A Review of the Present Knowledge of Mine Burial Processes

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LONG-TERM GOAL

The ultimate long-term goal of the ONR Mine Burial Prediction (MBP) Research Program is the development of mine burial probability models that incorporate dynamic coupled processes, seafloor material properties, and different mine types.

SCIENTIFIC OBJECTIVES

The immediate scientific objectives of this particular component of the MBP program is to aid in the production of a report that incorporates the present knowledge of mine burial processes and state-of-the-art mine burial modeling in the areas of present critical navy interest.

APPROACH

In this component project I have been working closely with Mike Richardson, Head of the Seafloor Sciences Branch of the Marine Geosciences Division of the Naval Research Laboratory. My portion of the report revision effort is a relatively small project, involving only 80 hours of personnel time from my institution. Together with Mike Richardson and Phil Valent at NRL, I have been helping to revise an existing draft report, entitled "Modeling of Mine Burial Processes: A Review", that was initiated by Daniel Lott, also of NRL. My focus has been on sections of the report involving modeling of mine burial by scour and by bedform migration.

WORK COMPLETED

I have delivered to NRL revised sections of the mine burial report focusing on the WISSP, NBURY, DRAMBUIE and Vortex Lattice models for scour burial and the Mulhearn model for bedform burial. These contributions are now incorporated into a revised report (Lott, 2001) by NRL personnel. My revisions of Lott's descriptions of the WISSP, NBURY, DRAMBUIE, Vortex Lattice, and Mulhearn models are attached here.

RESULTS

WISSP was originally written in the 1960's and is presently maintained by the U.S. Naval Coastal Systems Center. Availability of the source code allowed identification of the assumptions of this model. This model solves empirical relations for initiation of bedload and suspended load transport of sand to determine whether scour burial is likely. If near bottom wave orbital velocities are not large enough to initiate bed load, burial is assumed not to occur. If waves are sufficient to initiate bed load but not suspended load, partial burial is predicted. If waves are large enough to initiate suspended load, total burial is predicted.

NBURY is a scour model developed by Industrie Anlagen Bau Gesellschaft of Munich, Germany, for the German Navy (Stender, 1980). This model for wave-induced scour is based on the Carstens and Marten (1963) equations documenting the response of mine-like objects to wave-induced scour as observed in a laboratory wave tank. Availability of the Carstens and Marten report allowed confirmation of the NBURY implementation of the Carstens and Marten equations. Carstens and Marten (1963) derived separate empirical relations for the rate of wave-induced scour around mines due to bedload and suspended load.

DRAMBUIE is preliminary version of a current-induced scour model being developed by the United Kingdom (HR Wallingford Ltd, 1994). This model is based on empirical solutions for current-induced scour around pilings using standard formulations available in recently published textbooks by Soulsby (1997) and by Whitehouse (1998). Empirical coefficients in formulae derived for pilings have been modified to match results for current-induced scour observed around mine-like objects in laboratory flumes. The recent engineering literature allowed successful evaluation of this model's formulation.

The Vortex-Lattice model is a R&D model, developed by Jenkins and Inman at Scripps. There are two basic mechanisms in the present Vortex-Lattice formulation of mine scour and burial (Inman and Jenkins, 1999): (1) a near-field burial mechanism involving sediment transport by the vortices shed from the mine shape; and (2) a far-field burial and exposure mechanism that involves changes in the elevation of the seabed due to accretion or erosion of the entire nearshore profile. The near-field component of the model has an excellent physics-based foundation. However, in its present form it is strictly a developmental model that is geared toward science-based objectives.

The Mulhearn model for bedform migration was sponsored by the Australian Defence Science Technology Organisation and calculates time for burial of mines by large migrating bedforms. This model combines a bedload transport formulation based on mean current velocity (van den Berg, 1987) with a continuity relation for sediment transport based on bedform migration. This model is well documented by the available Mulhearn (1996) report. Although the Kalinske-Frijlink equation for bedload transport used in this model is not a widely accepted formulation, the Mulhearn approach is very simple, and it would be easy to substitute an alternative formula for bedload transport if necessary.

IMPACT/APPLICATIONS

The revised report entitled "Modeling of Mine Burial Processes: A Review" will help the operational Navy to make informed choices concerning the use of existing mine burial models. A documented knowledge of existing models will also aid the Navy in identifying what areas of mine burial prediction are most in need of more advanced formulations.

TRANSITIONS

My revisions have been delivered to Dr. Mike Richardson, Head of the Seafloor Sciences Branch of the Marine Geosciences Division of the Naval Research Laboratory. NRL is leading the final revision of the report and its delivery to the operational Navy.

RELATED PROJECTS

This project is part of the ongoing ONR Marine Geosciences Program in Mine Burial Prediction Research. Several additional projects in the MBP progam are listed under Marine Geosciences in the directory containing this report.

The following projects involving Friedrichs outside of the MBP Research Program also address sediment transport in coastal environments:

1. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (Marine Geology and Geophysics).

2. Integration of an Analytical Model for Shelf Sediment Deposition into SedFlux. Office of Naval Research (Marine Geosciences).

3. How Do Estuarine Turbidity Maxima Entrap Particles, Retain Zooplankton, and Promote Recruitment of Fish? National Science Foundation (Biological Oceanography).

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Inman, D.L. and Jenkins, S.A. 1999: Scour Mechanics of Aggregate Obstacle Fields with Application to Mine Countermeasures. ONR Annual Report, Contract No. N00014-95-1-0005.

Lott, D.F. 2001: Modeling Mine Burial Processes: A Review. With contributions by C. Friedrichs, M. Richardson, and P. Valent. Naval Research Laboratory, Stennis Space Center, MS, in preparation.

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Soulsby, R. 1997: Dynamics of Marine Sands: A Manual for Practical Applications. Thomas Telford Publications, London.

Stender, I. 1980: Die Versandung von Grundminen durch Seegang: Theoretische Grundlangen. FWG Rtp 1980-6. Forschungsanstalt der Bundeswehr für Wasserschall-und Geophysik, Kiel, Germany.

van den Berg, J.H. 1987: Bedform migration and bed-load transport in some rivers and tidal environments. Sedimentology, 34, 681-698.

Whitehouse, R.J.S. 1998: Scour at Marine Structures. Thomas Telford Publications, London.

NAME: Wave Induced Spread Sheet Prediction (WISSP)

GENERAL DESCRIPTION: WISSP was originally written in the 1960's (Bennett and Dolan, 2001) and is still the current US scour model. The PC-DOS interface for the program credits WISSP to the U.S. Naval Coastal Systems Center. This model is a “snapshot” of mine burial, is rather simplistic, has no time dependence, assumes unidirectional, monochromatic waves, and focuses on surface waves only for sediment transport (no tidal transport). The Nato NG-3 (1999) Mine Burial Prediction report indicates that this model is an implementation of the Carstens and Martin (1963) equations for wave-induced scour. However, examination of the available BASIC computer language source code reveals no relations that are obviously taken from Carstens and Martin.

The model is an interactive spreadsheet (Figure 21) where changing any of the environmental inputs immediately updates all other calculations. Changes to input using special function keys adjusts parameters. Sf Key 1 causes parameters to be either increased or decreased depending on which function has been toggled by using its appropriate key (e.g., Sf Key 4 is water depth). Thus changing, for example, wave height might require two key strokes. The first to select either increasing or decreasing the parameter of interest (sf key 1) and the second, the wave height key (sf 2). Toggling this key causes an increase or decrease of 0.1 ft for each subsequent keystroke. All the other parameter keys operated similarly.

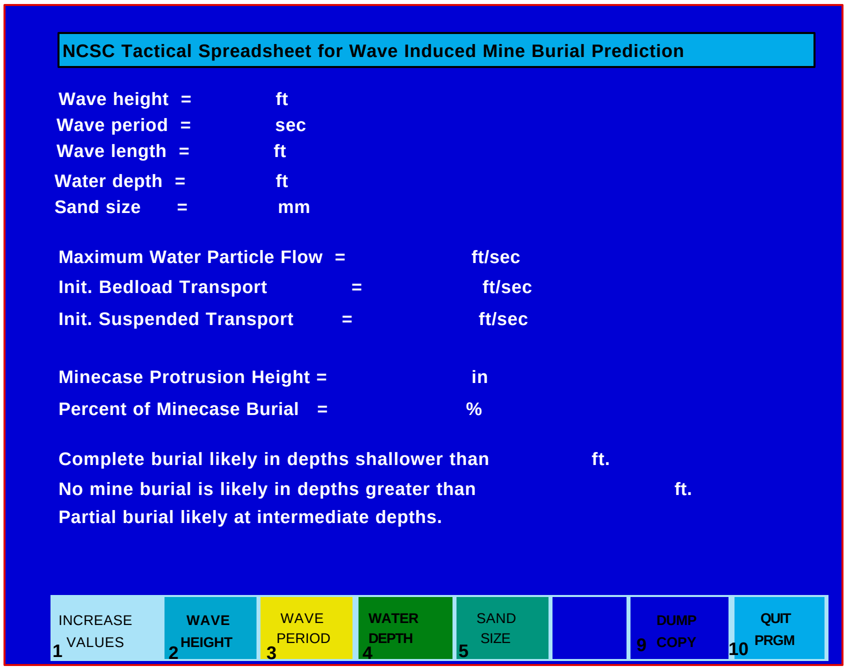


Figure 21. The computer screen of the NCSC Tactical Spreadsheet for Mine Burial Prediction

INPUTS:

Wave height, H (ft)
Wave period, T (sec)
Water depth, h (ft)
Sediment size, d (mm)

OUTPUTS:

Wave length, L (ft)
Bottom orbital velocity just above wave boundary layer, U_m (ft/sec)
Velocity for initiation of bedload sand transport, U_{bed} (ft/sec)
Velocity for initiation of suspended sand transport, U_{fly} (ft/sec)
Depth for initiation of partial burial, h_{bed} (ft)
Depth for initiation of total burial, h_{fly} (ft)
Mine protrusion height above bed, P_{inch} (inch)
Fraction of mine protruding above bed, $P_{\%}$ (percent)

SCIENTIFIC BASIS:

This scientific basis of this model as discussed here is based on the available source code written in the BASIC computer language. The source code indicates that wave length and bottom orbital velocity are calculated via an iterative solution of the linearized wave equations:

$$L = (T/(2\pi))^2/(g \tanh(2\pi h/L)) \quad \text{Eq. 1}$$
$$U_m = (H\pi/T)/(\sinh(2\pi h/L)) \quad \text{Eq. 2}$$

where $\pi = 3.14$, $g = 32.1$ ft/sec^2 is the acceleration of gravity, and tanh and sinh are the hyperbolic tangent and sine functions.

U_{bed} and U_{fly} are functions of grain size alone and are calculated in ft/sec from

$$U_{bed} = 2.85\,(d/10)^{1/2} \quad \text{Eq. 3}$$
$$U_{fly} = 14.4\,(d/10)^{1/2} \quad \text{Eq. 4}$$

where d is in millimeters. (The engineering/scientific source for Eqs. 3 and 4 is not indicated in the available source code.) h_{bed} and h_{fly} are then found by replacing U_m in Eq. 2 with U_{bed} and U_{fly} and solving for h. The solutions for h_{bed} and h_{fly} are not iterated, and the approximate solution employed results in errors in h_{bed} and h_{fly} on the order of 10% compared to an exact solution of Eqs. 1 to 4.

