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A Mathematical Model for Mine Burial by Mobile Underwater Sand Dunes

P.J. Mulhearn

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A Mathematical Model for Mine Burial by Mobile Underwater Sand Dunes

P.J. Mulhearn

Maritime Operations Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

Buried mines in the approaches to major ports and in shipping choke points constitute a significant problem in mine countermeasures operations because they are so hard to detect. One of the burial mechanisms which would occur in some important locations is burial by mobile underwater sand dunes (also called sand waves). In this report a new mathematical model is presented for this process and it is shown that the factors which are most critical for the time taken for a mine to become buried are firstly current strength, secondly dune size and thirdly the initial location of a mine in relation to crests and troughs of a sand dune field. As current strength increases the time taken for a mine to become buried decreases sharply. On the other hand the time till burial increases as a dune's size increases, and as a mine's initial distance downstream from a dune's crest increases.

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A Mathematical Model for Mine Burial by Mobile Underwater Sand Dunes

Executive Summary

Buried mines in the approaches to major ports and in shipping choke points constitute a significant problem in mine countermeasures operations because they are so hard to detect. One of the burial mechanisms which would occur in some important locations is burial by mobile underwater sand dunes (also called sand waves). Such locations include Charles Point Patches in the approaches to Darwin, and various choke points within Torres Strait. At these particular places, transiting ships have no choice but to go over, or very close to, an area of mobile sand dunes. Sand dunes are also common in parts of Bass Strait, Moreton Bay, and the mid and outer parts of the Northwest Shelf. In this report a new mathematical model is presented for this process and it is shown that the factors which are most critical for the time taken for a mine to become buried are firstly current strength, secondly dune size and thirdly the initial location of a mine in relation to crests and troughs of a sand dune field. As current strength increases the time taken for a mine to become buried decreases sharply. On the other hand the time till burial increases as a dune's size increases, and as a mine's initial distance downstream from a dune's crest increases. Strictly speaking the model only applies to those cases in which dune heights are much larger than mine diameters, but even when this is not so, it should still indicate the critical factors influencing burial by moving dunes.

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Contents

1. INTRODUCTION 1

2. BURIAL MODEL 2

3. RESULTS 5

4. DISCUSSION AND CONCLUSIONS 15

5. ACKNOWLEDGMENTS 15

6. REFERENCES 15

1. Introduction

Totally or even partially buried mines are difficult to detect so that a good knowledge of where mines are likely to bury on impact or be buried by sediment movement is important in planning mine countermeasures operations. Impact burial is mainly a problem in soft, muddy sediments (e. g Mulhearn 1993a), while burial by sediment movement is more of a problem on sandy sea floors.

There are three processes by which mines can be buried by sediment movement:

(1) Burial by scouring of sand from around a mine by currents; either the oscillating currents caused by wave and swell action or currents due to the action of tides or wind (Mulhearn 1993b, 1994 and 1995).
(2) Mine coverage by moving sand dunes.
(3) Burial by liquefaction; a processes which can occur under storm-wave action, whereby the pore-water pressure down to some depth within the sediment matrix increases to such an extent that it carries the weight of sediment above it. The sediment then looses shear strength and behaves like a liquid. This last process appears to have received little attention in relation to mine burial.

This report is concerned with burial by moving underwater sand dunes. Sand dunes are often referred to as sand waves, but the preferred scientific terminology will be used in this report (Ashley et al. 1990). While both impact and scour burial are likely to occur over much larger areas than burial by sand dunes the locations at which this last process is likely to occur are highly significant e. g. near Charles Point Patches in the approaches to Darwin and in various choke points within Torres Strait. At these particular places transiting ships have no choice but to go over or very close to an area of mobile sand dunes. Sand dunes are also common in parts of Bass Strait, Moreton Bay and the mid and outer parts of the Northwest Shelf. The ranges of sediment grain size and flow velocity in which dunes are encountered, for unidirectional flows, is shown in Figure 1 taken from (Ashley et al. 1990). It can be seen that dunes are found for grain diameters from approximately 0.15 mm (fine sands) up to 8 mm (fine to medium gravel). Most examples however are in the range 0.2 to 2 mm.

In a review of formulae for the movement of bedforms (van Den Berg 1987) it was found that the best formula for bed-load transport (i. e. weight of sediment moved /sec by the movement of bedforms) was one called the modified Kalinske-Frijlink equation. This gave bed-load transport estimates which agreed within a factor of two with field results. More recently (Harris 1992) information on mobile underwater sand dunes in Australian waters has been reviewed. In this reference a simpler bed-load transport equation was preferred (Hardisty 1983). However the modified Kalinske-Frijlink equation appears to give better results and is applicable over a wider range of conditions. Harris's estimates for the speed at which Australian sand dunes move range from 0.0012 m/day in Bass Strait to 2.9 m/day in Moreton Bay.

