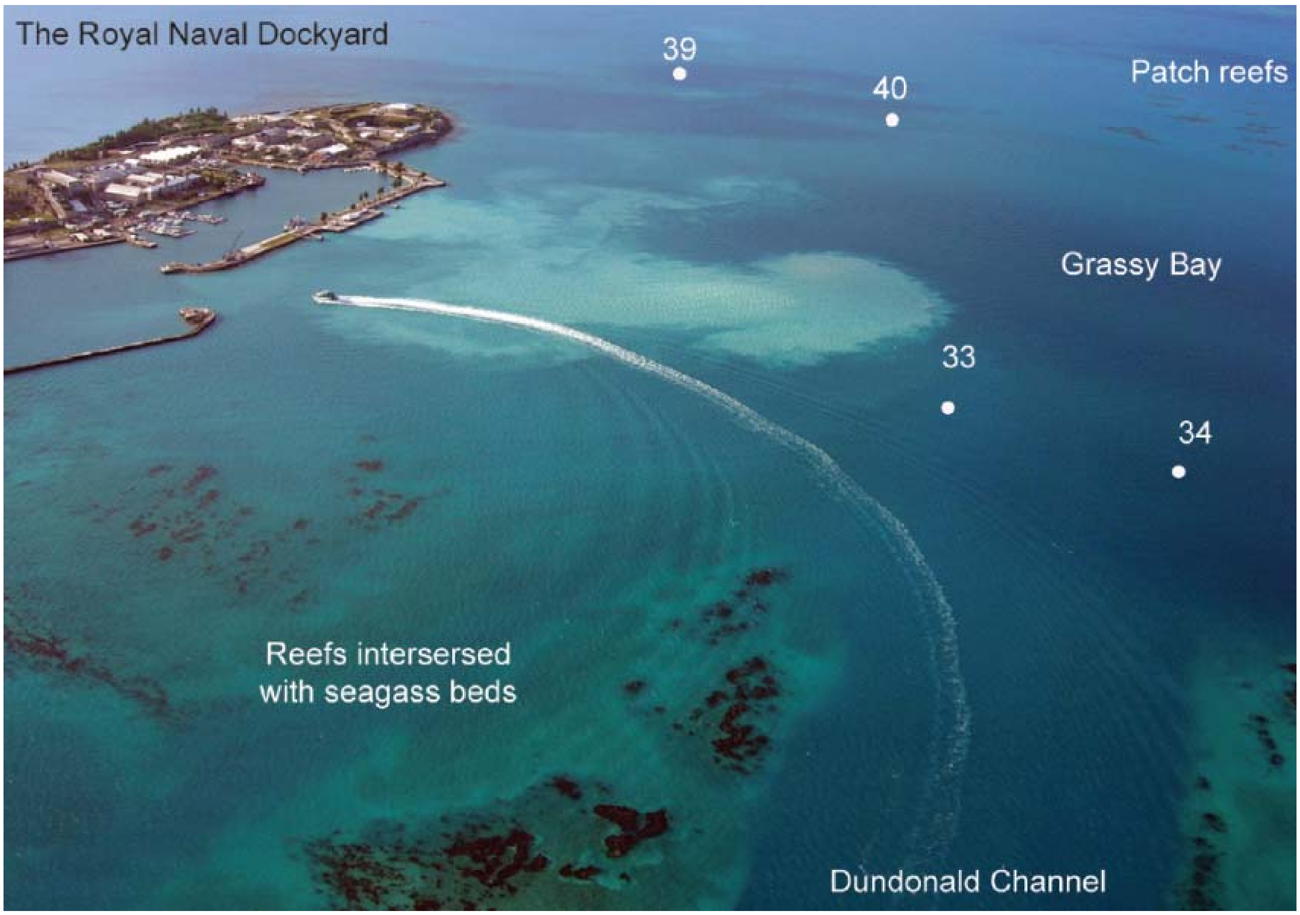

Figure 1.1 Turbidity Plume Generated by Cruise Ship Departure from The Royal Naval Dockyard, Bermuda (Source: Jones, 2011)

This Appendix presents a review and assessment of sediment re-suspension in George Town Harbour due to the operation of the proposed cruise berthing facility.

