# Fate of Suspended Dredge Material at Apra Harbor, Guam: Particle Tracking Around Coral Reefs

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**Abstract.** Model studies were conducted to investigate the potential coral reef exposure from dredging associated with development of a new deepwater wharf being considered by the US Navy in outer Apra Harbor, Guam. The Particle Tracking Model (PTM) was applied to quantify the exposure of coral reefs to material suspended by the dredging operations at the proposed sites. Key PTM features include the flexible capability of continuous multiple releases of sediment parcels, control of parcel/substrate interaction, and the ability to track vast numbers of parcels efficiently. This flexibility has allowed for model simulation of the combined effects of sediment release from clamshell dredging, of chiseling to fracture limestone blocks, of silt curtains, and of flocculation. Because the rate of material released into the water column by some of the processes is not well understood or *a priori* known, the modeling protocol was to bracket parameters within reasonable ranges to produce a suite of potential results from multiple model runs. Data analysis results included mapping the time histories and the maximum values of suspended sediment concentration and deposition rate. Following PTM exposure modeling, the next component of the study was an ecological assessment to translate the PTM exposure level predictions into predicted amounts of coral reef damage. The level of potential coral reef impact would be an important consideration in the final selection process for the new deepwater berthing site.

**Key words:** Particle Tracking Model, dredging, suspended sediment, coral reef, particle tracking.

## Introduction

The Particle Tracking Model (PTM) is a US Army Corps of Engineers-developed, computer model designed specifically to track the fate of suspended sediments and other constituents released from specific sources such as dredges, placement sites, outfalls, etc. in complex hydrodynamic and wave environments. Though the most common application has been for dredging activities, the model has also been successfully applied in other ways, such as tracking the dispersion of fish larva, dissolved contaminants, etc. (Lackey & Smith, 2008, Tate, *et al*, 2010). This report describes PTM's first application in a tropical coral reef environment.

The US Navy is studying alternatives for the possible construction of a new deep-water wharf at Apra Harbor, Guam. Potential sites are adjacent to large, diverse coral reefs, and there are concerns about site development impacts on those reefs. PTM has been applied to model the fate of suspended material released into the water column by the proposed dredging operations and to quantify the amount and rate of sediment interaction with the reefs. A separate team of coral reef biologists has converted these PTM exposure results into levels of biological impacts that can be anticipated at the reef sites.

Apra Harbor (Fig. 1, mod. from Smith, 2007), is home to a large, active US Navy facility. Its waters generally have low turbidity, though this can increase during wind events or from vessel propwash. The harbor is protected from most major wave influences that can re-suspend bottom sediments. Harbor

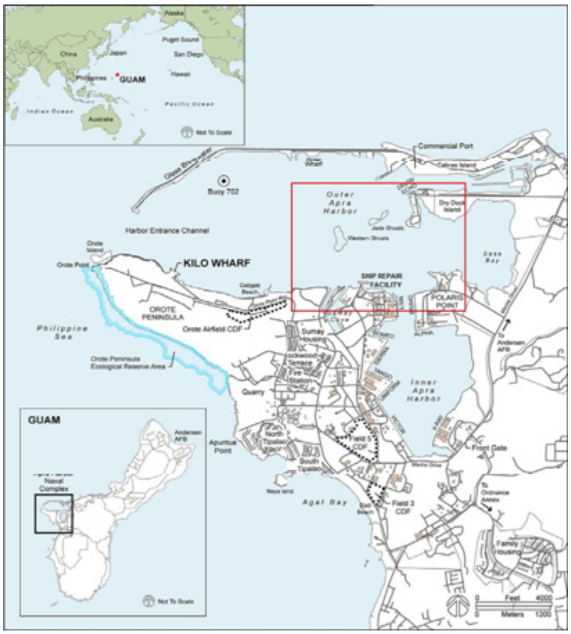

Figure 1. Apra Harbor, showing study area within red rectangle. Upper insert shows location of Guam in western Pacific, and lower insert shows location of Apra Harbor (black square) on western side of Guam.

currents are generally small and are driven by both tides and wind. Despite their proximity to ship traffic, large diverse coral reefs have existed adjacent to the shipping channel for decades.