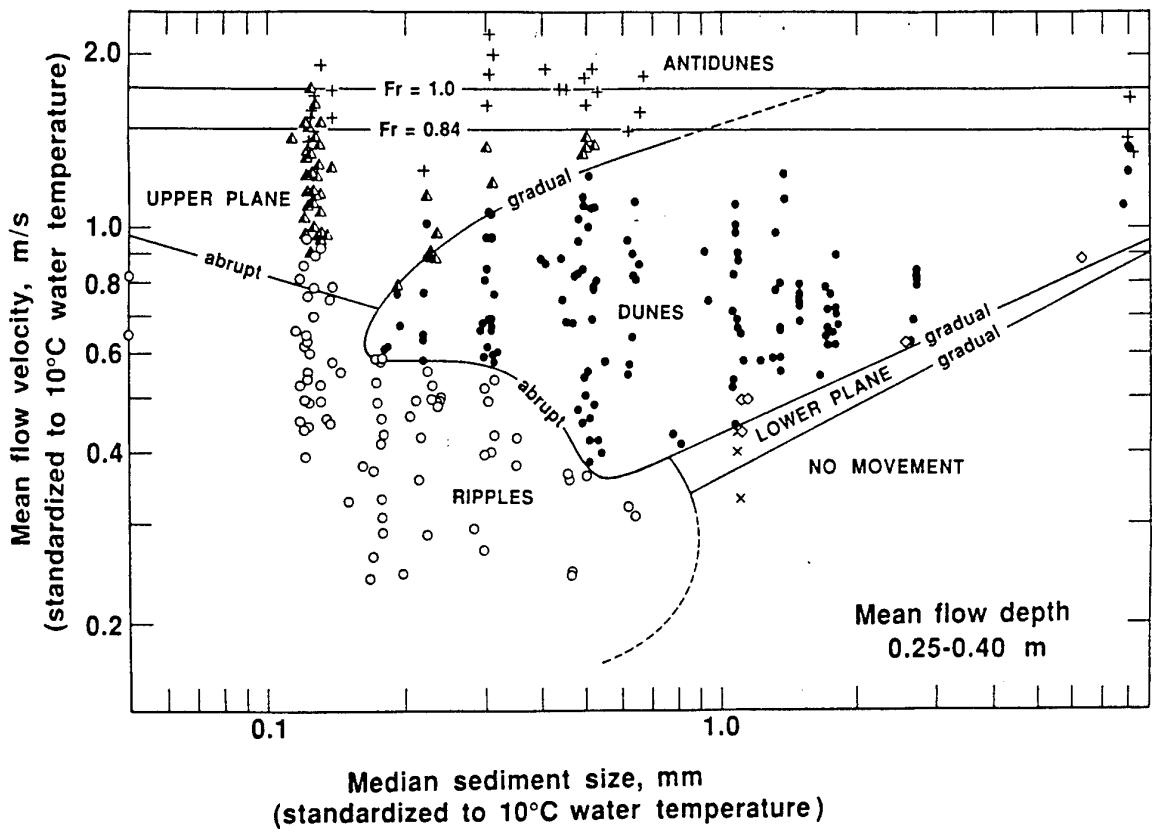

Figure 1: Bedform Domains (from Ashley et al. 1990).

2. Burial Model

The modified Kalinske-Frijlink equation for bed-load transport, S_b, is:

$$S_b = 5\rho_s D_{50} \sqrt{(D_{50} g \Delta \theta')} \exp(-0.27/\theta'), \qquad (1)$$

where ρ_s = grain density,
D_{50} = median grain diameter,
g = acceleration due to gravity,
Δ = $(\rho_s - \rho_w)/\rho_w$,
ρ_w = water density,
θ' = $\tau'/(\rho_w D_{50} g \Delta)$ and

τ' = fluid shear stress due to sand grain roughness alone, rather than the total fluid shear stress due to both the form drag of bed-forms and grain roughness.

Van Den Berg relates τ' to mean velocity, U, by a Chezy coefficient C′ such that:

$$\tau' = \rho_w g U^2/(C')^2,$$

but a simpler approach is to take

$$\tau' = \rho_w C_f U^2, \qquad (2)$$

where U is taken as the velocity 1 m above the bottom and $C_f = 0.003$. In practice there is a large scatter in *field* values of C_f, with little clear dependence on grain Reynolds Number or anything else, and 0.003 is a good representative value (Komar 1976).

If the cross-section of a dune is assumed to be triangular with a height, H, (Harris 1992) then

$$S_b = 0.5\rho_s(1-n)HC, \qquad (3)$$

where n = porosity, and
C = sand dune speed.

From equations (1) to (3) one then has

$$C = 10\, D_{50}\sqrt{(C_f)}\, U \exp(-0.27/\theta')/\ ((1-n)H), \qquad (4)$$

with $\theta' = C_f U^2/(D_{50} g \Delta)$.

Typically n = 0.4 and $\rho_s = 2650$ kg/m³ for quartz and 2720 kg/m³ for calcite. To a good approximation then Δ can be taken as 1.7.

As can be seen from equation (4), C is very dependant on the velocity, U, which will be made up of tidal and longer period flows. Given that, in Australian waters, C ranges from 0.0012 to 2.9 m/day, the higher frequency oscillations due to waves and swell are likely to be unimportant for sand dune movement and will be ignored in this analysis.

Assuming semidiurnal tidal currents with a spring-neap cycle, the tidal current, V, is modelled as:

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

where A = peak current perpendicular to sand dune crest at spring tide,
B = peak current perpendicular to sand dune crest at neap tide, and
t = time in hours.

This representation of tidal currents will be valid for areas like the Northwest Shelf and the approaches to Darwin. For these areas, values for A and B can be taken straight off nautical charts.

In practice longer period currents will be imposed on top of the tidal flow. Assuming that there is simply a mean current, which is constant for the period of interest, the total current is then:

$$W + \{(A-B)\,|\mathrm{Cos}(\pi t/336)|\,+B\}\mathrm{Sin}(\pi t/6),$$

where W is the mean current perpendicular to the sand dune crest.

Assuming the near-bottom current is 80% of this gives:

$$U = 0.8[W + \{(A-B)\,|\mathrm{Cos}(\pi t/336)|\,+B\}\mathrm{Sin}(\pi t/6)]. \qquad (5)$$

In practice W will vary with time but its variation will be poorly known.

In many places there will be a mixture of diurnal and semi-diurnal tidal stream components e.g. Torres Strait (Department of Defence 1995). In such cases A and B can be estimated as averages of peak current values over 24 hours at the times of spring and neap tides, respectively.