2.0 ASSESSMENT METHODOLOGY

2.1 Overview of Sediment Re-Suspension Process

The process of concern is illustrated in Figure 2.1; the spinning propeller (or Azipod or thruster) generates a high velocity, turbulent flow field that dissipates with distance from the propeller ("prop wash"). Interaction of the prop wash with loose sediments on the seabed may be sufficient to mobilize, suspend and entrain these sediments, with finer sediments being more prone to this "re-suspension" process, and the associated development of a turbidity plume. The presence of confining structure (such as a solid quay wall) may exacerbate the process.

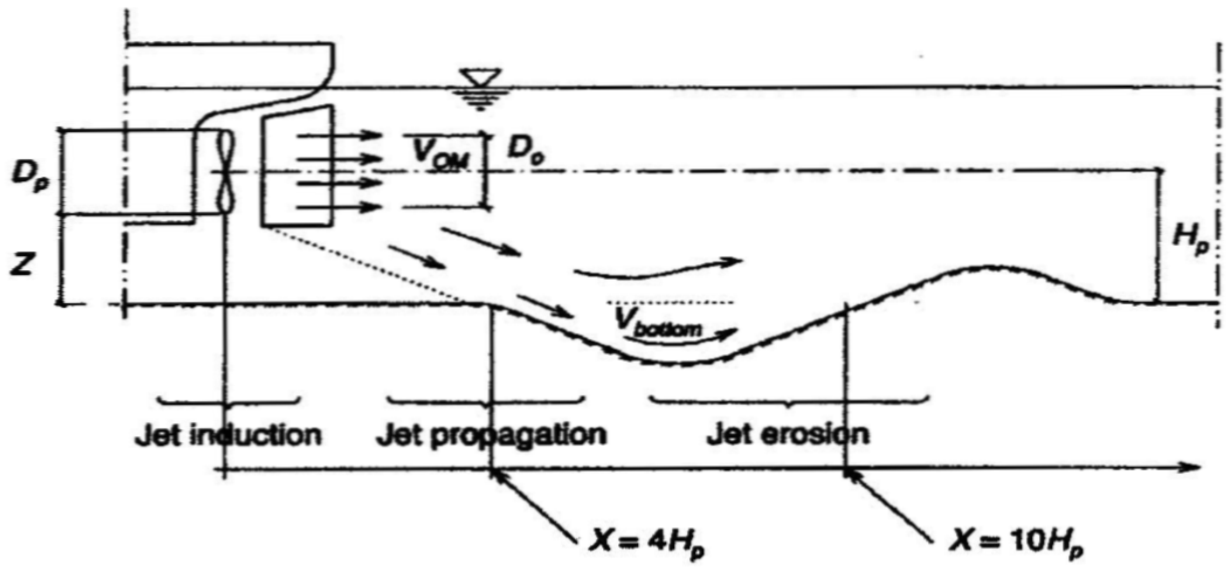

Figure 2.1 Schematic Illustration of Prop Wash (Source: PIANC, 1997)

2.2 Key Processes, Methodologies, Variables and Uncertainties

A summary of the key processes and available methodologies to assess them, and key variables and uncertainties, is presented below:

Flow Field

- Empirical models are available to estimate the flow field generated by propellers and thrusters;
- Key variables include the following:
  - Propeller type (i.e. ducted or non-ducted),
  - Propeller diameter,
  - Propeller height above seabed,

- Applied power,
- Presence of/proximity to structures (i.e. quay wall, revetment, etc.).

Sediment Mobility

- Empirical models are available to estimate the initiation of motion of loose granular sediments;
- In general, finer materials (i.e. silts) are more susceptible to mobilization than coarser materials (i.e. sands and gravels); the mobility of cohesive materials (i.e. clay) is difficult to estimate.

Sediment Entrainment

- While sediment may be mobilized by a particular flow field, it will not necessarily be entrained in the water column and create a plume;
- Finer materials are more prone to entrainment than coarser materials, and will stay in suspension longer;
- The entrainment process is very complex, and requires sophisticated three-dimensional numerical models of hydrodynamic and sediment transport processes to simulate it;
- Due to the complexities involved, available models have significant limitations;
- The entrainment process is a key uncertainty in estimating sediment re-suspension.

Seabed Composition

- As noted above, finer materials (i.e. silts) are more susceptible to mobilization and entrainment in the water column than coarser materials (i.e. sands and gravels);
- Once suspended, finer materials remain in suspension longer;
- The duration that sediment stays in suspension can be estimated using empirical estimates of fall velocity, which is principally dependent on the sediment grain size.

Water Depth

- The influence of the flow field on the bottom reduces as the water depth (and under keel clearance) increases.

