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Sediment Mobility, Closure Depth, and the Littoral System – Oregon and Washington Coast

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PURPOSE: Forty years ago, the depth of closure concept was introduced to provide a systematic, process-based approach to evaluate seasonal changes in cross-shore profiles and sediment mobility in the nearshore. This study aims to extend that theory by directly considering wave-asymmetry in the nearshore environment. This technical note introduces a methodology to calculate wave induced dispersal of dredged material placed in nearshore sites and summarizes analyses validating the approach using data from the South Jetty Site at the Mouth of the Columbia River. This investigation highlights the notion of a cross-shore gradient in nearshore placement effectiveness of dredged material that can assist project managers plan and execute sustainable sediment management practices at coastal inlets.

INTRODUCTION: Every year, the Portland District places millions of cubic yards of dredged sediment in the nearshore environment along the coasts of Oregon and Washington. Sustainable management of such large quantities of material relies on an accurate assessment of the capacity of the network of placement sites managed by the district as summarized in USACE USEPA (2021). To designate new sites and plan for future placement needs, a district must engage in effective partnering and communication between local stakeholders that is driven by reliable data/science. Traditional scoping level analyses for designating new and evaluating existing placement sites employ the closure depth criterion. However, this framework is generalized in nature and is limited to a binary confirmation of sediment movement that is applied discretely in the nearshore. To increase its practical value, the concept of closure depth needs to be supplemented to account for the continuum of sediment transport processes that occur across the entire nearshore profile. In reality, dredged material placed between "outer" and "inner" closure depths will provide a tangible benefit even if this benefit diminishes as one moves farther offshore toward the outer closure depth limit.

Nearshore Placement in Theoretical Context. In 1977, Robert Hallermeier (Hallermeier 1977) published a report summarizing calculations for the yearly limit depth for an active beach profile. Therein he presented an approach using linear wave theory to calculate the limit depth of wave-induced intense bed agitation (closure depth) as a function of wave height and wavelength. This approach was later expanded by Hallermeier (1980) and Birkemeier (1985) and shows very good agreement with observations of seasonal changes in cross-shore beach profiles. While the closure depth criterion provides a reliable indication of sediment transport, it does not quantify the dispersal rate of sediment.

To address sediment dispersal across the nearshore continuum, a different set of tools must be used to examine wave induced transport of material. Wave-induced transport is driven in part by non-linear wave asymmetry that is not considered in the depth of closure approach. McFall et al. (2016) begin to address wave asymmetry by using nonlinear stream function theory to calculate near-bed orbital velocities, which generally produce larger velocities than the linear theory. While this evaluation honors the increase in velocities induced by wave asymmetry, it does not consider the difference in sediment transport that occurs during the wave crest and trough. In this way McFall et al. (2016) improve predictions on the frequency of sediment mobilization, but not the volume or transport direction.

To address transport direction, numerous researchers have hypothesized that nearshore berm behavior should be similar to natural sand bars, and over the years various attempts have been made to predict their movement. Larson and Kraus (1992) proposed nearshore berm migration would be similar to the outer bar at Duck, NC, and used cross-shore profiles to correlate the onshore and offshore bar migration and hydrodynamic conditions from 1981 to 1989. The Dean Number, *D*, was found to reasonably predict the offshore bar migration and is given as

$$D = \frac{H_0}{\omega T} \tag{1}$$

where H_0 is the offshore wave height, ω is the sediment fall speed, and T is the wave period. When the Dean Number was greater than 7.2, the asymmetric waves migrated the bar offshore, and when it was less than 7.2, the bar migrated onshore. McFall et al. (2015), McFall and Brutsché (2018), and others have used this technique to estimate the cross-shore transport direction of sediment placed in the nearshore.

This study augments the Larson and Kraus (1992) technique by directly considering the effects of nonlinear wave motion on sediment transport. Orbital velocities are calculated throughout the wave cycle and are used as input to a simple model for bed load transport wherein the direction and magnitude of transport is indicated by the integrated sediment motion over the wave cycle. In this way, a theory can be applied to assess sediment mobility that spans a greater extent of the nearshore environment.