P_{inch} is found using the following formulae:

$$P_{inch} = 13.85 + 5.73 \log(d) \quad \text{Eq. 5}$$

If $U_m > U_{fly}$ or (Eq. 5) yields $P_{inch} < 0$, then $P_{inch} = 0$

If $U_m < U_{bed}$ or (Eq. 5) yields $P_{inch} > 18$, then $P_{inch} = 18$

where log is the natural logarithm function and d is in millimeters. The engineering/scientific source for Eq. 5 is not indicated in the available source code. Finally, the percent of the mine protruding above the bed is given by

$$P_{\%} = 100\,(1 - P_{inch}/18) \quad \text{Eq. 6}$$

SENSITIVITY ANALYSIS:

On initial startup, the default environmental parameters are:

Wave height (ft) = 2
Wave period (sec) = 6

Wave length (ft) = 179
Water depth (ft) = 60
Sand size (mm) = 0.4

As indicated by Eq. 1, changes to the wave height parameter do not change either wave length or wave period parameters; however, changes in wave period do impact wavelength numbers. Ignoring what might be unrealistic combinations of wave height, period, and length for the water depth used and varying wave height between 0 and 16 ft, we plot the height of the cylindrical mine protruding above the sediment's surface at 60 ft water depth, (Figure 22). From this plot, it is clear that there is little real sensitivity to wave height inputs. Only in two instances are there changes in the height protruding and these changes occur when bottom orbital velocity indicated by Eq. 2 exceeds the criteria for initiating either bedload (Eq. 3) or suspended sand transport (Eq. 4).

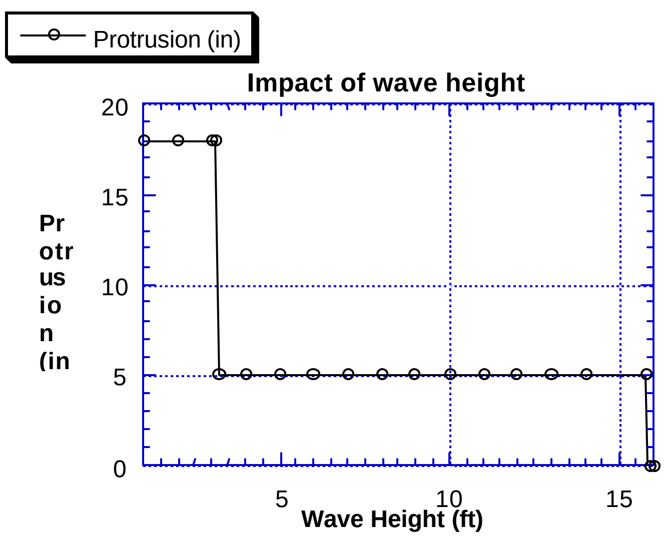


Figure 22. Impact of wave height on protrusion of a cylinder

Similarly, when looking at changes in water depth between 10 and 90 feet (Figure 23), there are two points where the protrusion height of the target changes. Again, these points are controlled by having the bottom orbital velocity large enough to initiate bedload or suspended transport.

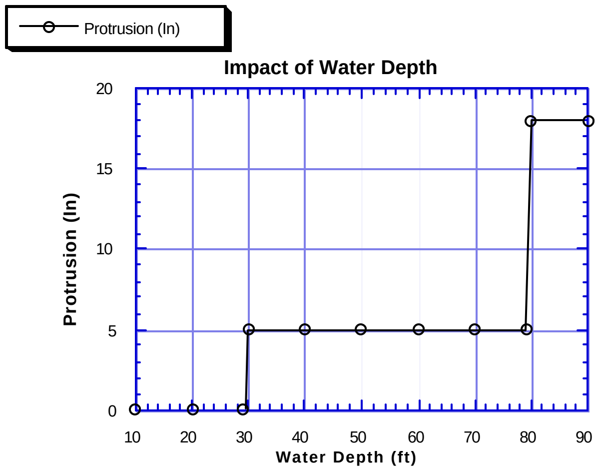


Figure 23. Impact of water depth on protrusion of a cylinder

Sediment grain size is a sensitive parameter, as indicated by Eq. 5. When wave height is set to 4 ft and water depth is decreased to 30 ft, the impact of grain size is clearly seen when size is varied from 0.05 mm to 2.0 mm (Figure 24).

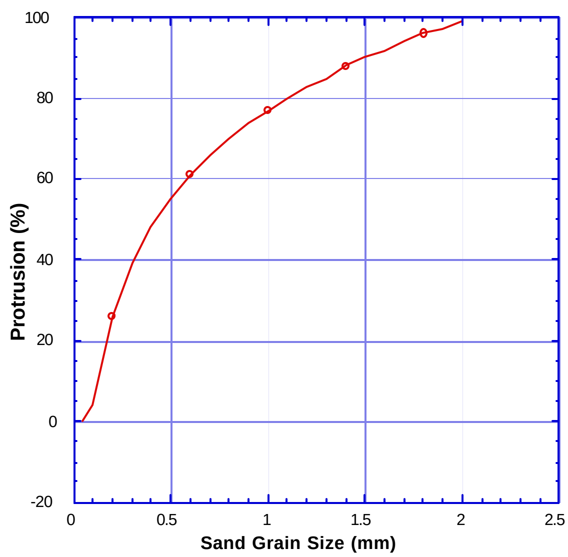


Figure 24. Impact of sediment grain size on protrusion of a cylinder (Eqs. 5 and 6)

COMMENTS:

This model is strictly empirical. There are no physics incorporated into the interaction of the mine and the sea bed. The percent burial is based only on sand size and whether or not the critical velocity for bed load or suspended load transport due to waves has been exceeded. No burial is predicted if velocities are too low for bed load; partial burial is predicted if velocities exceed bed load but not suspended load; and total burial is predicted if suspended transport occurs. Although this is an extreme approximation of real mine scour, it is qualitatively realistic to assume that bed load transport of sand buries mines much more slowly than suspended transport of sand.

Note that the model makes no distinction between cohesive and non-cohesive sediments. While this scour model was developed for sediment grain sizes typical for sand, it does allow grain size selection for values below that expected for fine sand (<0.065 mm), which is inappropriate. Sediment is typically a mixture of grain sizes thus differing rates of transport should be expected. This being said, it is not realistic to expect that a remote capability for determining the range of sediment grain sizes within a single seafloor sample is likely on-ship and the methodology of using a single, average grain size is the best available method in the current suite of models.

Another factor not included in the modeling is events that may serve as a precursor initiator of scour such as cyclic liquefaction. Nogami[51] theorizes that cyclic liquefaction could indeed be an initiator of scour due to the “pumping” action of waves at a suitable water depth. Also, it does not consider the effect of tides or other sources of currents. Finally, the model is an “all-or-nothing” estimate that has no time dependence. The estimate produced represents the maximum scour that results for the conditions specified. This means that the model is more useful for assessing the likelihood of buried mines rather than actual mine burial predictions.

Name: NBURY

General Description: NBURY is a scour model developed by Industrie Anlagen Bau Gesellschaft of Munich, Germany, for the German Navy. There are three choices in running the model: swell, wind waves or tidal currents. Scour burial due to swell and wind waves are based on the Carstens and Marten equations. The swell case bases bottom wave orbital velocity on a specified wave height and period, whereas the wind waves case calculates its own wave height and period based on a specified wind speed and duration. The tidal currents case is not based on Carstens and Marten, but involves generation of sediment ripples instead. The wave-induced scour model is an improvement over WISSP in that it includes time-variation and also includes a continual dependence of burial on wave orbital velocity.

NBURY has a user-friendly Windows-PC interface (Figure 38). The burial method and inputs are changed simply by clicking clearly labeled buttons in the program's startup screen. New parameter values are then typed directly into forms within the program. The output is updated immediately by pressing an "OK" icon. The basic output is percent burial by volume. Additional output information is seen by clicking the "details" button.

INPUTS:

The initial startup screen is seen in Figure 38. For swell, the required inputs are:

Mine:	Diameter, D (cm)
	Initial burial, Y_i (cm)
Sediment:	Grain size, d (mm)
	Layer thickness (cm)
	Density of sand relative to water, s (default 2.65)
	Angle of repose of sand, ϕ (default 35 deg)
Sea:	Water depth (meters)
	Wave height (meters)
	Wave period (sec)
	Wind (actually wave) duration, t (hours)

For wind waves, the required inputs are:

Mine:	Diameter, D (cm)
	Initial burial, Y_i (cm)
Sediment:	Grain size, d (mm)
	Layer thickness (cm)
	Density of sand relative to water, s (default 2.65)
	Angle of repose of sand, ϕ (default 35 deg)
Sea:	Water depth (meters)
	Wind velocity (meters/sec)
	Wave period (sec)
	Wind (actually wave) duration, t (hours)

For tidal currents, the required inputs are:

Mine:	Diameter (cm)
	Initial burial (cm)
Sediment:	Ripple height (cm)
Sea:	Water depth (meters)
	Current velocity at the sea surface (cm/sec)
	Tidal current duration (hours)

OUTPUTS:

For swell and wind waves, the outputs are:

Bottom orbital velocity above wave boundary layer, U_m (cm/sec)
Sediment Froude number, F (dimensionless)
Froude number threshold, F_l (dimensionless)
Mine burial depth, Y (cm)
Volume buried (percent)

For tidal currents, the outputs are:

Mean bottom current velocity (knots)
Sand ridge height (feet)

Average mine burial time (days)
Mine burial depth (cm)
Volume buried (percent)