Metocean Conditions

- Currents associated with prevailing metocean conditions (i.e. wind, waves and tides) will have a significant impact on the extent of turbidity plume; stronger currents will result in a larger plume;
- Turbidity plumes may also be generated by waves and currents, particularly under breaking wave conditions in shallow water.

Considering the information presented above, the key uncertainty in estimating the occurrence (or not), frequency and extent of turbidity plumes is the sediment entrainment process. While tools are available to estimate the flow field generated by propellers and thrusters, and the initiation of motion of seabed sediments, it is not yet possible to reliably quantify sediment entrainment and plume generation (i.e. suspended sediment through the water column).

Section 3 presents a review of baseline conditions associated with vessel operations at the existing port. Section 4 presents modeling and analyses undertaken to assess the risk of sediment re-suspension associated with cruise ship operations at the proposed project. Finally, Section 5 presents possible mitigation measures to limit sediment re-suspension during project operations.

3.0 BASELINE CONDITIONS

At this time, traffic to and from the existing port is limited to cargo ships, tenders and other smaller vessels. Cruise ships presently anchor at one of four offshore mooring points; on busy days (i.e. greater than four cruise ships), the additional vessels remain on power in offshore locations.

Anecdotal evidence indicates that turbidity plumes are frequently generated by cargo ships and tenders when they apply power in shallow water areas adjacent to the quay walls. In addition, drogue tracking measurements undertaken by the DoE indicate that the use of thrusters by cruise ships moored offshore may generate large scale gyres within George Town Harbour. Furthermore, the marine ecology assessment undertaken for this study (refer to Chapter 16 and Appendix J.1 of the Environmental Statement) identified evidence of sedimentation stress on corals within GTH, in particular those located in shallower water where vessel traffic is more likely to result in sediment re-suspension.

Although the DoE has collected water quality data in George Town Harbour intermittently since 2000 (refer to Chapter 12 and Appendix E), no specific measurements of turbidity plumes generated by vessel traffic area are available within George Town Harbour. As an extension to the present EIA study, additional turbidity measurements are being undertaken to provide additional data on baseline conditions. Specifically, two turbidity sensors have been deployed for an extended period at two locations within George Town Harbour (Cheeseburger Reef and Eden Rock). As part of this measurement program (coinciding with intermittent retrievals of the instruments to download the baseline data), specific efforts may be made to collect turbidity data within plumes generated by cargo ship operations at the South cargo dock.

4.0 IMPACT ASSESSMENT

The construction of the proposed facility will included nearshore dredging to allow large cruise ships to berth alongside the new piers. The extent and depth of the dredged area will be limited to that necessary to allow safe navigation of the largest cruise ships expected to use the facility, as defined through discussions with the cruise lines and review of published design guidelines. The proposed dredge depths are -36.5 ft CD for the North pier (to accommodate *Oasis* class vessels) and -35.0 ft CD for the South pier (to accommodate all other vessels). The resulting "under keel clearance" (UKC, the distance between the ship's hull and the dredged seabed) will be a minimum of 6.5 ft, but typically in the order of 8 ft. The centre/shaft of the vessels' propulsion systems are located further above the seabed (details are vessel specific).

4.1 Project Impacts

As noted earlier, the ability to accurately predict/quantify sediment re-suspension and turbidity plumes associated with vessel operations is limited by the complexity of the processes involved. That being said, the following tasks have been undertaken to assess the potential for impacts associated with this process over the operational life of the project:

- Empirical and numerical modeling of key processes, including propeller generated flows, sediment mobilization and entrainment;
- Literature review
- Review of experience at similar facilities;
- Identification of possible mitigation measures to limit impacts.

4.1.1 Empirical Modeling of Flow Field and Initiation of Motion of Seabed Sediments

Published empirical methods (EAU, 1996; PIANC, 1997) were used to estimate the flow field generated by cruise ship propellers and thrusters, and the initiation of motion of seabed sediments. Figure 4.1 presents a summary of the results for typical cruise ships anticipated to call at George Town based on the dredge depth of 35 ft. These results indicate that very fine sand (0.074 mm) may be mobilized up to about 825 ft from the main propellers (at 50% power), and up to about 340 ft from the bow thrusters (at 100% power). Finer sediments may be mobilized at greater distances.