Several methodologies for calculating wave-orbital velocities exist, each with increasing mathematical accuracy at the cost of simplicity. In this study, the relatively simple Stokes second-order theory is used for clarity of exposition. A consequence for simplicity is that the solution remains valid within a restricted parameter space in which the wave propagation is only weakly non-linear. However, the approach below can be easily supplemented with different wave theories if greater accuracy was desired across a wider parameter space.

In the linear regime, wave propagation is described by the Laplace equation using potential flow theory. The Laplace equation can be solved directly by assuming the wave amplitude is small relative to the wavelength (i.e., the wave is not too steep). As waves steepen in shallow water, the non-linearities in the surface boundary condition can no longer be ignored, and the first-order (linear) solution is invalid. Stokes (2009) provided a correction to the linear approximation with a perturbation expansion of the non-linear governing equations using the perturbation parameter $\varepsilon = \frac{kH}{2}$, where k is the wave number and H is the wave height. The horizontal wave orbital velocity under the second-order approximation is expressed as (Dronkers 2016) follows:

$$u_w(x,z,t) = U_0 - U_1 cos(kx + \omega t) - U_2 cos(2(kx + \omega t)) \tag{2}$$

where

$$U_0 = \frac{gH^2}{8ch} \tag{3}$$

$$U_1 = H\omega \frac{\cosh\,[k(z+h)]}{2\sinh\,(kh)} \tag{4}$$

$$U_2 = \frac{3}{16} H^2 k\omega \frac{\cosh\,[2k(z+h)]}{sinh^4(kh)} \tag{5}$$

and c is wave speed, h is water depth, t is time, ω is wave frequency, x and z are the cross-shore and vertical coordinates, respectively.

Equation 2 describes a wave with crests that are larger and shorter and troughs that are smaller and longer than linear wave motion (Figure 1). Because the wave orbital motion is asymmetrical, a net sediment transport occurs over the wave cycle. The magnitude and direction of transport is a function of how the magnitude/duration asymmetry manifests within the wave cycle and is driven by water depth, wave height, and wavelength.

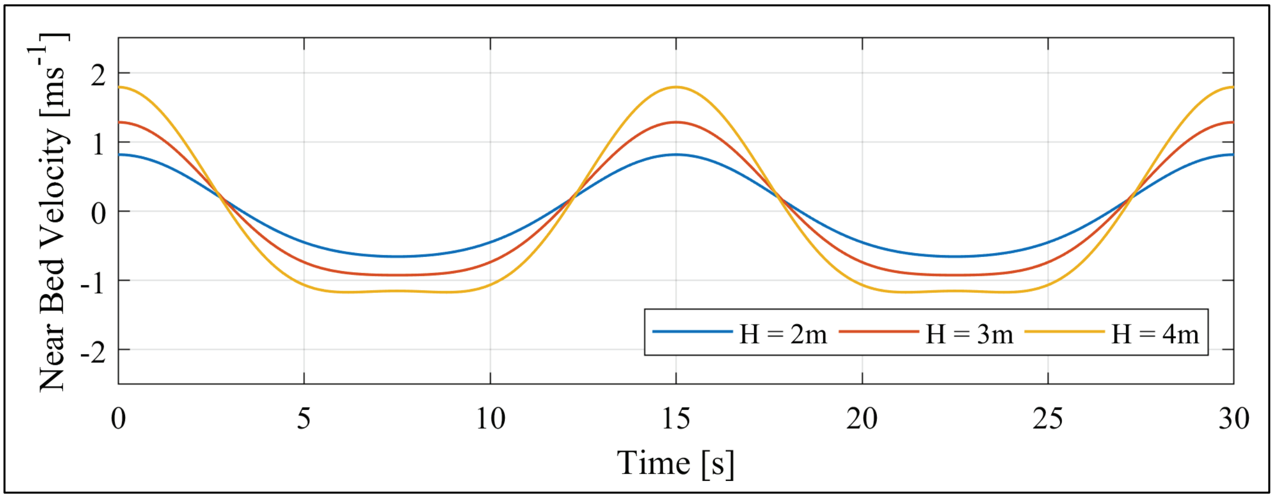

Figure 1. Time series of wave-induced velocities near the bed as estimated by Stokes second-order wave theory. Larger waves produce asymmetry in crest-trough magnitude and duration. Water depth is 15 m(1,2) and wave period is 15 s.

