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# LTFATE Cohesive Sediment Transport Model

**PURPOSE:** The Long-term Fate of Dredged Material (LTFATE) model is a combined local hydrodynamics and sediment transport model used to determine the long- and short-term stability of dredged material mounds. This technical note (TN) introduces a new cohesive sediment transport submodel for LTFATE, which includes a combined current-wave shear stress calculation and a layered sediment bed model. LTFATE can be accessed via the Internet at the following address: *http://www.wes.army.mil/el/elmodels.*

**BACKGROUND:** At some open-water placement sites, transport of fine-grained sediments outside the site can be a concern. First, fine-grained sediments often are cohesive and attract hydrophobic contaminants such as polychlorinated biphenyls (PCBs). The transport from dredged material mounds comprised of these sediments is significant because of the potential effects of the associated contaminants. Second, even uncontaminated fine-grained sediments can cause negative biological or aesthetic impacts if sufficient quantities are transported into sandy areas.

Unlike sands, which tend to settle back to the sediment bed rather rapidly, cohesive sediments remain in the water column for significantly longer time periods and therefore can be transported farther. This can result in significant bed contamination a considerable distance from the original mound location. It is therefore important to determine the stability of a mound, i.e., those conditions under which sediments in a mound remain in place. LTFATE (Scheffner et al. 1995; Scheffner 1996) was developed at the U.S. Army Engineer Waterways Experiment Station (WES) originally for simulating sand transport from dredged material placement sites. Sand often is used to cap contaminated sediments. However, before capping occurs, cohesive mounds are exposed to the water column and could experience sediment transport. In addition, due to the additional cost sometimes associated with obtaining sand for capping, there is interest in using suitable fine-grained cohesive sediments as cap material for open ocean sites. Therefore, LTFATE was expanded to include fine-grained, cohesive silt and clay transport. However, the original LTFATE cohesive sediment sub-model was basic and could not simulate the effects of large storms accurately. Thus, the improved cohesive sediment transport sub-model described in this TN has been developed.

Unlike sands, the interparticle forces of fine-grained sediments (due to their small mass) are significant when estimating transport processes. Sand erosion can be relatively simply related to the grain size. This is not true for fine-grained cohesive sediments. Several factors, including grain size distribution, mineralogy, bulk density, and organic content have been demonstrated to significantly affect the erosion rate. In fact, sediments that at first glance may seem similar may have orders of magnitude difference in their erosion rates (Lavelle 1984). Because of the various processes influencing erosion, the rates tend to decrease with depth below the sediment/water interface even for sediments of consistent grain size and mineralogy.

This TN documents the layered bed processes and combined current-wave shear stress processes that have been incorporated into the cohesive sediment transport sub-model of LTFATE. Future TNs will address additional LTFATE model improvements, including bed armoring, combined sand/clay sediment bed processes, cohesive sediment flocculation, and cohesive sediment settling speeds.

## LAYERED SEDIMENT BED MODEL

As previously stated, the rate and method by which cohesive sediments erode depend on several factors, including grain-size distribution, organic content, pore water content, and mineralogy, among others. Therefore, erosion of cohesive sediments varies significantly from location to location as well as with depth. A commonly used method to relate erosion to bottom shear stress has been incorporated into LTFATE. This method relates erosion to a function of shear stress to some exponential power. The equation for the erosion rate $\in$ in pounds (mass) per square foot per second is:

$$\in = A_0 \left[ \frac{\tau_{bm} - \tau_{cr}}{\tau_{cr}} \right]^m \tag{1}$$

where $A_0$ and $m$ are site-specific parameters, $\tau_{bm}$ (pounds (force) per square foot) is the near-bottom shear stress, and $\tau_{cr}$ is the critical shear stress below which no erosion occurs. To predict erosion at a given location accurately, several values of $A_0$ and $\tau_{cr}$ must be used in the vertical direction. Therefore, a vertically layered sediment bed has been incorporated into LTFATE, which includes varying values of $A_0$ and $\tau_{cr}$. These parameters can vary significantly from layer to layer, and erosion rate experiments on sediments extracted from the site are the best method for determining the vertically varying values. If such data are not available, reasonable values from similar sediments should be used. The figure below provides an example of the user-provided distribution of these parameters as well as possible initial thicknesses of each layer.