A review of existing borehole data for GTH in the vicinity of the proposed dredged basin showed that the loose sediments were relatively coarse (median grain size, D_{50} typically in the order of 0.2 to 2 mm) with an average of 7.4% fines (silt and clay sized particles, with $D < 0.074$ mm). However, it is noted that dredging in cemented materials may generate fines.

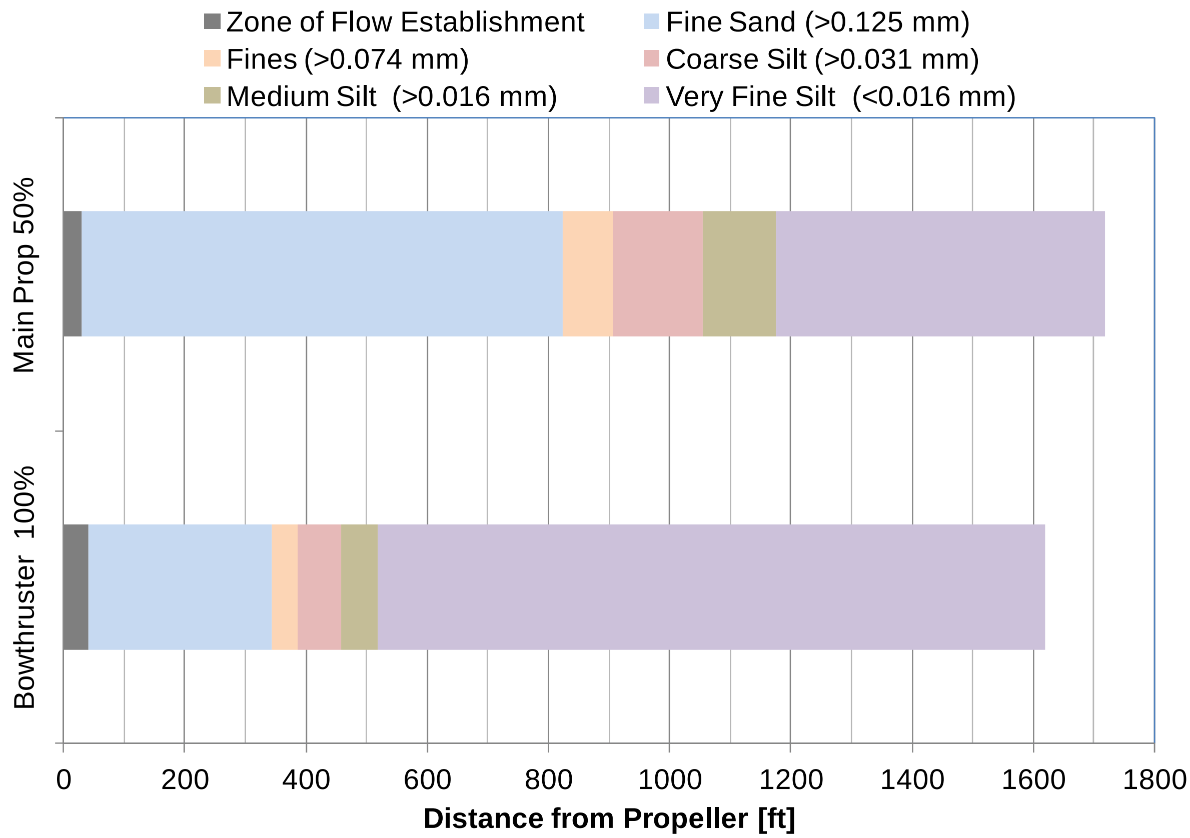

Figure 4.1 Estimated Mobilization of Seabed Sediments by Prop Wash

The input parameters used in these calculations are summarized below:

- 35 ft water depth (based on design dredge depth and low tide);
- Typical vessel characteristics - LOA ~ 1,000 ft, B ~ 122 ft, d ~ 27 ft, GRT ~ 90,000 to 140,000 t;
- Main propellers - 19 ft diameter, non-ducted, shaft 23 ft above the seabed, 50% power;
- Bow thrusters - 6 ft diameter, ducted, with shaft 20 ft above the seabed, 100% power.

The propeller and thruster details used in the calculations are based on a review of information for several vessels in the size range noted above. Larger vessels (with larger propellers and more power) may call at Grand Cayman, but relatively infrequently. The power application levels used in the calculations are based on discussions with Captains and published design guidance. Higher power levels are possible, but are typically only used in extreme or emergency conditions.