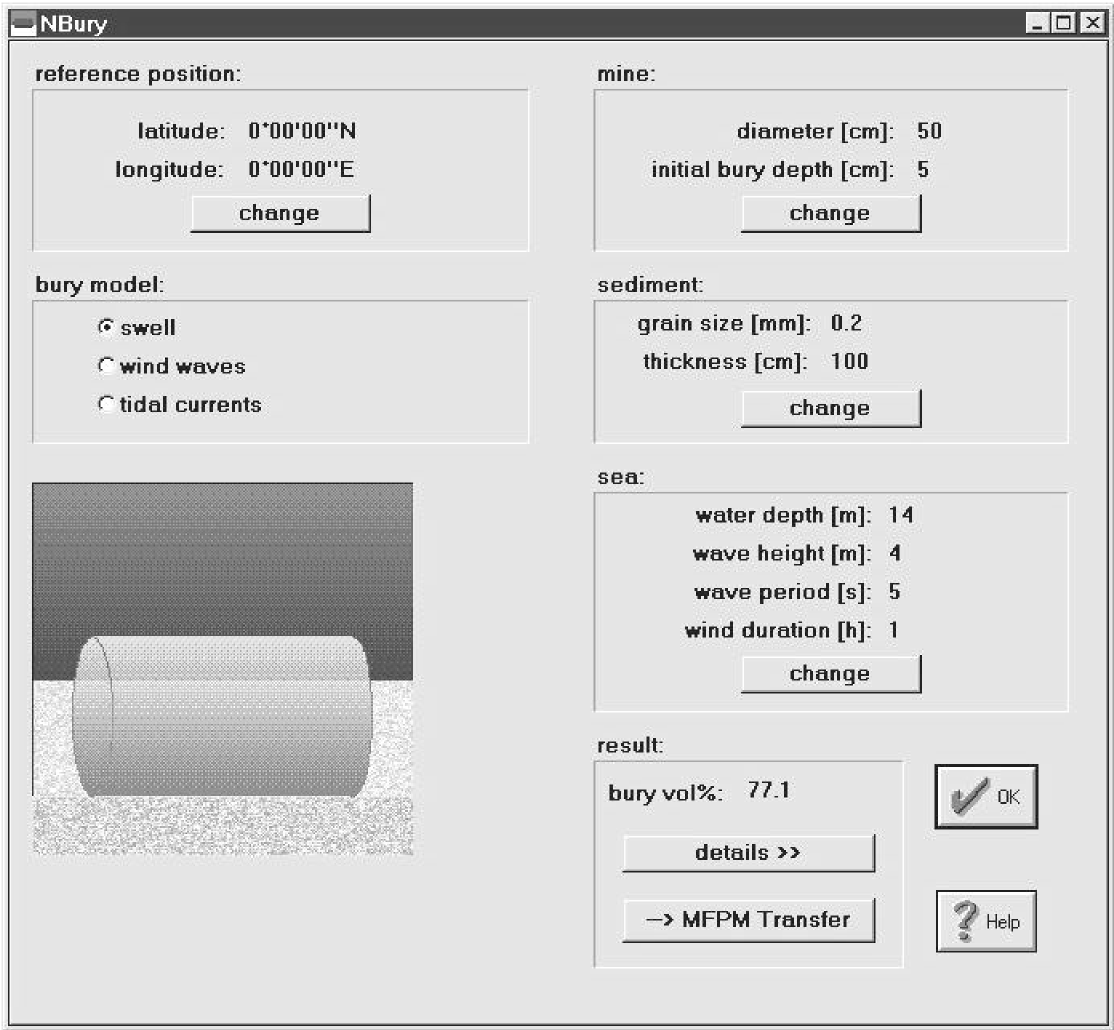


Figure 38. Startup screen for NBURY

SCIENTIFIC BASIS: The model supports swell, wind waves, and tidal currents as burial methods. As indicated by the help function in the program, the theory used in the swell and wind wave cases is presented in detail by Stender[53]. For swell, the model assumes a continuous swell showing a dominant wave period. U_m is then calculated using linear wave theory (for linear wave equations, see discussion of the WISSP model). The wind waves case assumes a fully developed sea state appropriate to a long fetch. U_m is calculated by assuming a Pierson and Moskowitz wave spectrum.

Once U_m is calculated, both the swell and wind wave models function exactly the same and apply the mine scour burial theory of Carstens and Martin[50] as follows:

The sediment Froude number is given by:

$$F = \frac{U_m}{\sqrt{(s-1)gd}}$$

Here (and in the following formulae) all the variables are assumed to be in consistent units (e.g., d in meters, U_m in m/sec, g = 9.81 m/sec^2, etc.). The Froude number threshold is given by

$F_l = 5.04\ (d/D)^{1/14}$

For cases with $F > F_l$, it is assumed that scour occurs by suspended load sand transport, and the mine burial depth is determined by solving the following equation for Y:

$$0.01F\left(\frac{d}{D}\right)^{0.5}\frac{U_m t}{D} = \frac{0.786}{\tan^2 f}\left(\frac{Y}{D}\right)^4 + \frac{4.45}{\tan f}\left(\frac{Y}{D}\right)^3 + 7.07\left(\frac{Y}{D}\right)^2$$

If Y is predicted to be less than Y_i, Y is set equal to Y_i. If Y is predicted to be greater than D, Y is set to D.

For cases with $F < F_l$, it is assumed that scour occurs by bed load sand transport, and the mine burial depth is determined by solving:

$$1.2\left(10^{-7}\right)F^8\frac{U_m t}{D} + 5.2\left(\frac{Y_i}{D}\right)^{0.63} = \frac{0.786}{\tan^2 f}\left(\frac{Y}{D}\right)^4 + \frac{4.45}{\tan f}\left(\frac{Y}{D}\right)^3 + 7.07\left(\frac{Y}{D}\right)^2$$

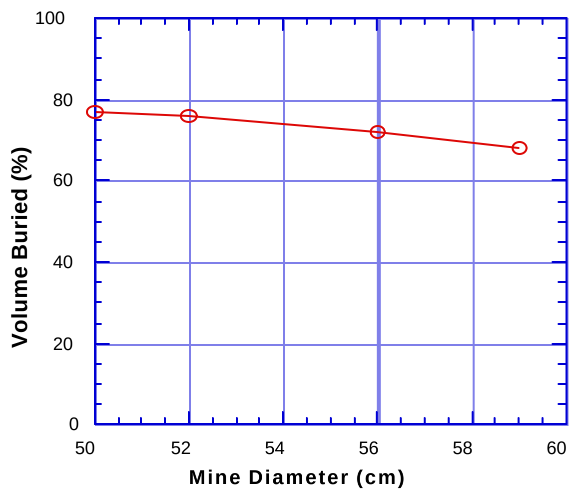
If Y is predicted to be greater than D, Y is set to D.

Finally, burial depth is translated into volume buried based on the geometry of a partially buried, flat lying cylinder. Although sediment thickness is an input to the swell and wind wave cases, the models do not appear to use this parameter in their scour calculations.

The tidal currents case uses an entirely different approach to solve for mine burial. Burial is based not on scour, but on generation of sand bedforms. The tidal model assumes an oscillating tidal current, causing generation of sediment ripples, and includes a burial velocity diagram from ATP6.

SENSITIVITY ANALYSIS:

The model demonstrates a relative insensitivity to mine diameter (Figure 39). However, the model maintains a 4:1 ratio of length to diameter for any specified mine diameter. This is imposed by the basic assumptions underlying the C&M equations.



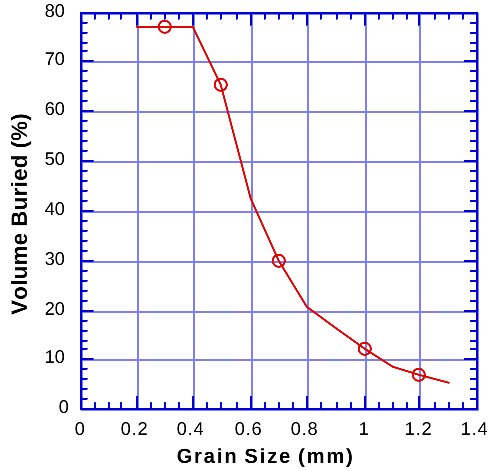
Conditions

sediment grain size 0.2 mm — water depth 14 m
wave height 2 m — wave period 5 sec
wave duration 4 hrs

Figure 39. Impact of mine diameter on mine burial predictions

As expected, there is a strong sensitivity to sediment grain size (Figure 40). As in most other scour models, a single grain size (e.g., median grain size) is used to represent sediment containing a spectrum of grain sizes. Since sediment transport does not begin until the critical threshold *for that grain size* is exceeded, the burial depth predicted is strictly an approximation. Should the grain size spectrum be skewed, the burial estimate will contain a large error.

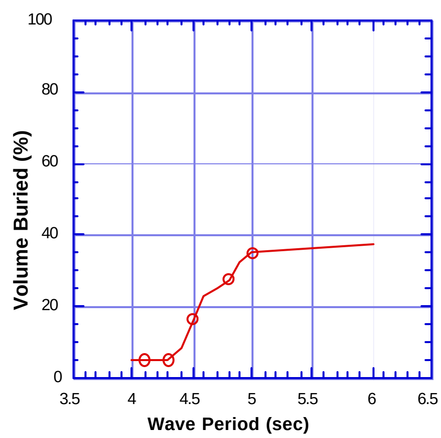
For a specified water depth and wave height, there is a maximum wave period beyond which no further burial is predicted. Over the range of wave periods tested (4 to 6 seconds), the burial prediction varies from about 5% to 35% (Figure 41). Wave period does not appear to be a first order factor. Remember that the prediction is made regardless of whether the relationship between water depth, wave height, and wave period is realistic. Wave height is a first order factor. As wave height varies from 1 to 5 m, the burial prediction changes from 0 to about 90% burial (Figure 42).



Conditions

mine diameter 50 cm	water depth 14 m
wave height 2 m	wave period 5 sec
wave duration 4 hrs	

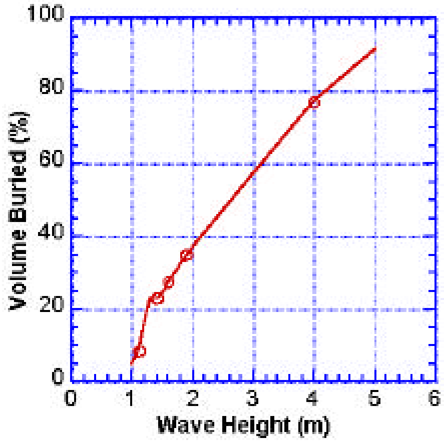
Figure 40. Impact of sediment grain size on mine burial prediction



Conditions

mine diameter 50 cm   water depth 14 m
wave height 2 m   sediment grain size 0.2 mm
wave duration 4 hrs

Figure 41. Impact of wave period on the mine burial prediction

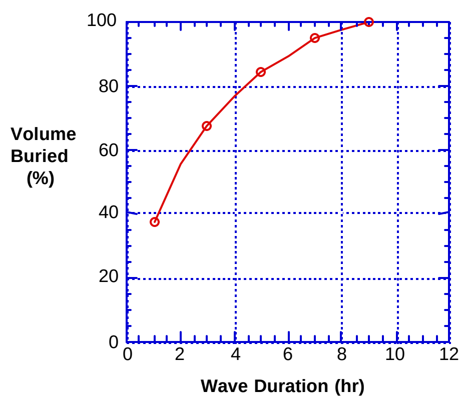


Conditions

mine diameter 50 cm   water depth 14 m
sediment grain size 0.2 mm   wave period 5 sec
wave duration 4 hrs

Figure 42. Impact of wave height on the mine burial prediction

The duration of mine exposure to wave orbital velocities, t, plays an important role in mine burial by scour (Figure 43). For the specified wave height, 9 hours of wave energy acting on the mine is necessary for complete burial at 14 m water depth.