| **Water Column** | | |
|---|---|---|
| **Sediment Bed** | | |
| $\tau_{cr} = 5 \times 10^{-4}$ lbf/ft$^2$ | $A_0 = 8 \times 10^{-6}$ | Initial thickness = 0.025 ft |
| $\tau_{cr} = 1 \times 10^{-3}$ lbf/ft$^2$ | $A_0 = 4 \times 10^{-6}$ | Initial thickness = 0.025 ft |
| $\tau_{cr} = 5 \times 10^{-3}$ lbf/ft$^2$ | $A_0 = 4 \times 10^{-6}$ | Initial thickness = 0.050 ft |
| $\tau_{cr} = 1 \times 10^{-2}$ lbf/ft$^2$ | $A_0 = 5 \times 10^{-7}$ | Initial thickness = 0.050 ft |
| $\tau_{cr} = 2 \times 10^{-2}$ lbf/ft$^2$ | $A_0 = 3.75 \times 10^{-7}$ | Initial thickness = 0.050 ft |
| $\tau_{cr} = 2 \times 10^{-2}$ lbf/ft$^2$ | $A_0 = 2.5 \times 10^{-7}$ | Initial thickness = 0.100 ft |
| $\tau_{cr} = 2 \times 10^{-2}$ lbf/ft$^2$ | $A_0 = 1 \times 10^{-7}$ | Initial thickness = 0.100 ft |
| $\tau_{cr} = 2 \times 10^{-2}$ lbf/ft$^2$ | $A_0 = 1 \times 10^{-7}$ | Initial thickness = 0.100 ft |

During a storm, erosion may remove any layer or layers completely, leaving only the bottom layers exposed. Initially, the top layers of cohesive sediment have, in most cases, high water content and are easily erodible. Wave and current action, as well as the effects of benthic organisms, keep these sediments in this state during nonstorm periods. Bottom sediments, protected from the wave and current action, become more compact and are more difficult to erode. Storm action will remove the upper layers, leaving the more compacted, erosion-resistant sediments exposed to the water. Also, freshly deposited sediments are added to the topmost layer and are easily resuspended. Over time, these deposited sediments will experience natural aging and compaction by freshly deposited sediments if there is a thick enough layer to protect some of them from current and wave agitation. The compaction and aging processes are not incorporated into the present version of LTFATE. The table below illustrates the erosion rate $\in$ for each of the eight layers (if that layer were exposed to the sediment/water interface) for conditions of a 13-ft wave in 82 ft of water with a 0.66 ft/s steady current in the same direction as the waves. For this example, the value of exponent *m* was set to 2, which experiments have demonstrated is a reasonable value. It can be seen from this table that the erosion rate will vary by orders of magnitude between the top and bottom layers.

| $A_0$ | $\tau_{cr}$ (lbf/ft$^2$) | $\in$ (lbm/ft$^2$/s) |
|---|---|---|
| $8 \times 10^{-6}$ | $5 \times 10^{-4}$ | $9.6 \times 10^{-2}$ |
| $4 \times 10^{-6}$ | $1 \times 10^{-3}$ | $1.2 \times 10^{-2}$ |
| $4 \times 10^{-6}$ | $5 \times 10^{-3}$ | $4.0 \times 10^{-4}$ |
| $5 \times 10^{-7}$ | $1 \times 10^{-2}$ | $1.0 \times 10^{-5}$ |
| $3.75 \times 10^{-7}$ | $2 \times 10^{-2}$ | $1.2 \times 10^{-6}$ |
| $2.5 \times 10^{-7}$ | $2 \times 10^{-2}$ | $7.8 \times 10^{-7}$ |
| $1 \times 10^{-7}$ | $2 \times 10^{-2}$ | $3.1 \times 10^{-7}$ |
| $1 \times 10^{-7}$ | $2 \times 10^{-2}$ | $3.1 \times 10^{-7}$ |