For comparison purposes, Baird estimated the wave conditions required for initiation of motion of sediments in a water depth of 35 ft. These calculations indicate that medium-coarse silt will be mobilized at this depth by wave height/period combinations in excess of 3 ft/6-8 s. Referring to the metocean report (Appendix D.1), these conditions are estimated to occur, on average, approximately 1% of the time, and would generally be associated with Nor'westers. Typical (less severe) wave conditions do generate turbidity plumes, but only in very shallow water (i.e. in the surf/breaking zone). This information indicates that initiation of motion of the seabed sediments does not necessarily result in sediment entrainment through the water column and the development of a turbidity plume. Hence, initiation of motion of the sediment is not directly indicative of the generation of a turbidity plume.

4.1.2 Numerical Modeling of Sediment Re-Suspension and Turbidity Plumes

A three-dimensional hydrodynamic and sediment transport model (MISED, an in-house model developed by Baird) was used to estimate the generation and dispersal of turbidity plumes caused by cruise ships berthing/de-berthing at the proposed facility. The processes-based model simulates the hydrodynamic flow field (including ambient nearshore currents, as well as the turbulent jet flow produced by propeller/thruster action), the mobilization/entrainment of seabed sediments, and the dispersion of the suspended sediment (i.e. the turbidity plume) around the project site. Key model input assumptions are summarized below:

- Typical vessel size and propulsion system details as summarized in preceding section;
- Seabed sediments include 7.4% fines (average for sediment samples in the project area);
- Propellers and thrusters operated for one minute duration (50% power for main props, 100% power for thrusters);
- Typical northerly or southerly flowing nearshore currents with average speed of 0.6 ft/s.

The severity, extent and duration of the turbidity plumes will be dependent upon various factors, including prevailing metocean conditions (in particular, wind) and ship power application levels (in general, more power is required to berth/de-berth under more severe wind conditions). For example, Figures 4.2 and 4.3 show the results of the MISED model simulations of the turbidity plume generated by the bow thrusters of a large cruise ship berthing/de-berthing at the north pier under moderate winds (15-20 knots) with typical northerly and southerly flowing currents (0.6 ft/s). As noted above, these simulations assume the bow thrusters are run at 100% power for one minute. These power application levels and durations are based on published design guidance and practical experience, including discussions with Captains and the results of navigation simulations completed for similar facilities.

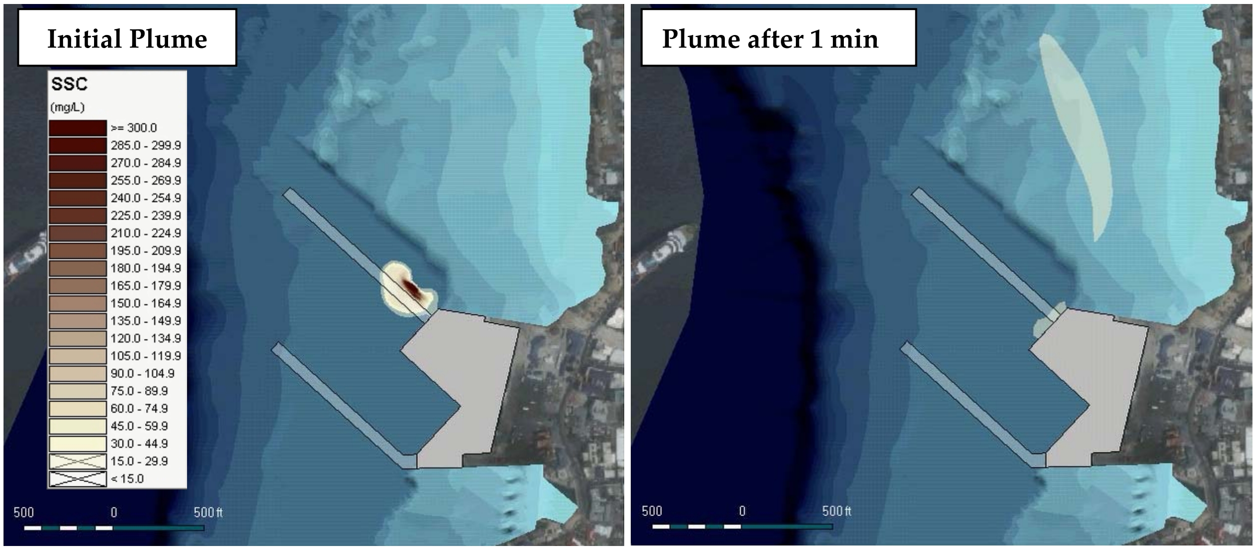

Figure 4.2 Estimated Turbidity Plume due to Bow Thrusters - Vessel at North Pier, North Currents