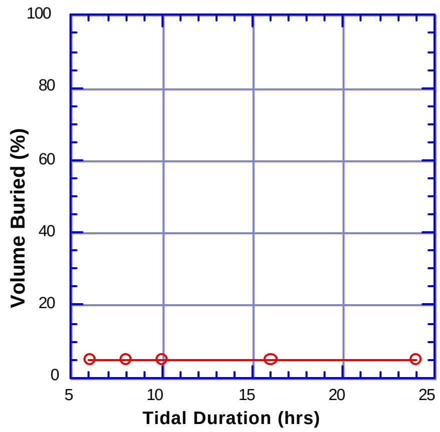


Conditions

mine diameter 50 cm   water depth 14 m
wave height 2 m   wave period 5 sec
sediment grain size 0.2 mm

Figure 43. Impact of wave duration on the mine burial prediction

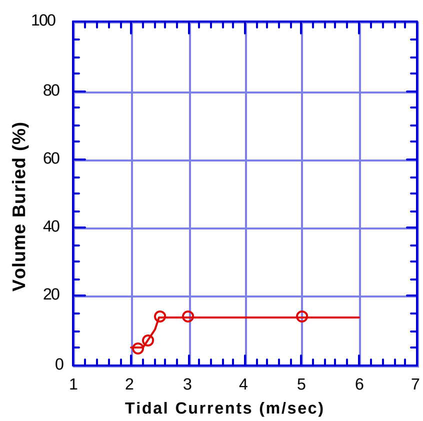
Tidal duration (i.e., over a tidal cycle) has virtually no impact on the burial prediction (Figure 44). Rather, it is current speed that is most important (Figure 45). When tidal current is varied between 2 and 6 m/sec for a 14 m water depth, burial changes for about 5 to 15%. The maximum impact of current speed occurs at 2.6 m/sec. Tidal currents beyond this speed yields no further burial.



Conditions

mine diameter 50 cm sand ridge height 10 cm
current speed 2 m/sec

Figure 44. Impact of tidal duration on the mine burial prediction



Conditions

mine diameter 50 cm sand ridge height 10 cm
current duration 12 hrs

Figure 45. Impact of tidal current speed on the mine burial prediction

COMMENTS:

The conditions under which Carstens and Martin developed their equations mine burial by wave scour were highly specific. All cases used cylinders with a length to diameter ratio of 4 and uniformly sized bed materials. Bed materials were either .297 mm glass beads or .585 mm Ottawa sand. Bedding material was approximately 4 inches thick within the bottom section of a “U” tube. The bottom section was 6 ft long and had a cross sectional area based on 1 ft vertical and 4 ft horizontal dimensions. This model is strictly empirical and has been developed with a limited data set, typically at the two extremes of current velocity.

Testing by Carstens and Martin was conducted with flow rates that did not generate sand ripples. This was critical due to the observation that when the cylindrical model was part of the ripple system, scour did not occur. Because the mine shape was scaled, whereas sediment grain size could not be similarly scaled, Carstens and Martin could conduct experiments at only two values of sediment Froude number (i.e., Froude numbers of 11.2 and 2.8). Intermediate Froude values resulted in sediment ripple formation and these ripples were on the same order in size as the scaled mine shape. Therefore, results needed at intermediate Froude values required Carstens and Martin to analyze data developed from other investigators.

Within the NBURY wind wave model, the P-M modifications provide a method of approximating an ocean wave spectrum semi-empirically. Note that the P-M spectrum is most relevant for open water, full developed seas and its applicability to shallow water is suspect. The P-M spectrum recognizes that natural waves in the sea are both irregular and random consisting of a spectrum of wave heights, period, and directions. The basic plot (wave energy as a function of the radian frequency) yields a curve with a distinct skewness to the low frequencies. Performing an inverse Fourier transform on the frequency spectrum yields estimates of wave height. Soulsby[54] states that rather than a P-M spectrum, a JONSWAP spectrum is more appropriate for growing waves in continental-shelf waters. This curve has a sharper peak with only a slight tendency to lower frequencies. It is more appropriate for sediment transport studies because it applies to limited water depths where the wave energy contacts the seafloor generating a sediment stress.

NBURY does allow the starting point for burial to begin at some value other than the sediment's surface (i.e., initial burial Y_i). Although this suggests that NBURY could be the natural follow-on to impact burial estimates, changing the initial burial depth within NBURY has no impact on the final burial prediction using the suspended sediment transport burial formula. For the suspended sediment transport case, the final burial estimate is calculated based on the mine starting the burial process from the sediment surface. If this estimate is less than the initial burial depth, the initial burial depth is reported as maximum burial depth. While this needs field tests to verify the unimportance of initial burial depth to final burial depth, it is highly likely that initial burial depth is critical to time required for burial.

NAME: DRAMBUIE

GENERAL DESCRIPTION: DRAMBUIE stands for Defense Research Agency Mine Burial Environment. The original UK DRAMBUIE model is site-specific for the Clyde Estuary and is primarily a database/display software capability that contains a sub-module devoted to scour burial (Figure 37). DRAMBUIE was developed by HR Wallingford as a demonstrator database to prove the concept of using a software package to determine the likelihood of finding buried mines along a given route (Bennett, 2001). This model is described in some detail in Nato NG-3 (1999) Mine Burial Prediction Report; full details can be found in the original model documentation (HR Wallingford Ltd, 1994).

The program includes a graphical link with color-coded contour maps of sediment type and peak tidal flow. The program which was written for the Clyde restricts the operator from modifying the data and generating new mine burial maps (Bennett and Dolan, 2001). The formulae used in the scour sub-model require sediment parameters (sediment specific gravity, grain size), mine properties (size, effect of shape on flow), and tidal flow parameters (depth, peak hourly current speed). The approach converts these inputs into a bed shear stress at the bottom and compares available shear stress to stress required to move the sediment. From this information, rate of burial is calculated.

The original UK DRAMBUIE scour model considered here includes only tidal currents. Enhancements to the original model have been proposed including scour effects from surface waves and swells, and non-scour burial processes such as sandwave migration, impact, gravity sinking, liquefaction by waves, and hydrodynamic loading stresses on mines (Bennett and Dolan, 2001).

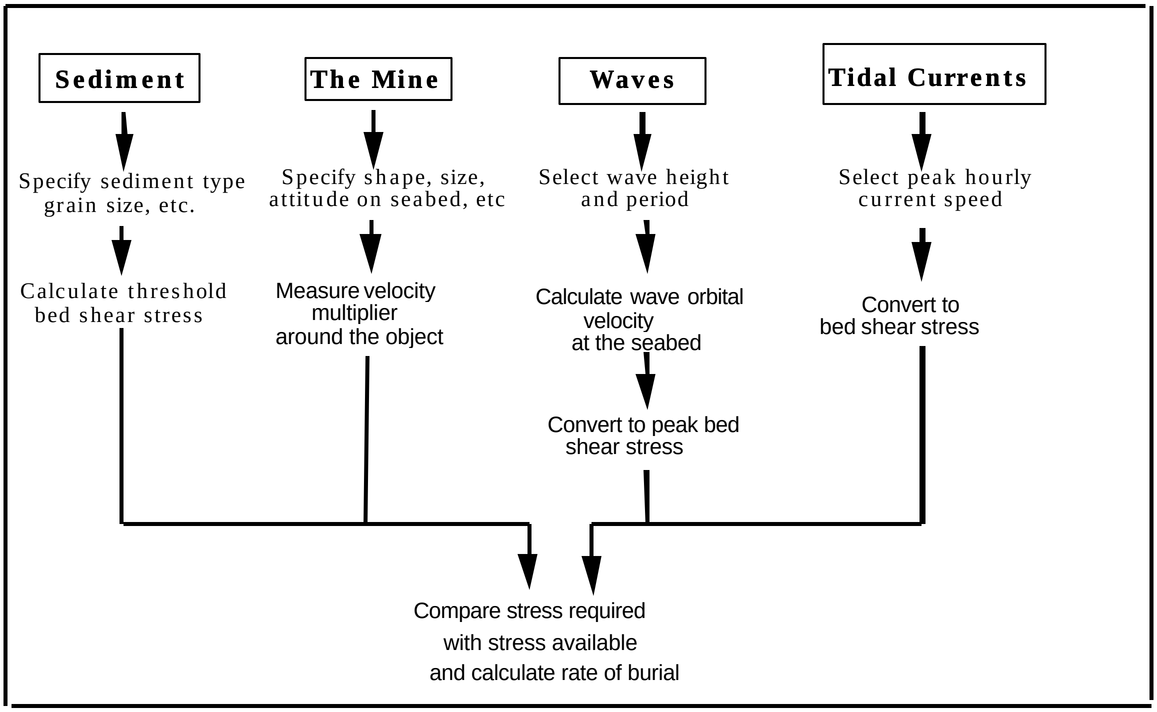


Figure 37. Flow chart for DRAMBUIE (including planned wave module)

INPUTS:

U(z)	Either current velocity at height z above the bed or
$\bar{U}$	Depth-averaged current velocity (both meters/sec)
h	Water depth (meters)
s	Specific gravity of sediment (2.65 for siliceous grains)
d	Median grain size of the sediment (meters)
D	Diameter of the cylinder (meters)

OUTPUT:

The underlying formulae provide a time-series of mine scour pit depth at given locations as output. Figure X displays example graphical output of the UK Scour model (taken from NATO NG-3, 1999) where scour pit depths have been interpolated onto an areal display.

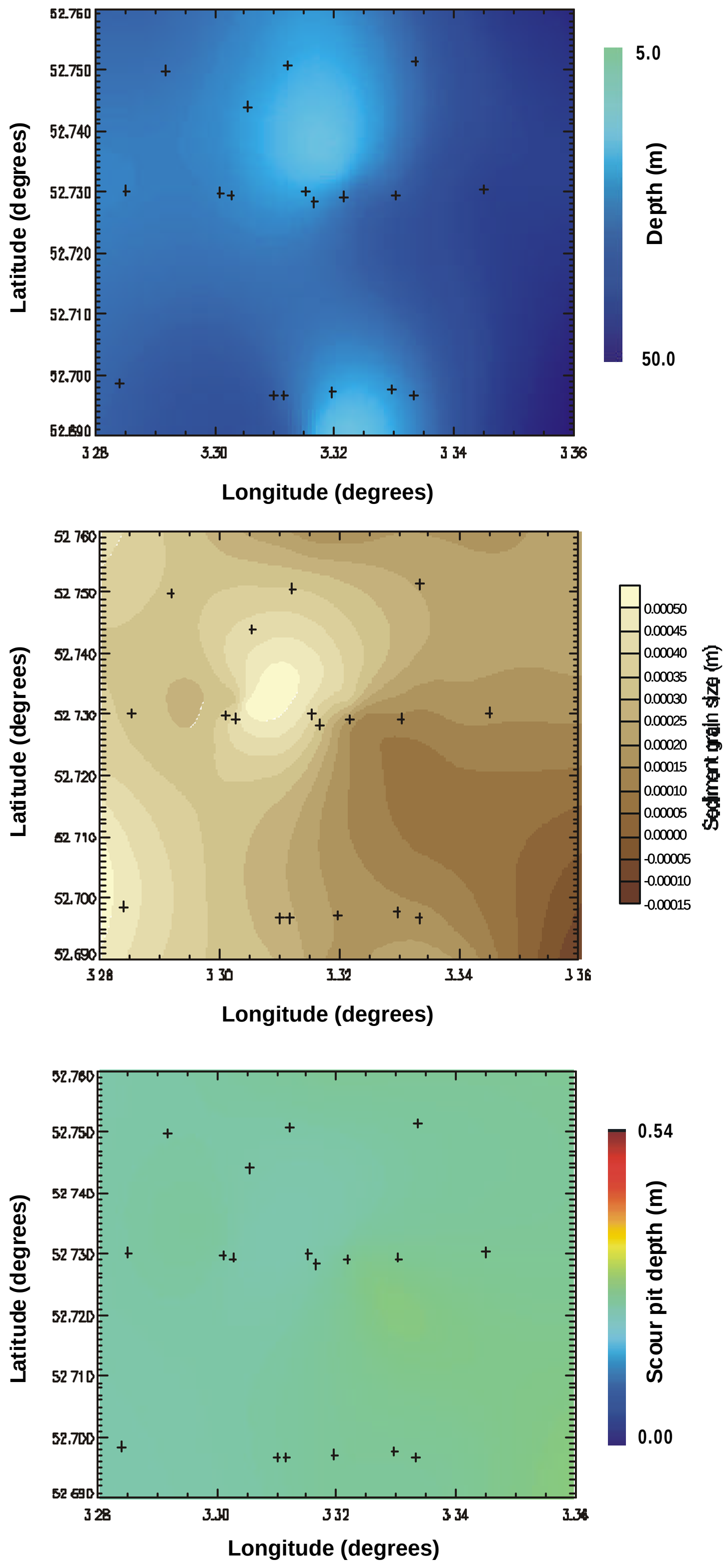


Figure X. Areal prediction of scour (lower plot) by the UK Scour Model given areal input of bathymetry (upper plot) and sediment grain size (middle plot), interpolated from point data (marked by crosses).