In recognizing the non-linear nature of wave-orbital velocities, Dronkers (2016) provides an expression for the bed-load transport, Q_{bed} ,as a balance between wave-driven transport and downslope transport:

$$\langle Q_{bed}\rangle = \alpha\left[\langle u_w^3\rangle\left(1-\frac{u_{cr}}{u_w^{max}}\right) - \gamma\langle|u_w|^3\rangle\frac{dz}{dx}\right] \tag{6}$$

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Where $u_w(x,t)$ is wave-orbital velocity near the bed, u_{cr} is the critical velocity for bed erosion estimated from Shields diagram, $\frac{dz}{dx}$ is the bed slope, and α and γ are empirical coefficients (set equal to 3E-5 and 1.7, respectively, within the range of values cited by Dronkers [2016]). Note that α was set in this study so that the slope of the linear regression is close to unity, and γ was set assuming an angle of repose of 30 deg (Dronkers [2016] provides more details). Angle brackets indicate wave-period average. In the case of sinusoidal wave-orbital velocities, the $\langle u_w \rangle$ term is zero (i.e., if the trough and crest velocities are equal in magnitude and duration on a flat bed, then no net sediment transport will occur).

Note that Equation 6 assumes material travels as bedload. This assumption is usually valid for placement sites in the Portland District because dredged material typically consists of larger grain fractions that reside in the authorized channels. If the material placed in the nearshore travels as suspended load in the physical context of the local environment, a different equation would need to be used that accounts for wave cycle correlations between the vertical profiles of velocity and sediment concentration.

METHODS: Before Equation 6 can be adopted to evaluate sediment mobility at dredged material placement sites, the predicted sediment transport must be compared to field observations to validate the equation's assumptions. Validation in this study focuses on dredged material placement at the South Jetty Site (SJS) (water depth of ~14 m), as shown in Figure 2, near the Mouth of the Columbia River (MCR) because bathymetric changes have been well characterized since the site became operational in 2014.