Two potential wharf development sites considered here, Polaris Point and the former Ship Repair Facility, are located along the south shore of outer Apra Harbor near the entrance to inner Apra Harbor (red rectangle in Fig. 1). Development of either site would involve the dredging of shore-side material along with removal of numerous elevated mound areas within the harbor to a depth of 15.7 m to accommodate a channel and turning basin.

## Material and Methods

### *PTM Overview*

The PTM, a Lagrangian particle tracker, simulates the movement of multiple constituents (sediments, chemicals, debris, etc.) in complex flow fields (Davies et al. 2005, Lackey and MacDonald 2007, MacDonald et al 2008). The model combines accurate and efficient transport computations with effective visualization tools, making it a broadly applicable analysis tool for studies that focus on such activities as dredging and placement operations, contaminant transport, sensitive habitat, endangered species, material re-handling, and beneficial use activities. Although the model has been utilized in a variety of coastal and river applications, PTM was specifically developed to predict the fate of material released during dredging and placement operations, and to address the stability and fate of in-place sediments including dredged material mounds, sediment caps, and contaminated sediment deposits.

PTM models the processes of settling, deposition, re-suspension, and particle-bed interactions to simulate the transport of both fine and coarse sediment. Instead of undertaking the impossible task of tracking every grain of sand, silt, and clay, the sediment is discretized into “parcels” where each parcel is representative of a specific mass of sediment. These parcels preserve the overall size distribution and total mass of the sediment source. The model then steps through time tracking the position of enough parcels to obtain statistically appropriate distributions. PTM output includes time histories of the horizontal and vertical positions of the parcels along with other attributes such as mass, density, and suspension status.

Particle settling parameters may be user-defined or determined by algorithms based on verified theoretical and empirical relationships. For this application, particle size and density were used to define settling. PTM also includes particle interaction with native sediments and the potential for re-suspension.

Re-suspension potential is based on known parcel sediment characteristics, native bed sediment characteristics, and water column processes (McDonald et al., 2006). PTM includes probabilistic methods to account for burial, hiding, etc. For this application, because of the surface irregularities in a coral reef environment combined with the generally low current velocities at this site, the model did not allow parcel re-suspension once deposition occurred.

### *Model Inputs*

To run PTM, the user must develop several types of model inputs, including bathymetry, hydrodynamics, sediment characterization, and sediment source release protocols.

PTM tracks particle positions that are located on a site specific 2-D or 3-D bathymetric grid. The hydrodynamic flow field is also established on the same grid. For the Apra Harbor study, a 3-D grid was required by the dramatic changes in relief. The horizontal component of this grid was curvilinear, with the smallest grid cells being in the vicinity of the proposed dredging operations and adjacent reefs. Cell resolution was approximately 30 m in these areas, expanding to approximately 200 m far from the areas of interest. In the vertical, there were a varying number of layers up to 26, depending upon the depth, each having a height of 2 m. The grid was developed using bathymetry data from several sources.

In PTM, the sediment is primarily driven by a hydrodynamic input that includes water velocities and surface elevations. Since the hydrodynamics and sediment transport models are not coupled, the hydrodynamics model can be set up and calibrated once, then used with multiple PTM variant runs. For Apra Harbor, the hydrodynamics were developed using CH3D-Z (Curvilinear Hydrodynamic in Three Dimension—Z-plane version), a general-purpose 3-D hydrodynamic model for simulating flows in rivers, lakes, and coastal areas (Johnson et al., 1993). The model solves primitive equations and is based upon the Boussinesq approximation and the hydrostatic assumption. Three-dimensional internal mode and depth integrated external mode use the same time step. For turbulence closure, a k-ε model is invoked. The simulation covered a three-month period which coincided with the availability of field data which were used for calibration.