SCIENTIFIC BASIS:

The theory behind development of DRAMBUIE is found in Whitehouse[12] and Soulsby.[54] It is Soulsby that provides the methods for determining bed shear stress as well as the threshold of motion for cohesionless sediments. Whitehouse builds on this foundation, developing a time-stepped procedure for estimating scour burial depth in response to both tides and waves as environmental forcing functions.

DRAMBUIE was developed "to predict the burial of isolated free-settling mines resting on a bed of mobile sandy sediment under the action of waves and tidal currents." DRAMBUIE assumes that the mine, resting on the bottom, induces an increase in flow rate that exceeds the threshold conditions needed to move the sediment grains. With movement, a scour pit is created and the mine settles into the pit to be covered to about 1/2 to 1/3 of its diameter.

An empirical formula is used to describe the increase in scour pit depth over time about a target located in a steady, unidirectional flow:

$$S = S_{\infty}\left[1 - \exp\left\{-(t/T)^{p}\right\}\right]$$

where

S_{∞} is final scour depth as time approaches infinity (meters)
T is the burial time-scale factor (sec)
p is a fitting coefficient related to the shape of the S(t) curve

The above formula was originally developed for scour around a fixed pile (Whitehouse, 1998). Based on empirical data, p = 0.6 for a horizontal cylinder and p = 0.5 for a vertical cylinder.

The time-scale factor is given by

$$T = \frac{A q_{\infty}^{B} D^{2}}{\sqrt{g(s-1)d^{3}}}$$

where

A = 0.095, B = -2.02 are empirical values from flume experiments
$g = 9.81\ m/s^2$ is the acceleration of gravity
s is sediment density relative to water (2.65 for silicious sediment)

The Shields parameter is given by

$$q_\infty = \frac{u_*^2}{g(s-1)d}$$

where $u_* = (\tau/\rho)^{1/2}$ is the friction velocity in meters/sec, τ is bed stress and ρ is fluid density.

If u(z) is known, u_* is given by

$$u_* = \frac{1}{7}\left(\frac{0.32d}{z}\right)^{1/7} u(z)$$

If u(z) is not known, but depth-averaged velocity $\bar{U}$ is known, u_* is given by

$$u_* = \frac{1}{7}\left(\frac{d}{h}\right)^{1/7} \overline{U}$$

Laboratory flume experiments indicate the following values for S_∞:

$S_\infty = 0$ for $0 \le U \le 0.75\ U_{cr}$

$$S_\infty = S_{\infty \max} \frac{U - 0.75U_{cr}}{0.5U_{cr}} \quad \text{for} \quad 0.75\ U_{cr} \le U \le 1.25\ U_{cr}$$

$S_\infty = S_{\infty \max}$ for $1.25\ U_{cr} \le U$

where

$S_{\infty \max} = 1.15$ D (meters) is the maximum depth of scour at large U
U (meters/sec) is the current velocity well above the mine
U_{cr} (meters/sec) is U for initial grain movement without a mine

Mine burial begins at $U \le U_{cr}$ because the presence of the mine locally speeds up the current velocity via an empirically determined “velocity multiplier”.

According to Whitehouse (1998), it is reasonable to assume

$$(U_{cr}/U)^2 = \theta_{cr}/\theta_{\infty}$$

where θ_{cr} is the critical Shields parameter for initial grain movement. θ_{cr} is given by (Soulsby, 1997) as

$$\theta_{cr} = \frac{0.30}{1+1.2D_*} + 0.055\left[1-\exp\left(-0.02\,D_*\right)\right]$$

where

$D_* = d[(s-1)g/\nu^2]^{1/3}$ is the dimensionless grain size.
$\nu = \sim 10^{-6}$ m²/sec is the kinematic viscosity of water.

The above equation for burial depth, S, assumes a constant burial time-scale factor. Whitehouse (1998) provides the following time-stepping equation for predicting burial depth assuming quasi-steady flow.

$$\frac{dS}{dt} = \frac{p(S_\infty - S)}{T\left[-\log\left(\frac{S_\infty - S}{S_\infty}\right)\right]^{(1/p)-1}}$$

This approach applied in DRAMBUIE is reasonably valid as long as the increment in burial, dS, and time interval, dt, are both sufficiently small. Integration of this equation provides the degree of burial, S. Calculation of the burial depth increment requires that the user know: (1) the length of the burial timestep, dt, (2) the depth of burial which has already occurred, S, (3) the final burial depth, S_∞, and (4) the timescale, T.

The DRAMBUIE model was developed for the Clyde Estuary where tides provide the dominant current. In principle, this model can incorporate wave orbital velocity as well. This would be accomplished by taking a vector sum of tidal current and wave-induced bed stress and solving for the combined wave-current shear velocity.

SENSITIVITY ANALYSIS:

Sensitivity tests were conducted for changes in sediment grain size (3 sizes) and flow velocity (3 flow velocities). Results indicated that the model was not overly sensitive to minor changes in grain size. In general, differences between predictions were about 0.2D for 1 day, about 0.2D up to a 10-day interval, and 0.4D when the time exceeds 10 days.

The model is more sensitive to flow rate. Increasing the flowrate by 5% resulted in an increase in the depth increment burial prediction of 0.08D and after 10 days, 0.14D. Reduction of the flowrate by 13% reduced the depth increment burial prediction by 0.18D for 1 day and 0.34D for a 10-day period. This is not unexpected since S_∞ varies strongly with U/U_{cr}.

COMMENTS:

This model has several of the same drawbacks present in most other mine burial models. The model is meant only for non-cohesive sand and does not consider the presence of multiple grain sizes. Because the model is largely empirically based, different mine shapes will require testing to determine appropriate flow enhancement factors and to determine whether equations developed for scour around pilings are widely applicable to general scour around arbitrarily shaped objects. Also the model has only been implemented to date for the Clyde Estuary as is not yet available for general use elsewhere.

Nonetheless, this model implements relatively well-proven equations for scour associated with steady currents. The general trends are based on engineering observations and formulations that have been widely applied in a variety of environments. For the time being, the DRAMBUIE equations are the most practical available for relatively simple prediction of mine scour under quasi-steady currents.

NAME: Vortex Lattice model

GENERAL DESCRIPTION: The Vortex-Lattice model is a R&D model, developed by S. Jenkins and D. Inman, Scripps Institute of Oceanography, San Diego, CA. This model is directed toward developing a time-stepped, numerical prediction of mine burial due to scour under shoaling and non-breaking waves in coastal waters (Figure 25). This model also includes alteration of bars in the nearshore region. There are two basic mechanisms in the present Vortex-Lattice formulation of mine scour and burial (Inman and Jenkins, 1999): (1) a near-field burial mechanism involving sediment transport by the vortices shed from the mine shape; and (2) a far-field burial and exposure mechanism that involves changes in the elevation of the seabed due to accretion or erosion of the entire nearshore profile.

As an R&D model, the Vortex-Lattice approach is not available for straightforward use. Nonetheless, the near-field component of this formulation is the only scour mine burial model reviewed by this report which is strongly based on underlying physics. (Note that the far-field burial component is not as strongly based on fundamental physics.)

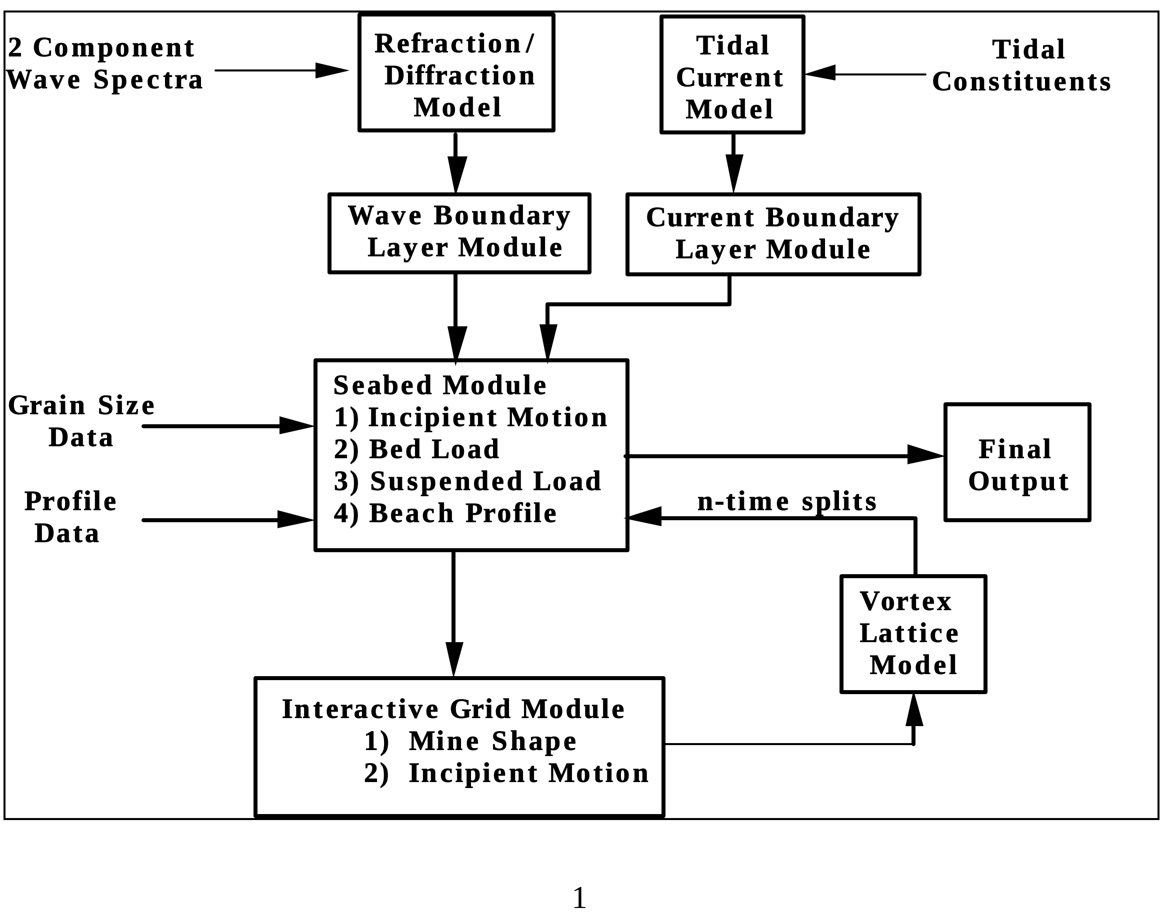


Figure 25. Flow chart for the vortex lattice model

INPUTS:

Tidal constituents
2 Component wave spectra with
- wave height
- wave period
- wave direction

Sediment grain size
Beach profile data
Mine shape data

SCIENTIFIC BASIS:

Initial model development was driven by the observations made with cylindrical mines placed at various water depths off the Scripps Institute of Oceanography, LaJolla CA. Critical observations included:

- mines at all depths scoured and buried and an increasing water depth impacted the time required for burial
- regardless of the mine's original orientation to flow, the mines invariably re-aligned themselves perpendicular to flow
- on and offshore flows resulted in a characteristic "horseshoe" pattern of scour characteristic of unidirectional flow patterns due to wave mass transport
- oscillatory flow under waves produce vortex filaments from the edges resulting in a "doughnut" shaped scour pattern
- for cylindrical shapes, wave forces typically cause the mine to roll into the scour depression. This initiates another cycle of scour and roll over that continues until the mine is buried. In contrast, flat-bottomed shapes bury by shear failure
- once buried, there is no surface indication of burial
- burial requires a net deposition of sand either from sand ridge migration or seasonal adjustments in beach profile

It is only recently that the various components have become available that allows a quantification of scour mechanics into a physics-based model. The four components combined here include:

1) a model that predicts seasonal and storm-driven changes in beach profile,

2) a theory addressing sediment porosity and its enhancement of bottom stress under waves in the onshore direction,

3) a precursor model addressing scour and erosion of a winged shape subjected to a tidal flow, and

4) a threshold shear stress equation for scour predicted from sediment engineering properties, include the bed load scour induced by tangential component of wake vortices as well as suspended load scour due to the vertical component.

The far-field burial mechanisms are presently formulated by changes in the equilibrium bottom profiles associated with seasonal changes in wave climate (Inman and Jenkins, 1999). High energy winter waves cause erosion of the bar-berm portion of the profile (exposing mines close to shore), and accretion of the shorerise profile (causing burial of mines further offshore). Low energy summer waves result in a reversal of the areas of exposure and burial. The formulation of the bathymetric evolution problem is based on successive equilibrium bottom profiles. The equilibrium bottom profiles are posed as states of thermodynamic equilibrium caused by the external work provided by prevailing wave climates and the potential energy reservoir stored in littoral sediment residing above closure depth (Jenkins and Inman, submitted, JGR). By this formulation equilibrium profiles are calculated from wave heights determined over a far-field grid using a refraction/diffraction model based on REF/DIF type.

The domain of the near-field (Figure 26) consists of one grid cell extracted from the far-field, which is divided into a rectangular lattice of panels and associated control points having sufficient resolution to define the mine shape (Inman and Jenkins, 1999). The vortex field induced by the mine is constructed from an assemblage of horseshoe vortices prescribed for every panel. This computational technique is known as the vortex lattice method (Jenkins and Wasyl, 1990) and has been widely used in aerodynamics and naval architecture. The strength of the vortices is derived from the potential flow pressure gradient over each panel and from the aggregate wave-current velocity in the grid cell. At the cross-stream boundary of each panel, the energy of the bound vortex is released into the wake as a pair of trailing vortex filaments. As these filaments diffuse outward, they decrease in strength. The model accounts for oscillatory flow by incorporating a reversed system of trailing filaments. The release of pairs of trailing vortex filaments from each panel causes scour of the neighboring seabed once the threshold shear stress is exceeded. Each pair of filaments induces a downwash flow that converges on the seabed and results in lateral bed load scour proportional to the cube of the vortex strength, Γ, and inversely proportional to the cube of the grain size, D. Beyond the lateral extent of the bedload scour, the vortex filaments induce an upwashing flow of suspended load, proportional to Γ^4 / D^4.

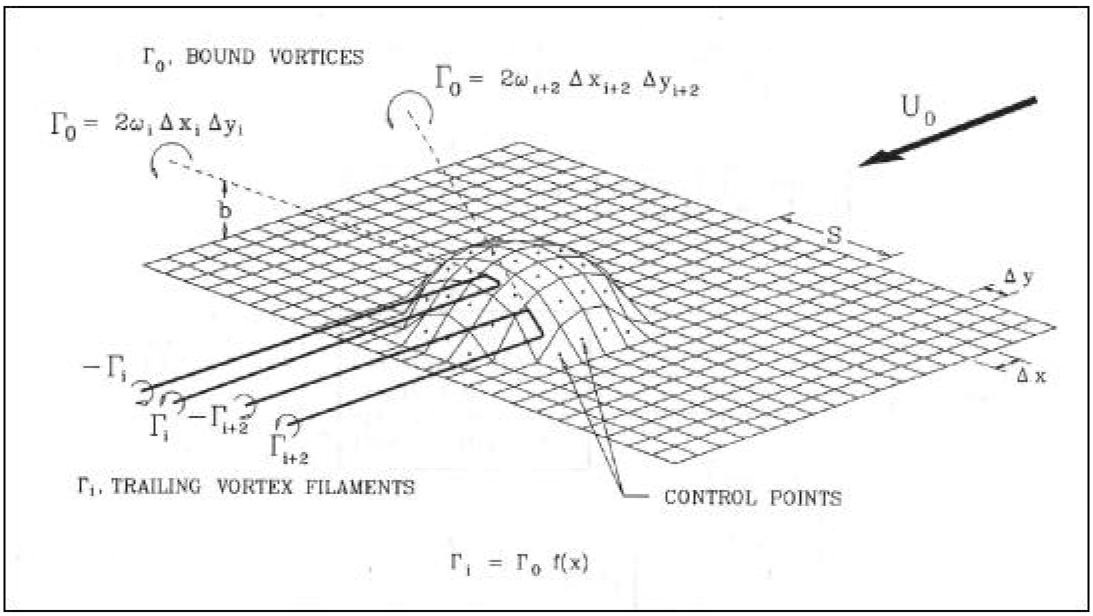


Figure 26. Vortex lattice method

This process is dependent on: (1) size of the sediments, (2) threshold shear stress, (3) cross-steam dimension of the body, (4) water depth, (5) the shape of the body, (6) the wave characteristics - height, period, direction, and (7) the strength and direction of mean currents. Bottom type influences both settling velocity and the threshold shear stress. The distribution of sediment sizes comprising the bottom is handled by dividing the range between clay and silt to coarse sand into ten particle size bins and running the above calculations for each bin. Because sediments can be both cohesive and non-cohesive, two different formulas are to predict threshold scour stress.

Model results have reproduced characteristic scour patterns observed in the field (Figure X) and indicate that downstream deposition of sediments will cause bedform and bedform slope changes. Results also indicate that the entire process is suitable for developing a time-stepped model since the bottom changes lag the vortex generation process.

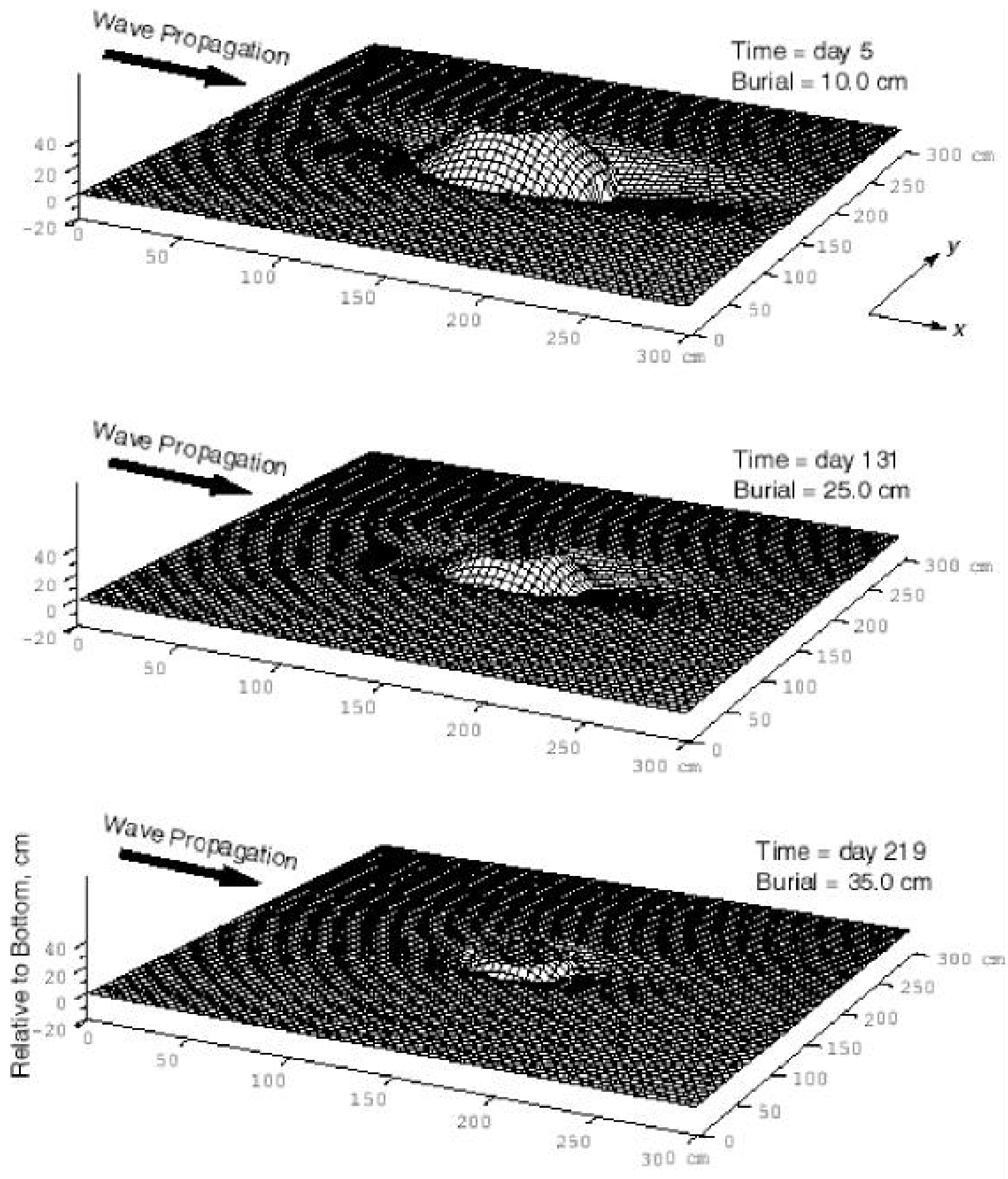


Figure X. Model simulation of near-field scour/burial of a MANTA mine in water depth of 7.6 m subject to waves measured at the Scripps pier (Inman and Jenkins, 1999).