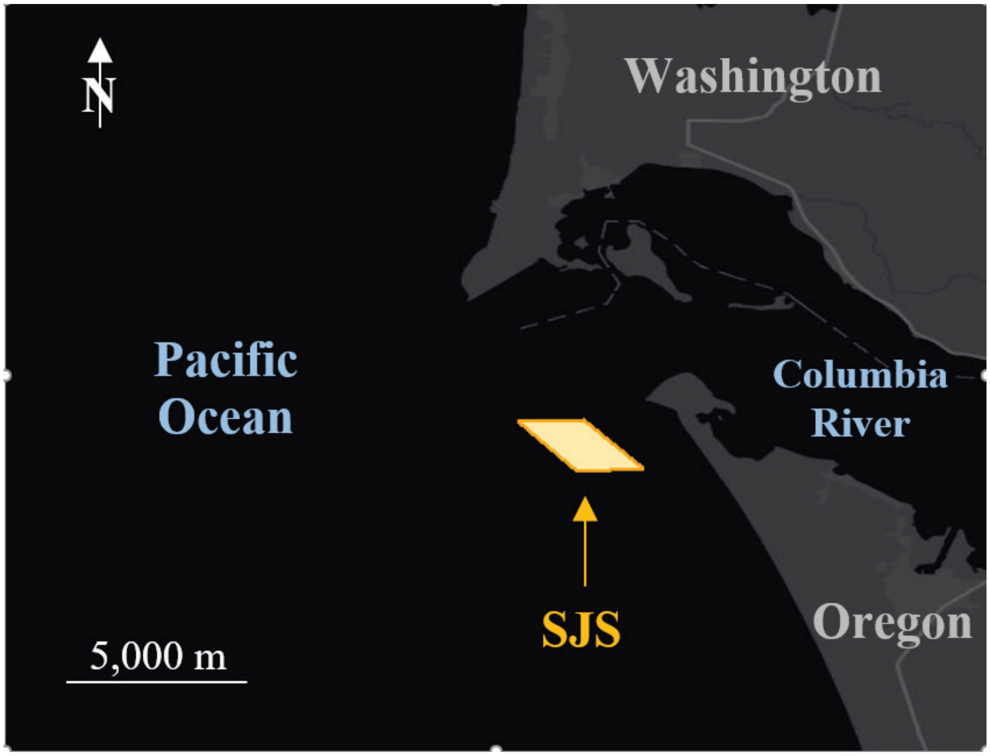

Figure 2. Location of SJS at the mouth of the Columbia River.

The MCR also hosts a rich repository of wave statistics observations between the National Oceanic and Atmospheric Administration (NOAA) offshore buoys 46029 and 46243. Validation of Equation 6 at the SJS followed the protocol below (three steps):

1. Estimate mass balance of sediment at SJS based on historical dredging records and bathymetric surveys. Mass leaving the site following placement was estimated using the difference between a baseline survey and post-placement surveys (Figure 3). It is assumed that the only material entering the site is the result of dredged material placement.
2. Calculate wave-induced sediment transport that occurred between placement and post-placement survey.
    a. Wave characteristics are translated from NOAA offshore buoy (station 46243) to the SJS using Snell's Law and a conservation of energy flux, following McFall (2016).
    b. u_w is calculated using Equation 2 based on wave statistics and water depth at SJS
    c. Bed load transport is calculated using Equation 6. Note that NOAA stations report wave statistics at 30 min intervals, so Equation 6 assumes constant wave statistics during each 30 min period.
    d. 30 min transport estimates are then integrated between the placement and survey dates to yield the net volume of sediment transport (V_{bed}) during that time interval as

$$V_{bed} = \int_{t1}^{t2} \langle Q_{bed} \rangle dt \tag{7}$$

3. Plot mass balance (Step 1) vs. wave induced dispersal (Step 2) for each pair of surveys.

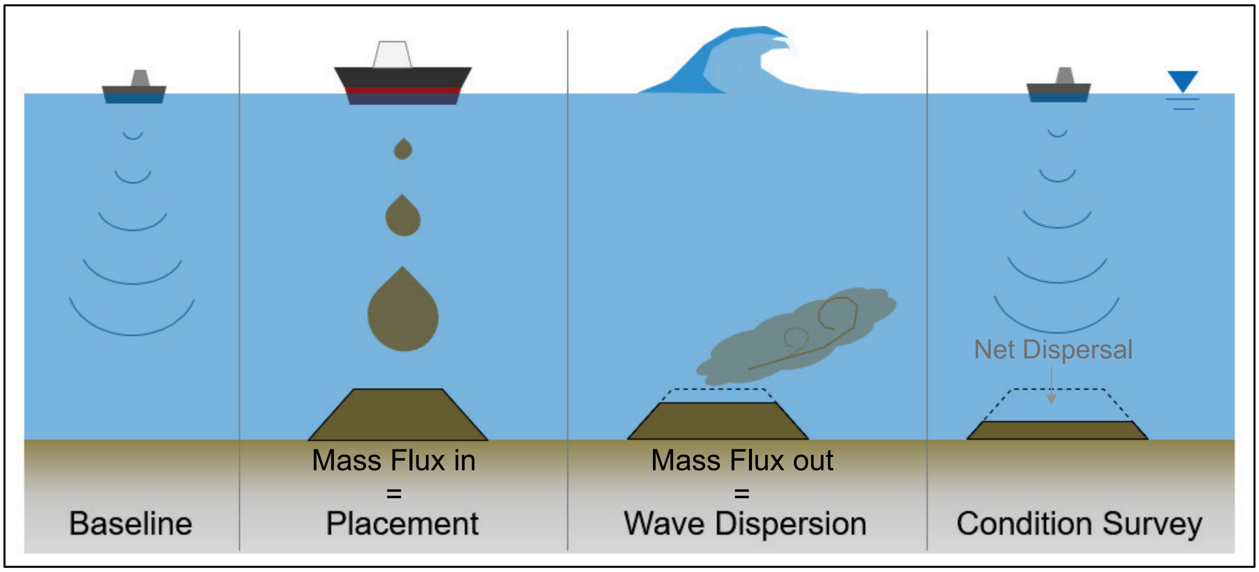

Figure 3. Conceptual diagram of dredged material placement and survey campaigns to estimate mass balance at nearshore sites.