In most cases sand dunes can be satisfactorily represented as having a triangular cross section with a forward (or lee) slope steeper than the trailing (or stoss) slope. In this model, a mine, with diameter less than dune height, H, is placed at some position in the dune field and the dunes are assumed to move with fixed shape at speed, C, to bury the mine within some time to be determined. It is assumed here that the mine's presence has negligible effect on the dune's speed and shape as it moves over it. This would , strictly speaking, only be true when the dune height is much bigger than the mine diameter. However the model should still provide order of magnitude estimates for burial times even when the dune height is not much bigger than a mine's diameter.

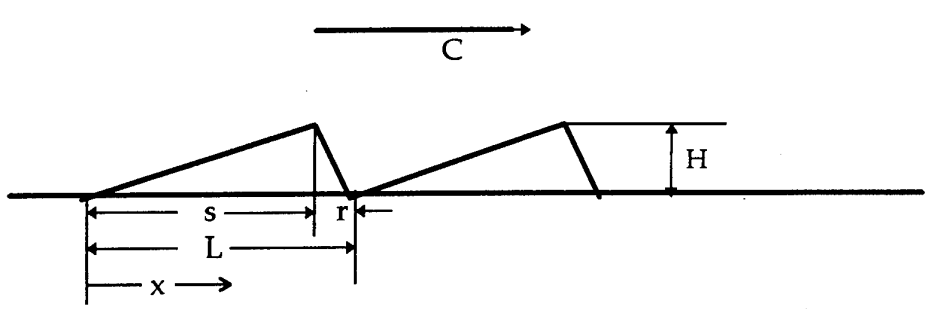

Figure 2: Sand dune geometry.

In some cases there is a space between dunes and L > s + r. The model can handle either case. A mine with diameter, d, placed at a position $x_0 \geq (s + r)$, will be buried at a time, t, such that:

$$\int_0^t C dt' = x_0 - (r + s) + rd/H .$$

A mine placed on the crest of a dune or on its stoss slope is assumed to maintain its horizontal position and to just move vertically downward as the dune moves to the right. A mine initially laid on a lee slope is assumed to immediately roll down to the foot of that slope at $x_0 = s + r$. Results from the model are presented in the next section and its computer code in the Appendix.

3. Results

Illustrative results for the model are shown in the following way:
The case for which median grain size, D_{50}, = 0.3 mm; dune height, H, = 2.0 m; spring tidal peak current, A, = 1.0 m/s; mine diameter, d, = 0.4 m and long term mean current, W, = 0.1 m/s is taken as a "standard." Additional input variables are the number of days, IT, after high spring tide at which the mine is deployed and the position, x_0, at which the mine is initially laid. For the "standard" case IT = 0 and $x_0 = s + r$., i. e. at the foot of the lee slope (see Figure 2). Each variable is varied individually to display the resultant variations in the time taken for a mine to bury and for it to reappear again as the sand dune passes. In addition, for these illustrative cases, it is taken that L = 10H, r = L/3, s = 2r, (see Figure 2) and that neap tidal peak current, B, = A/10; porosity, n, = 0.4; friction coefficient, C_f, = 0.003; Δ = 1.65 (see equation 1) and mine diameter = 0.4 m. These would also be suitable default values in situations where knowledge of a sand dune field is limited.

But first the behaviour of the model in the "standard" case is illustrated. In Figure 3 the time histories of the current and the depth of sand over the mine are presented. In this case the mine is initially buried quite quickly, but several spring-neap tidal cycles are required before it reappears. The time history of sand dune speed, C, is shown in Figure 4. It can be seen to vary strongly with the strength of tidal currents, with no motion near neap tides. Sometimes a mine will become buried in one half of a tidal cycle and then become exposed as the current reverses. It will then become buried as the current reverses once more and will remain buried for a considerable time. In the figures, below, burial is taken to start from the time the mine is first covered by sand and end when it is finally exposed on the other side of the dune.

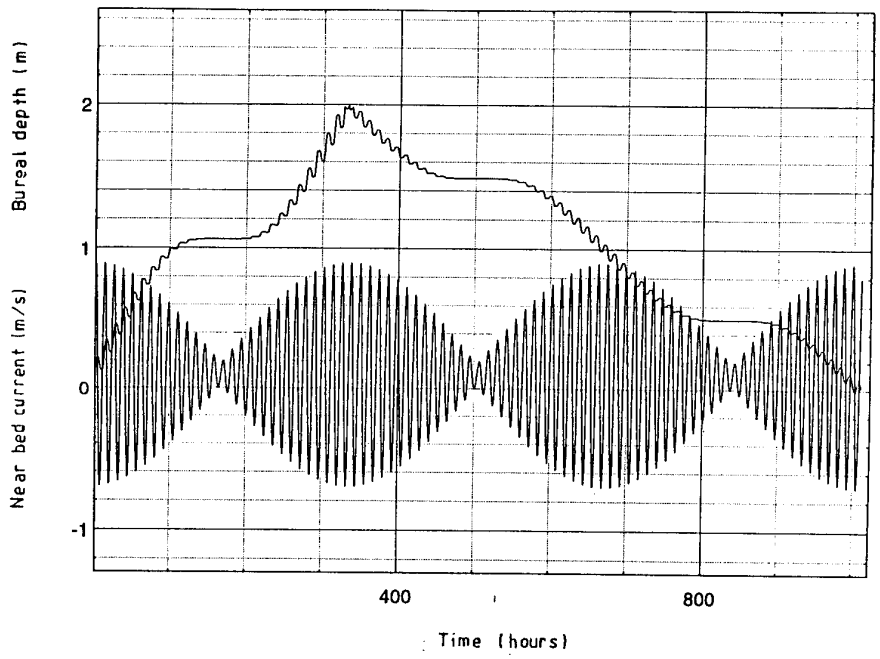

Figure 3: Burial depth and near-bed current speed versus time.