The second-generation model incorporates the following enhancements:

1) modifies the vortex lattice system such that complex mine shapes can be incorporated,

2) changes the model from a steady state to time-stepped predictions of scour,

3) applies mine motion equations to more fully predict mine movement due to currents and subsequent burial, and

4) integrates a capability for seasonal changes in beach profile.

Figure 27 (SOURCE?) clearly shows how scour holes develop in response to any shape target. Simply put, for each plane/plate of the target (and specifically, those in contact with the sediment), a pair of contra-rotating vortex filaments are generated. The rotation of these filaments results in a downwash between them that increases the bottom stress above the threshold necessary for sediment motion. The tangential reflection of this downwash impacts the now motile sediment and results in bedload scour transversely across the plane/plate, effectively moving the sediment toward the outside of the area where the vortices impact the sediment. Finally, an upwash results, again from the rotational motion of the vortices, which suspends the finer-grained fraction of the seabed and thus, the scour hole develops. Over time the scour holes enlarge, reducing the sediment available to support the target.

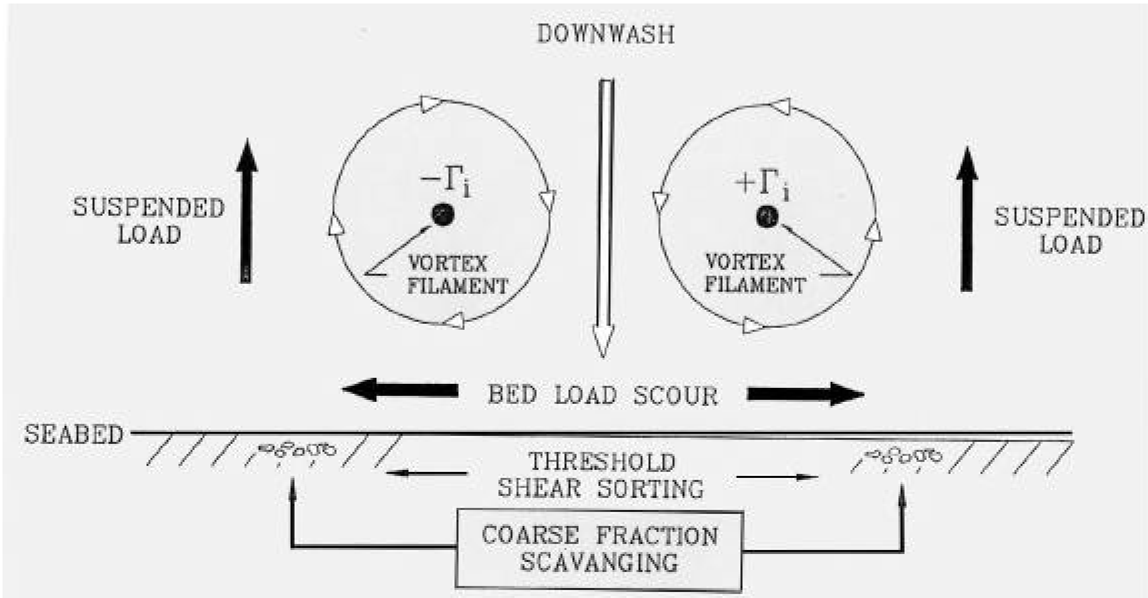
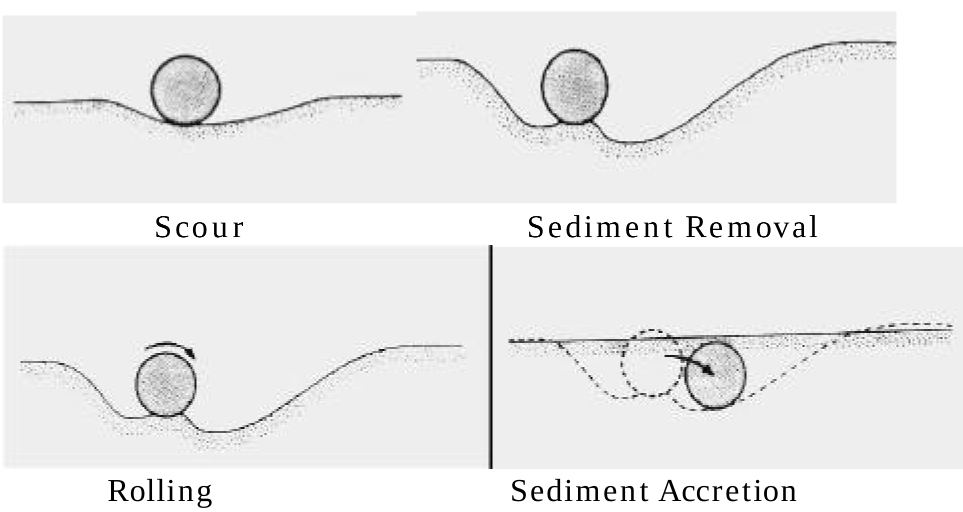
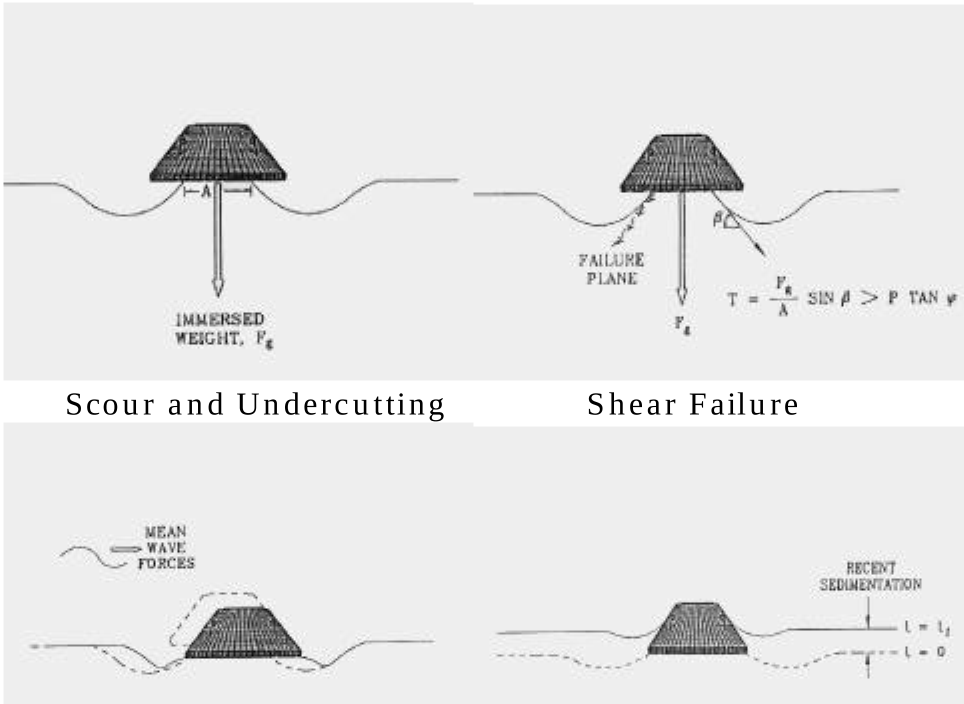


Figure 27. Vortex-lattice method for generating scour holes

Eventually, the remaining sediment is insufficient to support the target. One of two mechanisms leads to eventual burial. The first involves the scour and roll sequence seen in Part A of Figure 28. This mechanism is specific to cylindrical and spherical mine shapes. Atypical mine shapes, specifically those having a flat bottom, have a different burial mechanism (B, Figure 28). In this case, the sequence of events is scour, followed by shear failure, and then slumping. Finally, sediment accretiation completes the burial process.



A. Mechanics of burial for a cylindrical or spheroid target



Scour and Undercutting   Shear Failure

Slumping/Sliding Friction   Sediment Accretion

B. Mechanics of burial for an atypical, flat-bottomed target.

Figure 28. Sequence of events leading to burial for target shapes

As stated, the upgraded model has a capability for addressing a second burial mechanism, tentatively labeled as "far-field" burial mechanics. This mechanism involves seasonal changes not only of the shorerise (offshore) but also the bar-berm (inshore) bottom profile. These, in turn, respond to changes in the wave climate and sediment supply. It is the far-field mechanics that accounts for the deep burying and unburying of targets well below the ambient seabed elevation. Seasonal profile shifts are conceptually based on the second law of thermodynamics and react to the wave climate by maximizing the dissipation of wave energy.

In the shorerise profile, maximum dissipation results from bottom friction. Bottom friction reworks the sediment in response to the rotational component of the boundary-induced mass transport. Near the wave breakpoint, shoaling produces asymmetries in the wave profile that become the dominant mechanism for mean stresses. As a result, the bar-berm profile responds to Stokes harmonics for mean dissipation rates. The derivation of equations supporting these dissipation mechanisms has been discussed in Jenkins and Inman.[52]

SENSITIVITY ANALYSIS:

This has not been done since the model is not available for evaluation.

COMMENTS:

In its present form, the near-field component of the model has an excellent physics-based foundation. However, it is strictly a developmental model that is geared toward science-based objectives. It requires an intimate knowledge of how the model is constructed to effectively use it. Even in its present form, however, it produces results suitable for constructing a nomogram for a specific mine shape under the specified environmental constraints. It is not suitable in its present form for use by operational MCM forces.

NAME: Mulhearn:

GENERAL DESCRIPTION: This Australian bedform burial model (described by Mulhearn[55]) is a fairly simplistic approach devoted exclusively to the large class of migrating bedforms called dunes. Its primary inputs are current strength, bedform properties, and the initial location of a mine in relation to crests and troughs of a dune field. This model only applies when bedform heights are much larger than mine diameters. Bedload transport associated with bedforms is represented in this model by the Kalinske-Frijlink equations as described by van den Berg[56].

INPUTS:

Median sediment grain size (d) in meters
Mine diameter (D) in meters
Dune wave height (H) in meters
Dune wave length (r) from trough to crest on trailing (i.e., stoss) slope in meters
Dune wave length (s) from trough to crest on forward (i.e., lee) slope in meters
Initial location of the mine relative to dune trough (x_o) in meters
Maximum spring tidal current across dune (A) in meters/sec
Maximum neap tidal current across dune (B) in meters/sec
Time (t) in seconds or hours depending on calculation
Long term mean current speed across dune (W) in meters/sec

SCIENTIFIC BASIS:

Extracting Mulhearn's[55] discussion for his model, bedload transport is represented by the modified Kalinske-Frijlink equation

$$S_b = 5 r_s d \sqrt{dg(s-1)q}\, \exp(-0.27/q) \qquad \text{(Eq. 1)}$$

where

r_s	=	~2700 kg/m³ is sediment grain density
g	=	9.81 m²/sec is acceleration due to gravity
θ	=	Shields parameter
s	=	2.7 is ratio of sediment grain to water density

The Shields parameter is given by

$$q = \frac{t'}{dg(s-1)}$$

where τ' is bed shear stress associated with sand gain roughness alone, rather than the total bed shear stress due to both the form drag of bed-forms and grain roughness.

Mulhern relates bed stress to tidal velocity according to:

$$t' = r_w C_f U^2$$

where U is taken as the flow velocity 1 m above the bottom and C_f = 0.003. Estimates of C_f (friction coefficient) from field measurements contain a large degree of scatter and there is poor correlation with Reynolds Number or any other parameter. Therefore, a representative value of 0.003, derived by Komar[57] is used.