RESULTS: At the time of this study, the SJS hosted 4 years of placement and survey data. Placement of dredged sand at SJS occurs during mid-August and mid-October. Between each placement event, two surveys were collected for all but the 2018 season, yielding nine data points where the material dispersed from SJS (V_{SJS}) could be measured. Volumes placed by hopper dredges ranged from 285K CY to 400K CY. A thin-layer placement method is used to ensure that dredged material does not accumulate higher than 1 ft on the seabed, for each year that the SJS is used (USACE USEPA 2021). Dispersed volumes ranged from 83K CY to 257K CY, depending on the time between survey and placement and the size and duration of winter storms (Table 1). The timing of pre- and post-placement surveys for the SJS is highly dependent upon seacoast weather conditions. In some cases, the onset of fall storms soon after completion of SJS use (October) may preclude the post-construction survey until the following spring. A longer period of time between post- and pre-surveys allows for added cumulative dispersion of the placed dredged material following the post-placement survey. Sometimes, early fall wave events may disperse a larger proportion of the placed sediment soon after the annual placement event is concluded.

Least-squares regression between V_{bed} and V_{SJS} reveals a correlation coefficient of 0.81, and a Root Mean Squared Error (RMSE) of 30K CY in the predicted dispersed volume as compared to bathymetric measurements (Figure 4). The paucity of data points will inflate confidence in the linear regression model, yet the results are still promising, and the method warrants further development using data from other sites. The slope of the regression is close to unity indicating a reasonable mapping between predicted and measured dispersion (Equation 8).

$$V_{SJS} = 0.95V_{bed} + 98kCY \tag{8}$$

An intercept close to 100K CY was unexpected and could be due to unaccounted effects not related to wave-induced dispersion. It is highly likely that ambient current is present at the SJS, and this current is partially responsible for the sediment transport at SJS during the dredging season, combined with longshore transport and some weak wave-driven dispersion. Further investigation with coupled wave and current observations could provide further insight into this result.

Table 1. Summary of mass balance calculations (Step 1) at SJS from 2014 through 2018.

Event	Start Date	End Date	Volume Placed [KCY]	Volume Remaining [KCY]	Volume Dispersed (V_{SJS}) [KCY]
Placement	2014-08-31	2014-09-29	287	-	-
Survey	-	2014-10-07	-	204	83
Survey	-	2015-07-20	-	84	203
Placement	2015-09-02	2015-09-30	285	-	-
Survey	-	2016-04-18	-	28	257
Survey	-	2016-08-02	-	43	242
Placement	2016-08-26	2016-09-14	301	-	-
Survey	-	2017-05-31	-	103	198
Survey	-	2017-07-28	-	114	187
Placement	2017-08-23	2017-09-08	300	-	-
Survey	-	2018-05-07	-	175	125
Survey	-	2018-08-07	-	172	128
Placement	2018-08-17	2018-09-26	402	-	-
Survey	-	2018-10-16	-	317	85