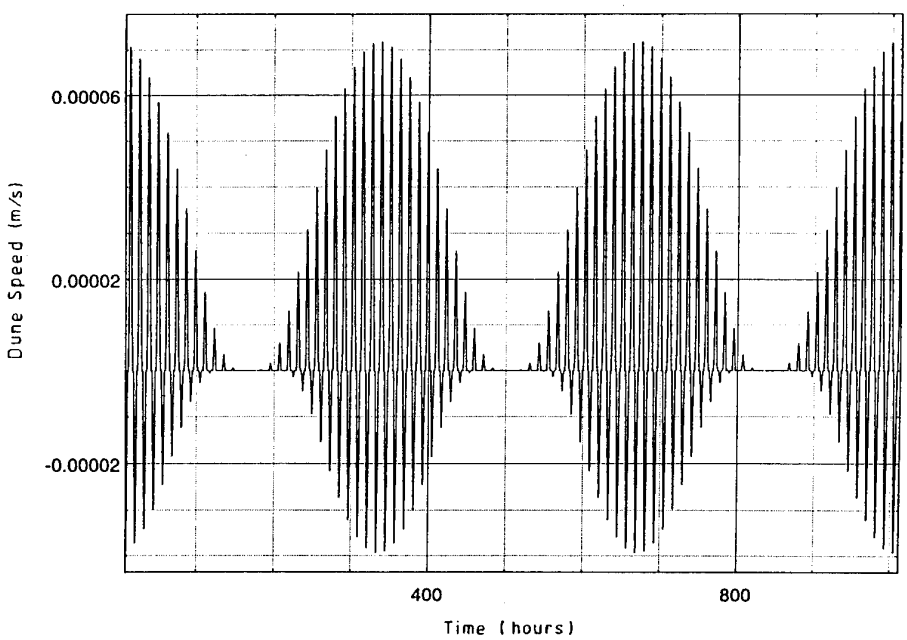

Figure 4: Dune speed versus time.

Figure 5 presents the times for a mine to bury as the median grain diameter is varied, for IT = 0 and IT = 4 days, keeping all other variables in the "standard" case unchanged. (IT is the number of days after spring tide at which a mine is laid). Neap tide occurs at IT = 7 days, so that IT = 4 days is approximately half way between spring and neap tides. The burial times for IT = 4 days are of order ten times those for IT = 0, showing the dramatic effect that current strength has. The effect of grain size, D_{50}, is not so marked, except for the largest size examined. The marked increases in burial times as grain size increases beyond 1 mm is due to the increasing force required to move larger grains.

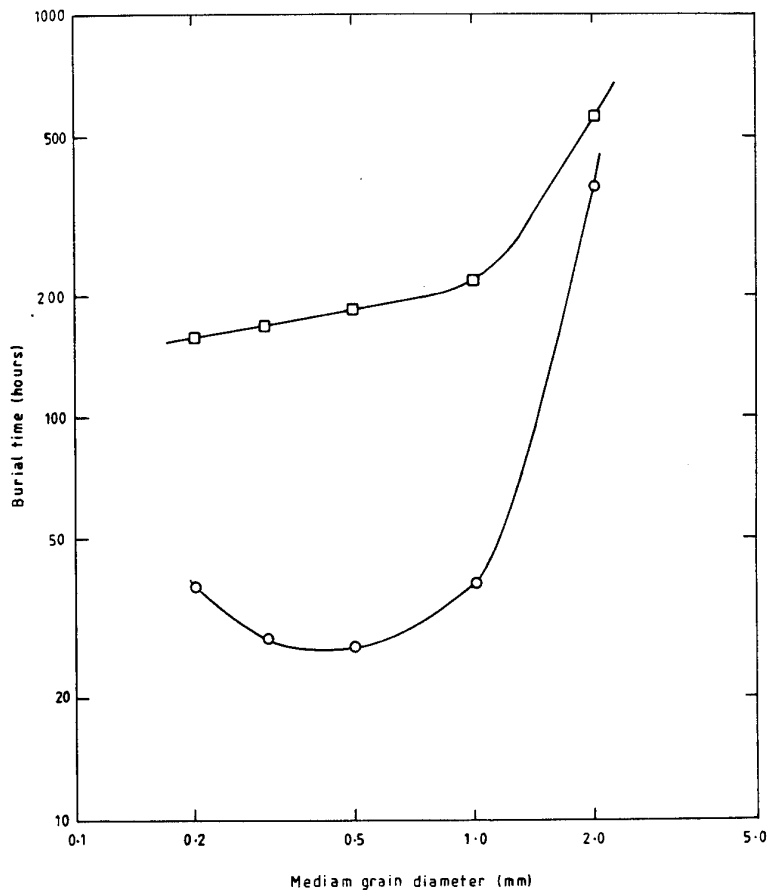

Figure 5: Time for a mine to bury versus median grain diameter for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

The length of time a mine stays buried under a moving dune is shown in Figure 6 for a range of grain sizes and for IT = 0 and 4 days. Calculations were not run for more than 3000 hours (125 days), and for a grain diameter of 2 mm times for which a mine remained buried were greater than this. Because several spring - neap cycles pass in both cases the differences between results for IT = 0 and 4 days are not great.