To characterize the sediment at the potential dredge sites, a total of 75 sediment samples were collected as cores and grab samples at four different times. A grain size analysis of these samples showed no consistent spatial trends, so all the turning basin samples were averaged as were all the samples at each of the shore-side sites. These average samples were assumed to be representative of the size distributions of the material that would be released during dredging operations. Each of these average samples was then divided into sand, silt, and clay percentages.

The loss of material at each dredging location was simulated in PTM as a series of co-located vertical line source releases. The sand, silt, and clay fractions were released separately to allow the parcels to behave differently because of the great differences in their diameters and settling velocities.

Along with the size distribution of the material being released, PTM also needs to have a specification of the rate, the position, and the length of time of each release. To define these, estimates were needed for the average daily dredging production rate, the rate that material was introduced into the water column by dredging and by chiseling, the vertical distribution of the losses within the water column by a clamshell dredge, the effects of a silt curtain, and the effects of flocculation. Because there are significant sources of uncertainty in these numbers, the approach taken was to bracket several of these quantities, using representative high and low (or high and average) values. In selecting these values, it was assumed that a dredger would conscientiously be attempting to follow best practices procedures.

Using data from several sources (Sea Engineering, 2009, Sea Engineering, 2010), average daily dredging rate values were bracketed at 1800 and 1110 $yd^3$/day as being representative of the rate on a good day and a long term average rate for a clamshell dredge working 24 hrs/day.

Clamshell dredging loss rates typically average less than 1% of production rates (Hayes and Wu 2001; Hayes et al. 2007; Bridges et al. 2008). Loss rates of 2% and 1% were modeled as representative of maximum and average values.

For this project, dredging will occur at locations not dredged before, and it is assumed that the dredger will encounter large limestone blocks that will need to be fractured prior to removal. For modeling purposes, the chiseling of limestone blocks prior to dredging was considered as a separate source term that added additional material to the water column near the bottom at a rate equivalent to that of low bracket dredging rates.

Loss material is introduced into the water column at the bottom as the clamshell bucket picks up a load, while the bucket is ascending to the surface, and at the surface while the material is being transferred to a barge or other holding facility. A typical estimate is that 40% is introduced near the bottom, 30% within the water column, and 30% near the surface (Paul Schroeder, personal communication, 2010). Thus, each release was modeled as a vertically stacked series of co-located (in x and y) vertical line sources.

Silt curtains are expected to be used during dredging operations and to be deployed with a bottom gap to reduce hydrodynamic drag. Curtains are assumed to be 100% effective at stopping all sand and silt sized particles (i.e., thus releasing all of these larger size fractions at the bottom gap) while stopping all or most of the clay fraction (USACE 2005). To bracket the results, the modeling assumed that silt curtains would be 90% or 100% effective at stopping the finest particles. A typical example of how PTM distributed the release of a kilogram of sediment is shown schematically in Fig. 2.

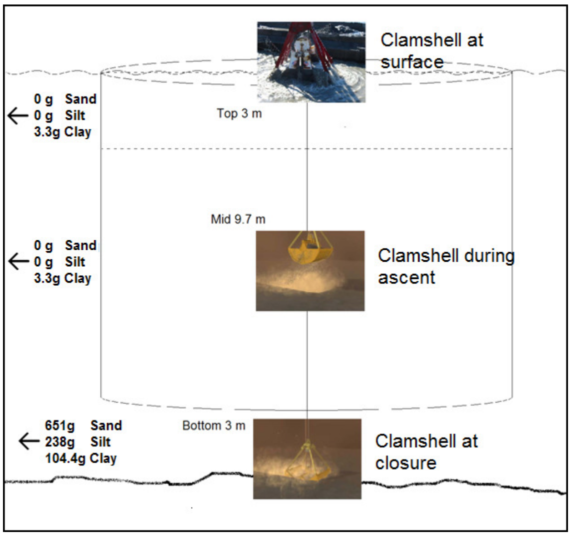

Figure 2. Example of PTM distribution of each kg of sediment released assuming a 90% effective silt curtain and a sediment distribution of 65.1% sand, 23.8% silt and 11.1% clay.