As previously stated, the values of $A_0$, $m$, and $\tau_{cr}$ are considered to be site-specific. It is well-known that the erosion rates of fine-grained and mixed cohesive/noncohesive sediments are related to the previously mentioned bulk properties. To date no method has been developed to associate these bulk properties to erosion rates despite the fact that these properties are easily measured, i.e., no general quantitative theory of fine-grained cohesive and mixed cohesive/noncohesive sediment erosion and resuspension properties exists. Pending research under the DOER Program involves developing methods to associate erosion rates (and vertical variation in erosion rates) to these bulk properties using a high-shear-stress straight flume. The methods developed by this research will be incorporated into LTFATE, resulting in greatly improved ability to predict fine-grained and mixed sediment bed erosion during storms and a useful tool for improved site management. Prior to availability of these erosion rate methods related to bulk properties, this flume is being used to obtain high shear stress erosion rates for specific sites. This information is being incorporated into site-specific applications of LTFATE. Current studies include the Los Angeles/Long Beach Harbor and New York Mud Dump sites.

## COMBINED CURRENT/WAVE SHEAR STRESS

The method incorporated into LTFATE to estimate bottom stresses due to combined current and wave action ($\tau_{bm}$ in Equation 1) is described in this section. Large water bodies such as lakes, oceans, and estuaries are subject to both current velocities and wave-generated orbital velocities. As a result, the bottom shear stress will depend on the relative magnitude of both velocities and the angle between them. In general, the bottom shear stress is assumed to follow a quadratic law:

$$\tau_{cb} = \frac{\rho \, f_c \, u^2}{2} \tag{2}$$

where $\tau_{cb}$ is the near-bottom shear stress due to currents (lbf/ft$^2$), $\rho$ is the density of water, $f_c$ is the current-related friction factor, and $u$ is the current velocity outside the boundary layer. For pure currents, $f_c$ ranges from 0.002-0.005, depending upon the bed roughness. If waves are present, a similar equation for the wave-related shear stress $\tau_{wb}$ is assumed:

$$\tau_{wb} = \frac{\rho \, f_w \, U^2}{2} \tag{3}$$

where $U$ is the near-bottom orbital velocity for the wave and $f_w$ is the wave-related friction factor. The coefficient $f_w$ ranges from 0.002-0.05, depending on $U$ and the wave period $T_s$.

Often, for simplicity, these two effects are simply added together. As will be described later, this will produce a shear stress that is too low, often by a factor of two or more.

The physical problem is described by Grant and Madsen (1979). Summarizing the main points of the wave-current interaction, the near-bottom flow is influenced by the relatively low-frequency currents and high-frequency surface waves. The bottom boundary layer is assumed to consist of an oscillatory wave boundary layer nested within a relatively steady current boundary layer. When the maximum bottom orbital velocities of the waves are of the same order as the steady current velocities, the small scale of the wave boundary layer causes the boundary shear stress that would be associated with the wave to be much greater than that associated with the current alone. The wave and current interact to generate a shear stress that is different from that generated by the sum of the two components. This interaction is a nonlinear process and numerous assumptions are necessary to derive it.

The process discussed here relies upon the same basic physical description as that provided by Grant and Madsen (1979) but is somewhat simpler in its description of bottom shear stress. Bottom shear stresses are predicted using a method developed by Christoffersen and Jonsson (1985), referred to hereafter as CJ. Shear stresses predicted by the CJ model compare well with experimental data.

As defined in the CJ model, bed shear stress due to combined current and wave action may be calculated from:

$$\tau_{bm} = \frac{1}{2}\rho\ f_w\ u_{wbm}{}^2 m \tag{4}$$

where $\tau_{bm}$ is the maximum bed shear stress, and $u_{wbm}$, the amplitude of the bottom orbital velocity at the top of the wave boundary layer (or maximum bottom orbital velocity), is calculated from linear wave theory by:

$$u_{wbm} = \frac{H_s gkT_s}{4\pi \cosh(hH_s)} \tag{5}$$

where $H_s$ is the wave height, $g$ is the acceleration of gravity, $k$ is the wave number, $T_s$ is the wave period, and $h$ is the total water depth.