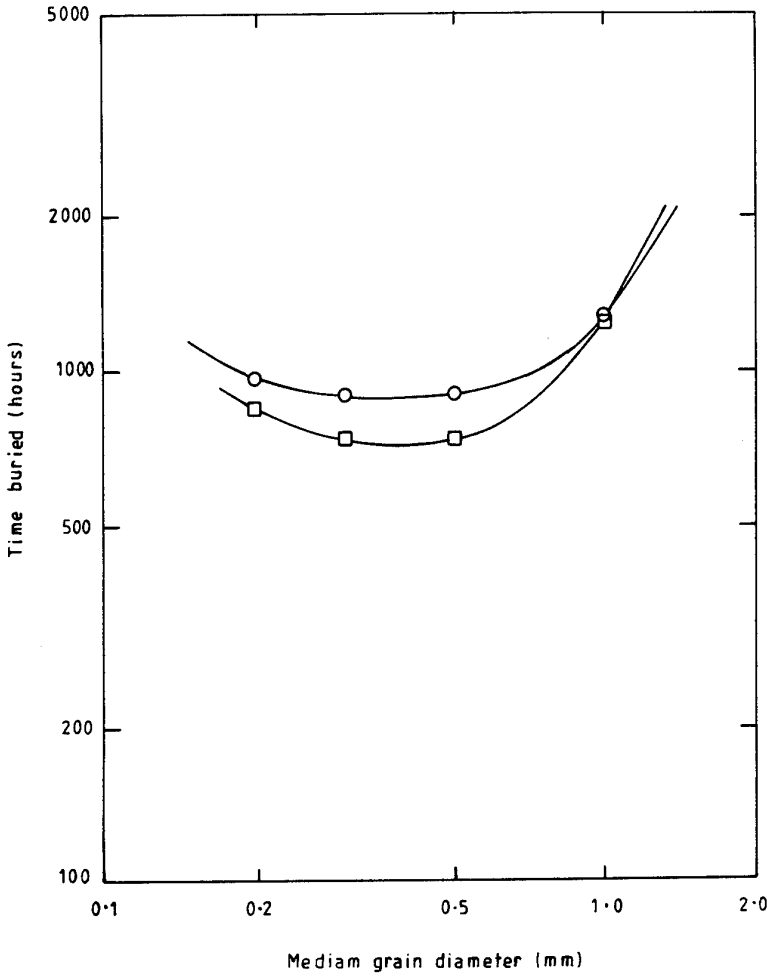

Figure 6: Time for which a mine remains buried versus grain diameter for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

The variation in time for a mine to bury as a function of dune height, H, is presented in Figure 7. Note that other dune dimensions remain proportional to H. Because dune wave-length, L, increases as H does, i. e. dune crests become further apart, the time for a mine to bury increases rapidly with dune size. For IT = 4, the increase is not as sharp for dune height ≥ 1.0 m. Figure 8 shows the variations in the length of time a mine

remains buried as dune size varies. The increase in time buried as dune height increases is again sharp, but there is little difference between cases for IT = 0 and 4 days.

As the peak current at spring tide increases, the time for a mine to bury decreases rapidly, while the length of time for which it remains buried decreases less rapidly, as shown in Figures 9 and 10. The differences between the cases for which IT = 0 and IT = 4 days are not as marked as in previous examples.

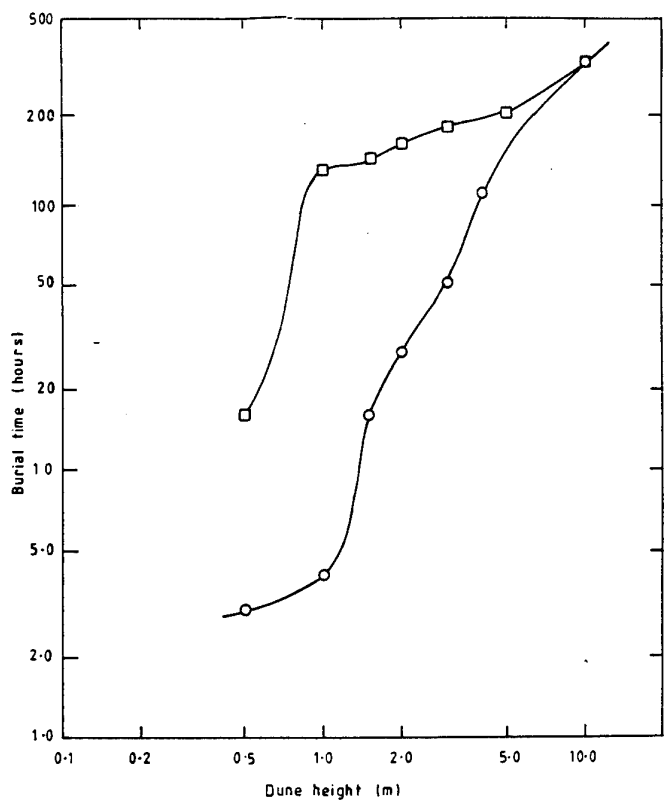

Figure 7: Time for a mine to bury versus dune height, H, for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

The effects of varying the long term mean velocity, W, over a realistic range, are presented in Figure 11. The time for a mine to become buried decreases with W, but the effect is not as dramatic as it is for variations in the peak current at spring tide. Differences between cases for IT = 0 and IT = 4 days are large for times taken for a mine to bury, but small for the times for which a mine remains buried, as one would expect.