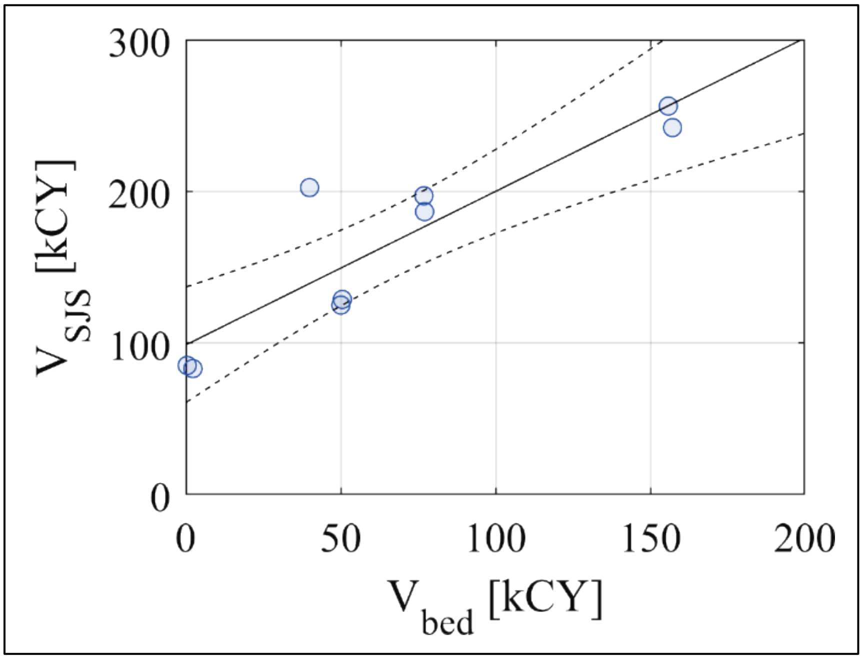

Figure 4. Measured dispersal vs. calculated dispersal at MCR SJS (blue dots). Linear regression model with 95% confidence limits shown as black dashed lines.

DISCUSSION: Reliably calculating dispersion of sediment placed in the nearshore using widely available wave field observations allows designers and planners to work together to manage and designate nearshore placement sites at a district's projects most effectively. In the case of the SJS, the data show that under the current operating conditions, the site can accept up to 250K CY every year without accumulating additional material (Table 1, dispersal between 2015 and 2016). If the need arises to place more than this capacity, an estimate can be derived for the site's serviceable life.

What about locations without survey data? What about new placement sites? How does one design a network of nearshore placement sites that can reliably meet dredging needs every year? These are precisely the type of questions the sediment transport model (Equations 6 and 7) is intended to address. For example, consider a placement site in 14 m of water at the MCR (similar water depths to SJS). During most conditions, material is not mobilized by wave motion. However, when wave heights exceed 4 m, material begins to disperse and in which case movement is in the offshore direction if the wave period is less than 13 s, and in the onshore direction if the wave period is greater than 13 s (Figure 5a). In this water depth at the MCR, the observed wave conditions typically fall in a region of the parameter space where material is either not moving or is moving in the onshore direction (black dots in Figure 5a). In this example, the sediment transport model predicts a total dispersion of 165K CY between October 2015 and October 2016 (Figure 4).

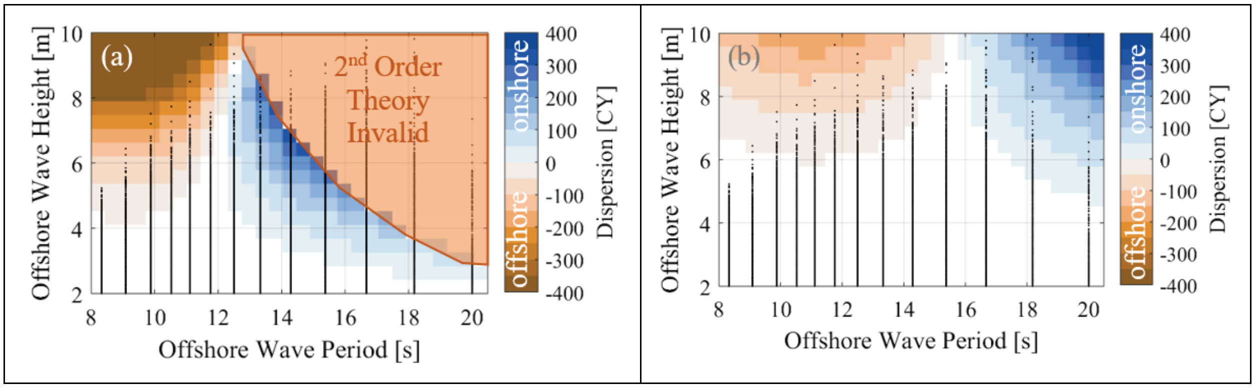

Figure 5. Sediment mobility parameter space in (a) 14 m of water and (b) 24 m of water at MCR. Colors denote theoretical dispersion volumes, evaluated for 1 hr of wave action. Black dots indicate observed wave statistics at NOAA buoy 46029.