Flocculation is a complex process that causes sediments to loosely bind with each other and with other material within the water column which changes their settling velocity. This process was addressed in the modeling by bracketing. One extreme was to assume no flocculation, where all particles had a fall speed based upon their grain size. At the other extreme, all silts and clays were assumed to be flocculated and have a fall speed of 3 mm/s, based upon the work of Asaeca and Wolanski (2002).

The bracketing of four parameters meant that the model needed to be run 16 times for each potential wharf location simulation. The cases that caused maximum and minimum amounts of sediment exposure to the reefs were generally chosen for additional post-processing analysis.

## Results

Four types of data analysis techniques were utilized in this project. The PTM provides time dependent particle positions as output. These data were evaluated to help understand the general sediment movement. In addition, three types of contour maps were developed by post-processing the data, which presented the distributions of total accumulation, maximum deposition rate, and maximum water column concentration. These results were also made available in tabular form.

### *Particle Positions*

Particle positions produced by PTM help to monitor model performance and to determine particle pathways and general sediment movement. Fig. 3 shows settled particle locations at various times within the first two months for the Polaris Point scenario. This example result applies for Case 1 bracketed parameters (i.e., production rate of 1800 yd$^3$/day, 2% loss rate, 90% silt curtain efficiency, and no flocculation). The particles are color coded from red to blue based on the time of their release. The modeling assumed that turning basin sites would be dredged generally from north to south. Panel A) at the end of dredging day 1 shows that most of the particles have settled in close proximity to the northernmost dredge site. As dredging progresses southward, Panels B) and C) show that almost all particles continue to settle in the immediate vicinity of their release locations. It should be noted that only the early days of dredging are shown for this site. It requires 300 days to complete the dredging for this scenario using the Case 1 bracketed parameters.

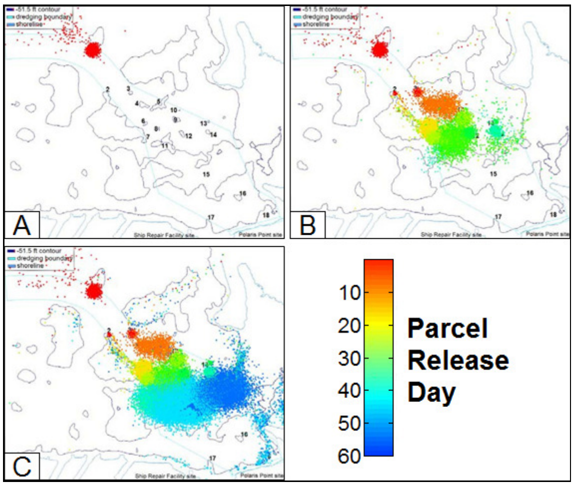

Figure 3. Settled particle distribution after: A) 1 day, B) 30 days, and C) 60 days. Particles are color coded based upon the time of their release.

### *Total Accumulation*

In post-processing, the PTM parcel output locations were gridded and various numerical attributes for the parcels were summed within each grid cell. This allowed the qualitative results presented above to be quantified. Contour maps were then generated from the gridded data. Fig. 4 shows the thickness of total sediment accumulation over the grid at the end of dredging for the two wharf loctions using Case 1 bracketed parameters. The colored contours allow for easy visual comparison of the results. Uncolored portions of the pictures do not indicate a zero value of the parameter at that location, rather merely that the value is below the minimum threshold.