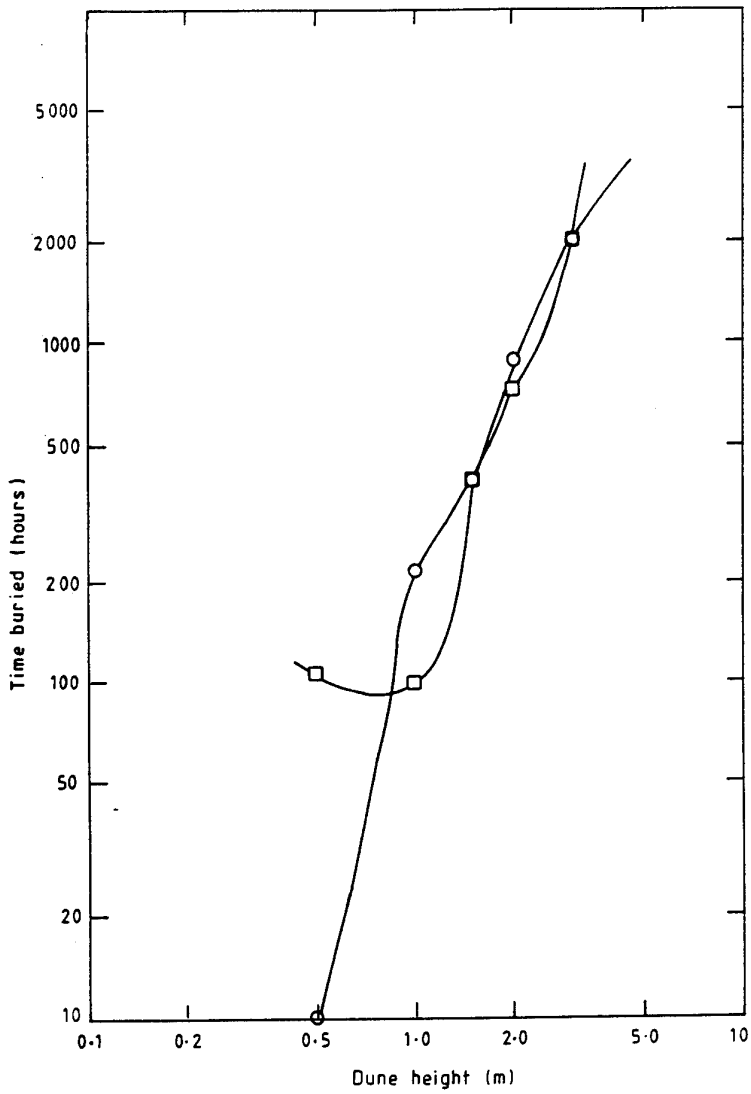

Figure 8: Time for which a mine remains buried versus dune height, H, for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

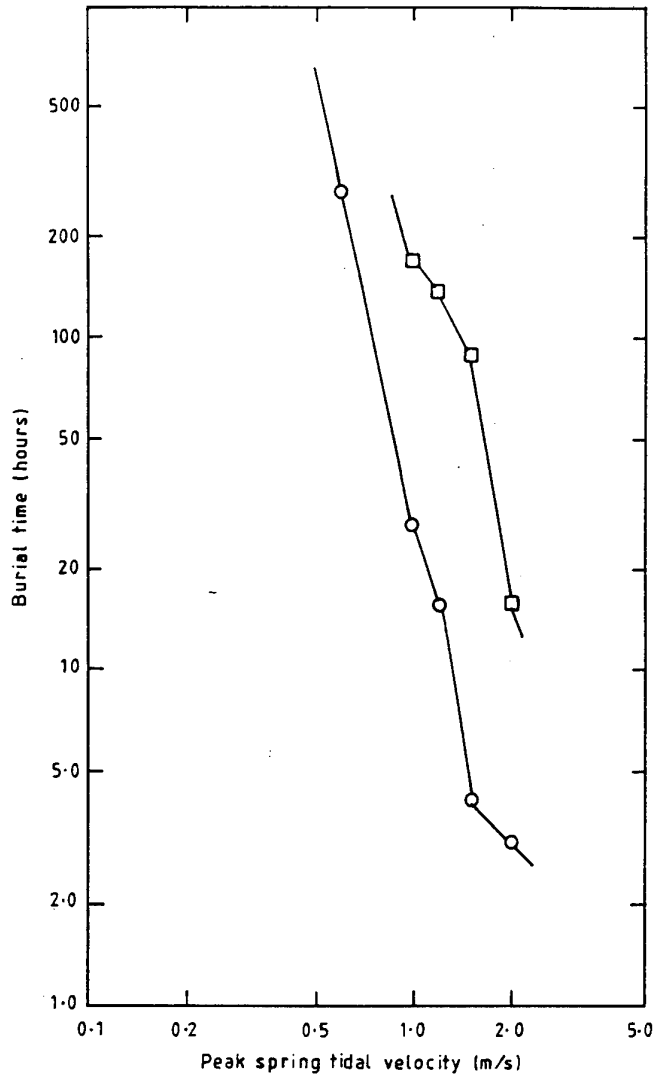

Figure 9: Time for a mine to bury versus peak spring tidal velocity for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