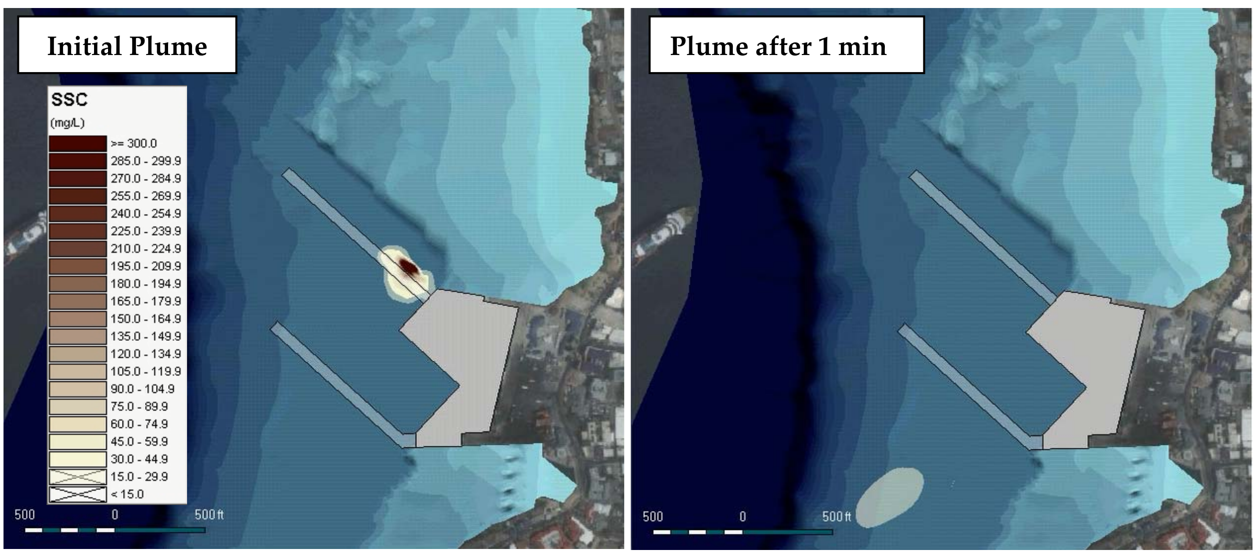

Figure 4.3 Estimated Turbidity Plume due to Bow Thrusters - Vessel at North Pier, South Currents

The MISED model appears to provide a reasonable simulation of the turbidity plume associated with the sediment re-suspension process. However, it is important to note that the model has not been calibrated or validated for this application. Given the complexity of the processes involved (i.e. turbulent flows generated by ships' thrusters and propellers, and resulting mobilization/ entrainment of seabed sediments), there is considerable uncertainty in the model results, including the severity, spatial extent and duration of the resulting turbidity plumes. A field observation/ measurement program of turbidity plumes generated by existing operations (i.e. cargo ships at the south cargo dock) could be undertaken to provide a better understanding of sediment re-suspension at the project site, and calibration data for the model.

Review of the MISED model results leads to the following conclusions regarding sediment re-suspension by cruise ships:

- Suspended sediment concentrations may exceed 100 mg/L in localized areas for short periods of time (as noted above, there is considerable uncertainty in these values);
- Elevated turbidity levels over the adjacent reefs may persist for several minutes;
- Sediment entrainment does not occur for coarser materials (i.e. sands and gravels), as these materials rapidly fall out of suspension;
- Sediment entrainment, and the severity of turbidity plumes, decreases as the proportion of fines in the bottom sediment decreases;
- Sediment entrainment, and the severity of turbidity plumes, decreases as the water depth increases.

4.1.3 Literature Review

A literature review was undertaken to identify other cruise ship facilities where sediment re-suspension and turbidity plumes have been identified as an issue of concern. A number of relevant papers were identified and reviewed (Gelinas et al, 2013; Jones, 2011; Thomas J. Murray & Associates, Inc., 2005). Specific sites where this process has been identified as a concern, and has been subject to study, include Bermuda, Key West and Venice. It is noted that the relevant characteristics of these three sites are very different from the George Town site, as follows:

- Projects are located in shallow, sheltered areas;
- Projects include long, dredged approach channels with bends/turns that require significant ship power application;
- Shallow water depths and high percentages of fine sediments adjacent to the dredged channels.