In contrast, consider a placement site in 24 m of water. At this location, material is less dispersive than that placed in 14 m of water requiring approximately 6 m waves to induce transport. The transition between on/offshore transport occurs at wave periods of approximately 15 s (Figure 5b), and as a result, the observed wave conditions occupy a proportionally larger domain of the offshore transport parameter space. However, the deeper site does experience some onshore transport during large wave events and is not entirely disconnected from the littoral system.

As mentioned above, the second-order Stokes theory employed herein is only valid for weakly non-linear waves. As the wave profile steepens, the theory begins to produce a fictitious peak within the wave orbital trough (Figure 1). Therefore, direct application of Equation 6 can misrepresent the nature of transport at the SJS during large wave events when wave propagation becomes increasingly non-linear. Unfortunately, these are the same conditions under which most of the wave induced sediment transport is expected to occur. Traditionally, the second-order theory is valid when $\frac{kH}{2} < 1$, but experimentation with near bed wave orbital velocity calculated from Equation 6 showed that a spurious peak during the trough formed under large wave heights and wave periods at the SJS (Figure 5). It is assumed that under these conditions, Equation 6 becomes invalid and overpredicts the magnitude of onshore transport. Strong correlation between the predicted dispersion and observations despite this shortcoming in the wave velocity model suggests the empirical coefficient α in Equation 6 can accommodate this systematic error. By employing more accurate wave velocity theory (e.g., higher-order Stokes or Fenton’s theory), the approach would not need to rely on empirical coefficients to compensate for the overestimated onshore transport during large wave events.

CONCLUSION: Every year, the Portland District places millions of cubic yards of sediment in the nearshore environment. Effective management of this material depends on reliable estimates of the transport characteristics of sediment in the nearshore environment. Traditional analyses use the concept of the inner closure depth and the Dean Number to provide insight into sediment fate. However, most dredged material placement along the Oregon coast occurs in water depths greater than were considered in the development of these criteria and thus limit their applicability to Portland District operations.

This study presents a new approach to estimate wave induced sediment transport in the nearshore environment by considering the wave cycle asymmetry of orbital velocities responsible for sediment movement along the bed. The evaluation provides a proof of concept by comparing calculated dispersion to in situ measurements at the South Jetty Site at the MCR. Results indicate the approach correlates well with observations ($R^2 = 0.81$), yet further investigation is warranted due to the limited sample size of the comparison and the large y-intercept.

The sediment transport model considered herein employs a second-order Stokes approximation to the shallow water, non-linear wave behavior. While this study found that the wave environment conducive for large sediment transport events along the Oregon coast is outside the parameter space where the second-order theory is mathematically valid, the close agreement between the theory and observations suggests the model has potential for accurately predicting transport at placement sites throughout the region if higher-order wave theories are used. Another omission is that the theory does not consider transport induced by processes other than waves (e.g., bottom current induced by winds, tidal exchange, upwelling, and adjacent inlet processes). The model can reasonably predict dispersion, indicating these processes are relatively consistent over the spatial and temporal scales considered in this study, which introduces a systematic error in the correlation that is compensated by the empirical coefficients in Equation 6 and the y-intercept in Equation 8. Future investigations that explore more sophisticated wave theories and potentially account for other coastal processes affecting transport would be worthy complements to the work presented herein.

Direct consideration of the wave cycle asymmetry reveals that sediment movement at the SJS (water depth of 14 m) favors onshore transport in the context of the ambient wave environment. In contrast, transport within a placement site located in 24 m of water favors the offshore direction, though some onshore transport is still expected. Further exploration of the cross-shore gradient in sediment transport direction using the methods presented above can help define the nearshore placement effectiveness wherein the relative near- and long-term littoral benefits of existing and potential placement sites can be quantitatively assessed at coastal inlets.

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