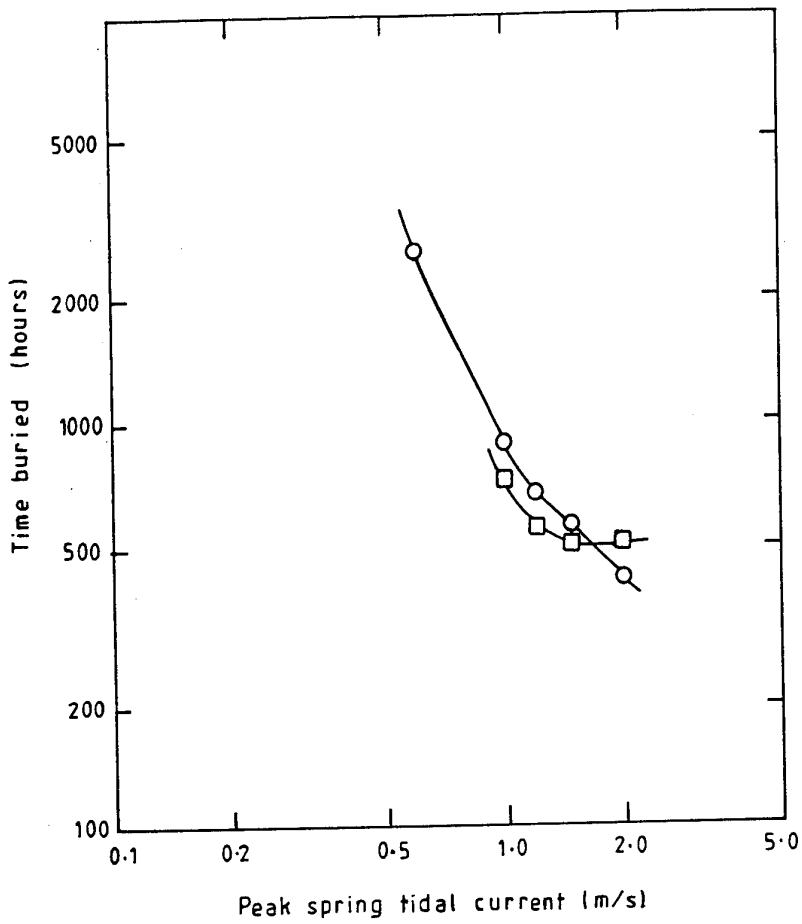

Figure 10: Time for which a mine remains buried versus peak spring tidal velocity for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide.

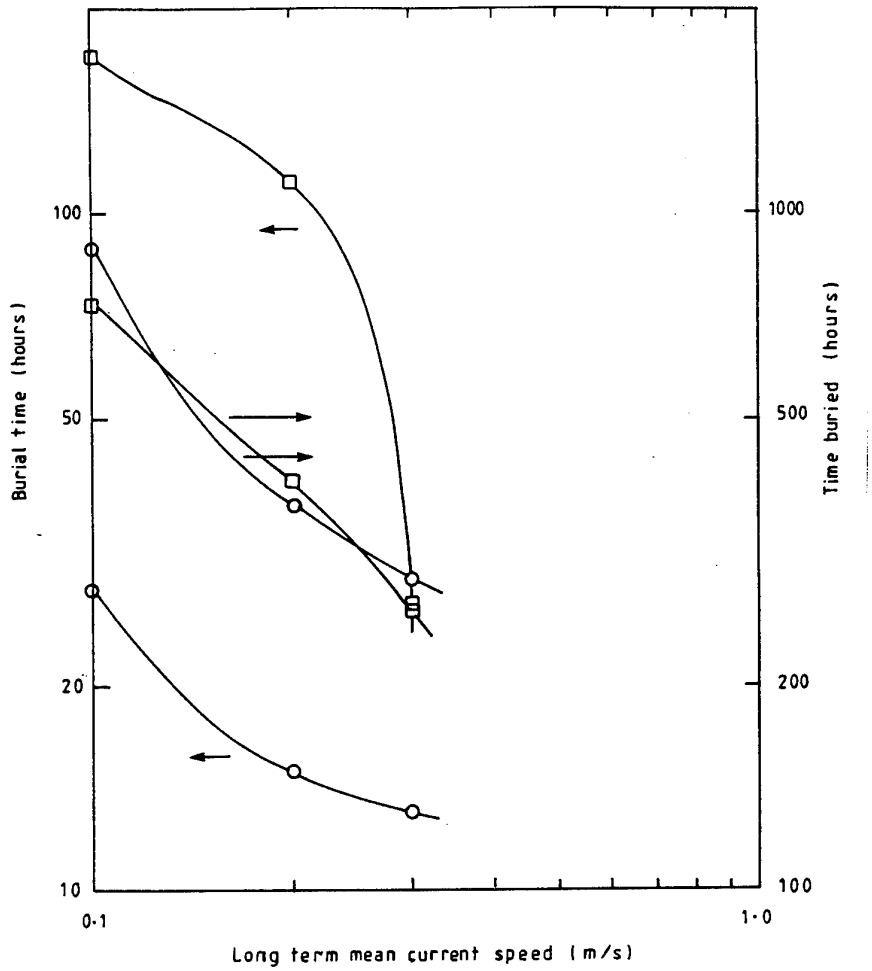

Figure 11: Time for a mine to bury, and time for which a mine remains buried, versus long term mean current speed, W, for (o) mine laid at spring tide (IT = 0), and for (□) mine laid 4 days after spring tide. (Arrows indicate the vertical axis which applies to each curve).

Finally in Figure 12 the effect of varying the mine's position along the dune profile from the trough at $x_0 = r + s$ to the next crest at $x_0 = r + 2s$ is presented (see Figure 2). The time for a mine to become buried increases approximately linearly with distance from the foot of the lee slope at $x_0 = r + s$, but there are oscillations on this linear trend because of the influence of the spring - neap tidal cycle. The length of time for which a mine stays buried, while very approximately constant, also shows variations because of the number of spring and neap tides undergone between initial burial and re-emergence of the mine.