These factors result in a significantly greater potential for sediment re-suspension at these sites as compared to George Town Harbour. In particular, the following factors are noted:

- Shallow water depths and finer sediments increase the risk of sediment re-suspension by propeller and thruster generated flows;
- Course changes at channel bends require significant power application, particularly in shallow water;
- Shallow water depths adjacent to a dredged channel introduce another sediment re-suspension mechanism, that being the “displacement wave” generated by the movement of a large vessel through a confined channel.

4.1.4 Review of Experience at Similar Facilities

As part of an EIA for a proposed new cruise berthing facility in Barbados, Baird completed a review of turbidity plumes associated with cruise ship operations in the existing Port of Bridgetown. Key points are summarized below:

- Sediment re-suspension is not a significant issue in the existing port, despite limited under keel clearance for large cruise ships and the presences of fine grained sediments;
- Turbidity plumes associated with vessel operations are generally localized, and typically dissipate within 20 minutes;
- Localized turbidity levels may reach 10-60 NTU, versus background levels of 3-4 NTU;
- Turbidity plumes are more prevalent with departures than arrivals;
- More severe turbidity plumes are associated with more complicated maneuvers, which require increased power application.

Considering the characteristics of the Bridgetown site, the risk of sediment re-suspension is considered to be lower in George Town Harbour due to following factors:

- Coarser seabed sediments;
- Open pier structures (versus closed quay walls);
- Simpler vessel maneuvers (requiring less power).

4.1.5 Discussion of Anticipated Project Impacts

The information presented herein indicates that there is a potential for cruise ship operations at the proposed cruise berthing facility to result in sediment re-suspension and turbidity plumes. Due to the complex nature of the processes involved, in particular uncertainty related to quantifying the sediment entrainment process, it is not possible to systematically estimate the frequency of occurrence, extent or severity of turbidity plumes. The results of empirical and numerical model simulations indicate that the risk of sediment re-suspension decreases significantly as the water depth increases. Hence, the risk of sediment re-suspension is greatest in the dredged berthing area.

Comparison of relevant characteristics at the project site to those at other cruise ship facilities where sediment re-suspension is an issue indicates that the risk of sediment re-suspension is significantly lower at the George Town Harbour site. In particular, the coarser seabed sediments and limited extent of shallow water approaches to the site reduce the risk of sediment re-suspension events and associated turbidity plumes. In addition, ongoing vessel traffic will tend to “filter” out the relatively small proportion of fines present in the seabed materials; as such, it is anticipated that the risk of sediment re-suspension and turbidity plumes will decrease over time.

However, the proximity of the dredged berthing area to coral reefs to the north and south warrant consideration of measures to mitigate the risk of sediment res-suspension and turbidity plumes associated with project operations. Potential mitigation measures are discussed in Section 5.

4.2 Climate Change Impacts

The anticipated effects of climate change are not expected to have a significant impact on the sediment re-suspension process, or the frequency/extent/severity of associated turbidity plumes and sedimentation.

5.0 POSSIBLE MITIGATION MEASURES

The mitigation measures listed below could be utilized to reduce the risk of sediment re-suspension due to project operations.

<u>Project Design/Construction</u>

- Overdredge berthing area;
- Vacuum berthing area after capital dredging to remove fines;
- Install seabed stabilization measures in critical areas of berthing area.

The design and cost of such measures has not been estimated at this time.

<u>Project Operations</u>

- Limit vessel approach speeds to the minimum necessary for safe handling of the vessel;
- Limit power application at berth to the minimum necessary for safe handling of the vessel;
- Sequence ship arrivals and departures such that the first arrival/last departure provides shelter to the other ships from the prevailing winds;
- Require "bow-in" berthing unless prevailing or forecast weather conditions dictate otherwise (this puts the more powerful and larger main propellers in deeper water).

Finally, it is recommended that an environmental monitoring program be established and undertaken for at least the first season of operation of the facility. Specific details of this monitoring program should be determined through consultation with the DoE, but would likely include monitoring of turbidity and sedimentation, coral health and fish populations at specific locations surrounding the project. The results of the monitoring program should be compared to baseline measurements to determine if sediment re-suspension is an issue that requires ongoing monitoring and/or the implementation of additional mitigation measures.