$m$ is calculated by:

$$m = \left(1 + \sigma^2 + 2\sigma\left|\cos(\delta - \alpha)\right|\right)^{0.5} \tag{6}$$

$$\sigma = \frac{\tau_{cb}}{\tau_{wbm}} = \left[\frac{f_c}{f_w}\right]\left[\frac{U}{u_{wbm}}\right]^2 \tag{7}$$

where $\sigma$ is the ratio of $\tau_{cb}$ (bottom shear stress due to currents) and $\tau_{wbm}$, the amplitude of $\tau_{wb}$ (i.e., $\tau_{wbm}$ is the maximum value of the oscillatory $\tau_{wb}$, bed shear stress due to waves). $\delta$ is the angle of the current direction and $\alpha$ is the angle of the wave direction. Note that if $\tau_{cb} >> \tau_{wbm}$, then:

$$m \rightarrow \left[\frac{f_c}{f_w}\right]\left[\frac{U}{u_{wbm}}\right]^2 \tag{8}$$

and thus $\tau_{bm} \rightarrow \tau_{cb}$. Similarly, if $\tau_{cb} << \tau_{wbm}$, then $m \rightarrow 1$ and $\tau_{bm} \rightarrow \tau_{wbm}$.

Ultimately, the prediction of the shear stress depends on the turbulence-related friction factors. There are separate friction factors $f_c$ and $f_w$ for current and wave-related processes. It is beyond the scope of this TN to describe the methods for estimating the friction factors. It will suffice to say that the friction factor equations are experimentally determined. The procedure for computation of bottom shear stress is as follows:

*a.* Compute $f_c$ for pure currents by the following equation (note, for pure current the second term on the right-hand side of this equation is zero):

$$\left[\frac{2}{f_c}\right]^{0.5} = \frac{1}{\kappa}\left(1n\left[\frac{30h}{ek_N}\right] - 1n\left[\frac{k_A}{k_N}\right]\right) \tag{9}$$

where $k_N$ is the Nikuradse roughness coefficient (assumed to be 0.015 ft), $k_A$ is the apparent roughness (described below), $\kappa$ is the von Karman constant (=0.4), and $h$ is the water depth.

*b*. Compute $f_w$ and parameter $J$ for pure waves ($m$=1):

$$f_w = 2\left[\frac{\beta k_N \omega_a}{u_{wbm}}\right]^{\frac{2}{3}} \tag{10}$$

$$J = \left[\frac{u_{wbm}}{k_N \omega_a}\right]\left[\frac{m f_w}{2}\right]^{0.5} \tag{11}$$

where $u_{wbm}$ is the maximum value (amplitude) of the oscillatory wave particle velocity at the top of the wave boundary layer, $\omega_a$ is the angular frequency ($2\pi/T_s$), and $\beta$ is an experimentally determined constant (=0.0747). Now recompute $f_w$ using:

$$f_w = \frac{2\beta m}{J} \tag{12}$$

*c*. Keeping $f_c$ fixed, iterate to find $\sigma$, $m$, $J$, and $f_w$ using Equations 6, 7, 11, and 12.

*d*. Compute $\delta_w$ (wave boundary layer thickness), and $k_A$ (apparent roughness):

$$\delta_w = r\ k_N\ \pi\left[\frac{\beta J}{2}\right]^{0.5} \tag{13}$$

$$k_A = 30\delta_w \exp\left[\frac{-\kappa\delta_w}{\beta k_N}\left(\frac{\sigma}{m}\right)^{\frac{1}{2}}\right] \tag{14}$$

where $r$ is an experimentally determined constant (=0.45).

*e*. Recompute $f_c$ from *a*.; this time the second term on the right-hand side will not be zero.

*f*. Repeat steps *b*. through *e*. until $f_c$ converges.

*g*. Calculate $\tau_{bm}$, maximum bed shear stress, using Equation 4.

Now that the maximum bottom shear stress due to both currents and waves is known, erosion rates can be estimated as described in Equation 1.

WES is involved in several projects where the improved LTFATE model is being applied. These projects include erosion rate parameter information from the high shear stress flume for better quantification of the vertical variation of erosion. A future TN will provide details on the results of these projects. These applications will be relevant to site management concerns.

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> U.S. Army Engineer Waterways Experiment Station. (1998). "LTFATE cohesive sediment transport model," Technical Note DOER-N1, Vicksburg, MS.

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