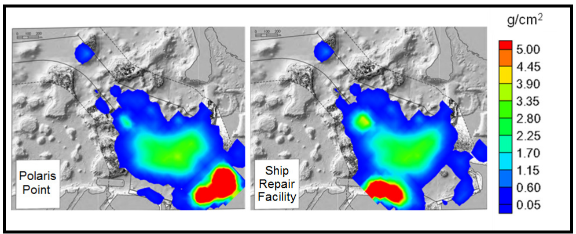

Figure 4. Example Case 1 total accumulation (g/cm$^2$) contours at two potential project sites.

### *Maximum Deposition Rate*

Maximum deposition rate is defined as the greatest daily rate of sedimentation that occurs at each grid cell during any time in the simulation. Therefore, the resulting plots are not indicative of any snapshot in time, but rather are a compilation over time of the maximum sedimentation rate value in the time series at each individual grid cell. It is expected that these rates can be compared to rates that are injurious or lethal to corals. Fig. 5 is an example output. It shows maximum deposition rate contours over the grid for Case 1 parameter values.

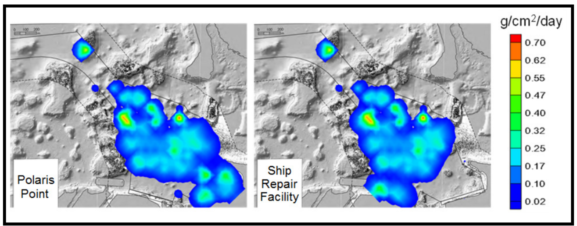

Figure 5. Example Case 1 maximum deposition rate (g/cm$^2$/day) contours at two potential project sites.

### *Maximum Suspended Solids Concentration*

The concentration of sediment within the water column (total suspended solids (TSS)) is important when determining light attenuation and ultimately the effect of lack of light on the coral. Similar to sedimentation rates, TSS values are maximum values at each grid cell for any day during the simulation. They therefore do not represent a snapshot in time, but rather a compilation of the greatest values over time. TSS values were calculated by vertically averaging the parcels throughout the water column. Results are provided in units of kg/m$^3$.

It should be noted that these values are only the dredging-induced TSS and do not include background levels, which would need to be added prior to determining the total light attenuation or turbidity. Fig. 6 is an example output showing maximum dredge-induced TSS over the grid for Case 1 parameter values.

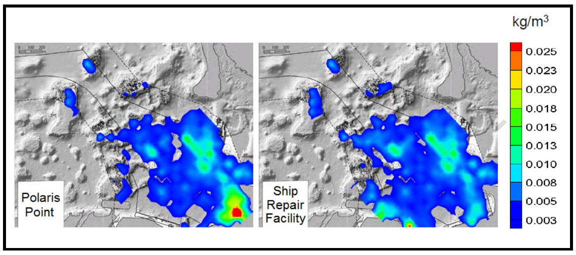

Figure 6. Example Case 1 maximum suspended solids concentration contours at two potential project sites.

## Discussion

A highly successful set of PTM simulations were performed to model the transport of sediment suspended during proposed dredging operations at Apra Harbor, Guam. The primary concern is the exposure of nearby coral reefs to the suspended sediment. By bracketing multiple parameters and using generously conservative bracket values, the most likely range of results between Case 1 (which produces the maximum exposure) and Case 4 (minimum exposure) has been captured. Further data analysis was performed on the PTM output to produce maps and tables for total accumulation, maximum deposition rate, and maximum suspended sediment concentration.

In designing the cases to be modeled, an implicit assumption was that best dredging practices would be followed (USACE, 2005). Conditions such as the chronic spillage of dredge material outside the containment of silt curtains and barge aprons or major accidents such as a catastrophic silt curtain failure were not included within the conditions modeled and could lead to elevated levels of sediment exposure to the adjacent reefs.

Further details about this study are available in Gailani *et al* (2011a, 2011b).

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