If the cross-section of a dune is assumed to be triangular with a height, H then

$$S_b = 0.5\, r_s (1-n) HC \qquad \text{(Eq. 2)}$$

where n = ~ 0.4 is the porosity of sand.

Combining Eqs. 1 and 2 and solving for C results in:

$$C = 10d\sqrt{C_f}\,U \exp(-0.27/q)/((1-n)H) \qquad \text{(Eq. 3)}$$

From equation Eq. 3, sand dune speed (C) is very dependent upon bottom water velocity, which results, in turn, from tidal and longer period flows. Mulhearn states that higher frequency oscillations due to waves and swell are likely to be unimportant in sand due fields.

Next, Mulhearn develops the case for modeling velocity (V) due to the tidal current. He assumes a semidiurnal tidal current with a spring-neap cycle and represented velocity as follows:

$$V = \{(A-B)\,|\,Cos\,(pt/336\ \,| + B\}Sin\,(pt/6)$$

where t here is in hours.

Since tidal flow will also have longer period currents imposed on this value, a mean current, which is considered a constant over the period of interest, is factored into the equation by

$$U = W + V$$

where W = mean current perpendicular to the sand dune crest. Mulhearn then assumes that the near bottom current is 80% of the total current therefore

$$U = 0.8*(W+V)$$

He recognizes that W will vary with time and states that the variation, in practice, will be poorly known. Additionally, he notes that for many places, there will be a mixture of diurnal and semi-diurnal tides. For this case, he recommends that A and B be estimated as averages of peak current values over 24 hours at the time of spring and neap tides, respectively.

For estimating the time required for burial, Mulhearn uses the sand dune geometry shown in Figure 52.

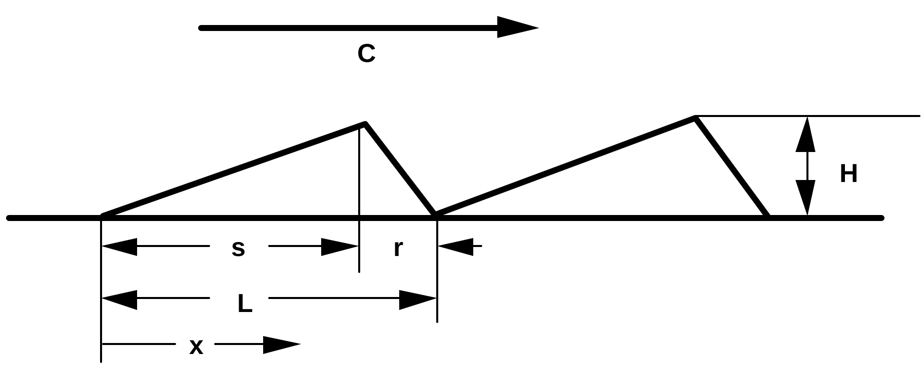


Figure 52. Sand dune geometry (from Mulhearn[55])

In this model, the sand dune is assumed to have a triangular cross section with a leading slope that is much steeper than the trailing slope. The mine is assumed to have a diameter that is less than the dune height, H, and the dunes move at a fixed speed, C, while retaining a fixed shape. Another assumption is that the mine itself does not alter the dune's speed or shape as it moves over the mine. While this is not true for smaller dune heights, the model is expected to provide order of magnitude estimates for burial times. Time of burial is the parameter to be calculated.

The model assumes that any mine placed on the sand dune crest or trailing slope merely moves vertically downward and the dune moves to the right. A mine laid on the leading slope is assumed to immediately roll down into the trough between dunes such that x_o=s+r. Thus, for a mine with diameter, D, located at x_o >=s+r, the mine will be buried at a time, t, such that

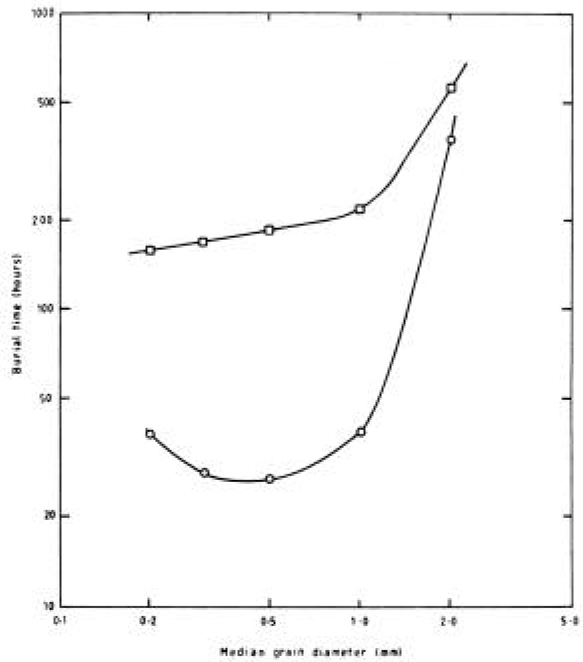
$$\int_0^t C\,dt' = x_o - (r+s) + rD/H$$

In this case, t in the above equation is in seconds.

SENSITIVITY ANALYSIS: Based on his model, Mulhearn ran a "standard" case wherein each of the input parameters was individually varied to determine the time required for a mine to bury and reappear. From the model, Mulhearn makes the following observations:

- Sediment grain size below 1 mm does not have a major impact on burial time for a single current speed (Figure 53). However, as sediment grain size increases beyond 1mm, there is a marked increase in the time required for burial.

- As dune crests move farther apart (i.e., dune height increases but with dune dimensions remaining proportional), the time required for a mine to bury increases rapidly, and when the mine is laid in relation to the tidal cycle impact becomes much less critical (Figure 54).



(from Mulhearn, 97)

Figure 53. Impact of grain size on burial time when mine is laid at spring tide (o) and 4 days later (☐)

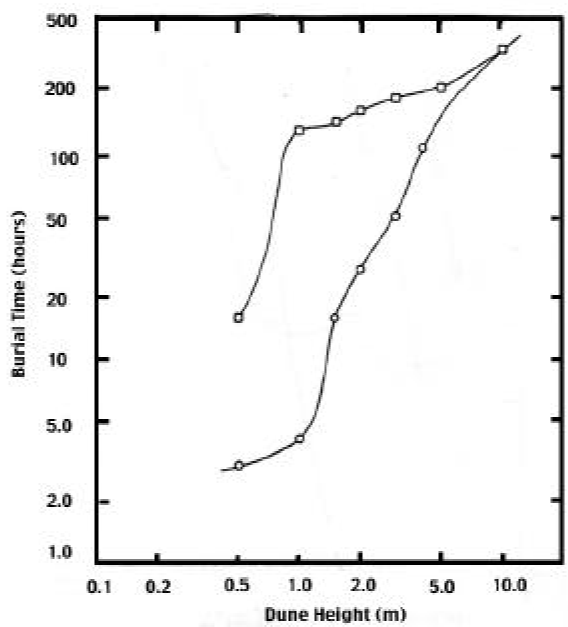


Figure 54. Variation in time for a mine to bury as a function of dune height with (o) representing a mine laid at spring tide and (☐) representing a mine laid 4 days after spring tide

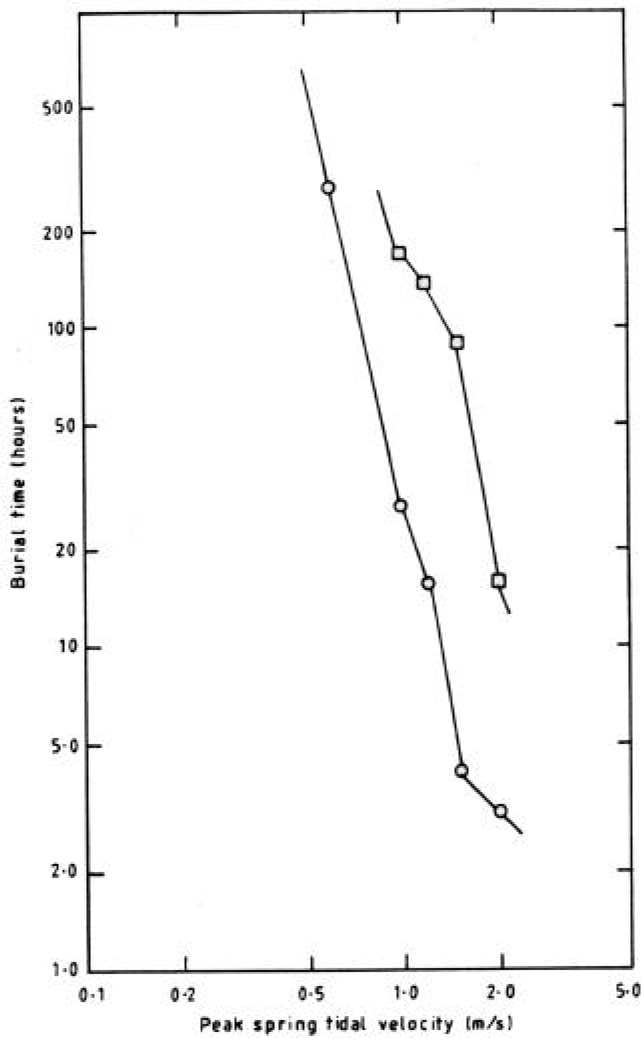


Figure 55. Time required for a mine to bury versus peak spring tidal velocity with (o) representing a mine laid at spring tide and (□) representing a mine laid 4 days after spring tide

- When a mine is laid in relation to the tidal cycle is critical. A mine laid prior to the spring tide will bury quickly whereas a mine laid after the spring tide will require significantly more time to bury (due to the lower current speed).

- The time history of sand dune speed varies strongly with an increase in tidal current and the mine buries quickly (Figure 55). However, as should be expected, there is no motion at slack current.

- The number of hours a mine remains buried within a sand dune does not vary greatly when mean grain diameter is varied for a given tidal current.

- The time required for a mine to bury is dependent on its initial position along a dune profile. That is, time required to bury varies linearly from the mine's position away from the foot of the lee slope (i.e., x_o=s+r). Note that there are oscillations within this linear trend that are driven by the influence of the tidal cycle and the number of tidal cycles needed to bury and unbury the mine.

COMMENTS:

Like most other mine burial models, the MULHEARN bedform model is meant only for non-cohesive sand and does not consider the presence of multiple grain sizes. Although van den Berg[56] found the Kalinske-Frijlink bedload formula to be a good choice for modeling bedform migration, it is not a widely accepted formulation. On the plus side, the MULHEARN approach is very simple, and it would be easy to substitute an alternative formula for bedform migration if necessary. In any case, more work is needed in identifying the best available models for bedform migration.

The perceived lack of a viable bedform migration model has been recognized by NATO's MBST. This group has asked that the US assume responsibility for developing a bedform migration model. There is no "real" model available and there is only limited validation with the two simple models/equations that do exist. They do, however, form a good basis for beginning the modeling effort. Thus, there is a need, first, to distill the two simple models into a single model. Note that the listed models address only the larger dunes and not those smaller bedforms migrating across the larger (i.e., slower) dunes. Additionally, neither model provides a true time history of burial nor handles oscillatory water and/or tidal currents.