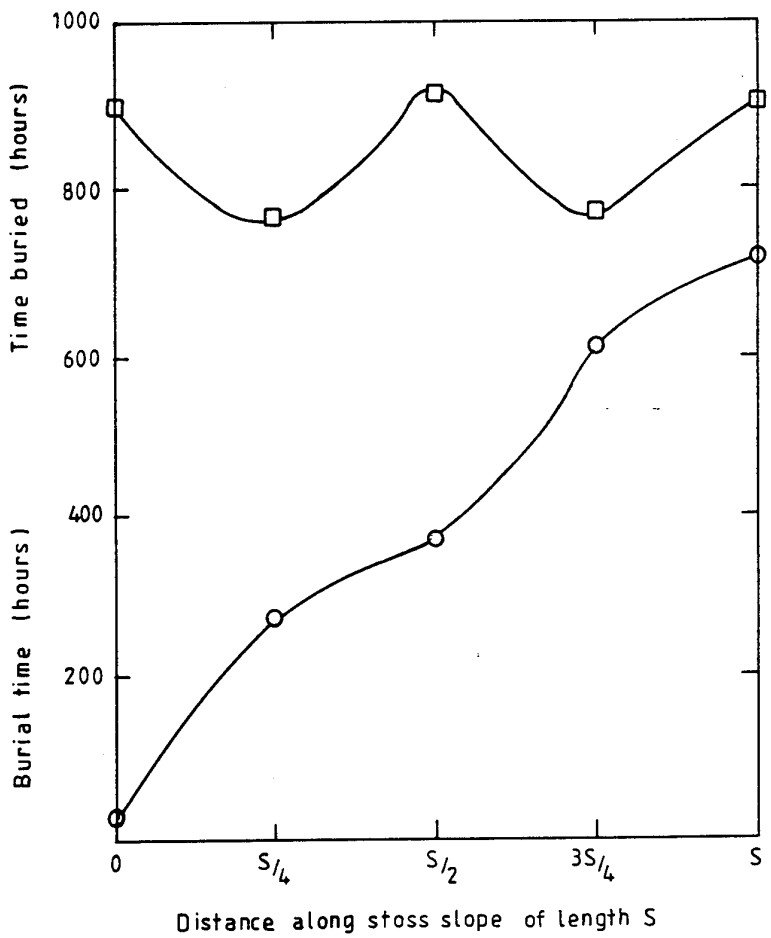

Figure 12: Time for a mine to bury (o), and time for which a mine remains buried (□), versus distance along the stoss slope at which the mine is initially deployed.

4. Discussion and Conclusions

From the above results it can be seen that the time taken for a mine to become buried is very dependent first on current strength and secondly on sand dune size. In practical situations current strength will often not be very well known, and this will be a major limitation on the usefulness of estimates of burial times. Although the modified Kalinske-Frijlink equation appears to be the best available, it is worth recalling that its estimates for bed-load transport only agree with field data within a factor of two. In using the model described here, it will always be best to calculate burial times for the expected range of currents rather than just single values for each of the peak neap and spring tidal currents and the long term mean current. (The peak neap current will often not be very important). It will also be necessary to calculate burial times for mines initially laid at the foot of a lee slope, and at the next downstream crest, in order to obtain the range of burial times arising from variations in mine locations relative to crests and troughs in the sand dune field.

5. Acknowledgments

The form in which semidiurnal tidal currents are described in section 2, between equations 4 and 5, is taken from a vacation scholar's report by Adelle Coster.

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Appendix

Specimen Program for Sand Dune Calculations

```
PROGRAM SANDUNE
C     FOR SEMI- DIURNAL TIDES

      IMPLICIT NONE
      REAL D, AN, H, AL, DELTA, CF, S, R
      REAL A, B, W, DMINE, X1, PI, X
      REAL Z, BDPC
      DOUBLE PRECISION T, V, U, THETA, C
      INTEGER IT1, ITF, IT
      CHARACTER*20 FILENAME

      PI = 3.1416

C  INPUTTING INPUT PARAMETERS.
      WRITE (*,*) 'INPUT FILENAME FOR RESULTS'
      READ (*,'(A)') filename
      OPEN (2, FILE = filename, STATUS = 'NEW')

      WRITE (*,*) 'Enter sediment grain size (mm) '
      READ (*,*) D
      WRITE (*,*) 'ENTER SANDWAVE DIMENSIONS: H, AL, S, R (m)'
      READ (*,*) H,AL,S,R
      WRITE (*,*) 'Max. spring & Neap tidal streams (m/sec)'
      READ (*,*) A, B
      WRITE (*,*) 'Time of mine drop (integer days) before (-ve) or
     * after(+ve) spring Tide'
      READ (*,*) IT1
      WRITE (*,*) 'Long-term mean current speed (m/sec)'
      read (*,*) W
      WRITE (*,*) 'HOURS (integer) (AFTER MINE DROP) CALCNS. ARE TO
     *GO FOR'
      READ (*,*) ITF
      WRITE (*,*) 'Mine diameter'
      READ (*,*) DMINE
      WRITE (2,*) D, H, AL, S, R, A, B, IT1, W, ITF, DMINE
```

```
C      POROSITY, FRICTION COEFFICIENT, DENITY DIDDERRENCE/WATER
DENSITY:
      AN = 0.4
      CF = 0.003
  DELTA =1.65
  D = D/1000.0

  X1 = AL
      IT1 = IT1*24
  BDPC = 0.0
  X = X1
  Z = 0.0

C  CALCULATING DUNE SPEED VS TIME, & DISTANCE, X.
C  DISTANCE MOVED = X-X1. V = TIDAL CURRENT.
C  U = TOATAL NEAR-BED CURRENT
      DO IT = IT1+1, IT1 + ITF
      T = FLOAT(IT)
      V = (A-B)*ABS(COS(PI*T/(14.0*24.0))) + B
      U = W + 0.8*V*SIN((T)*PI/6.0)
  THETA = CF*U*U/(9.81*DELTA*D)
  C = 10.0*D*SQRT(CF)*U*EXP(-0.27/THETA)
  C = C/((1.0-AN)*H)
  IF (THETA .LT. 0.001) C = 0.0
      X = X + C*3600.0

C  GETTING BURIAL DEPTH, Z:
  IF (X-X1 .LE. R)  Z = (X-X1)*H/R
  IF (X-X1 .GT. R .AND. X-X1 .LE. AL)  Z = (S+R-X+X1)*H/S
  IF (X .GT. X1+AL)  Z= 0.0

      BDPC = 100.0*Z/DMINE
  IF (X-X1 .GT. AL+S) THEN
   GOTO 70
   END IF
      WRITE (2,60) IT, U, C, X, Z, BDPC
 60   FORMAT(I4, 5E13.5)

 70    END DO

      CLOSE(2)
      END
```

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19. ABSTRACT

Buried mines in the approaches to major ports and in shipping choke points constitute a significant problem in mine countermeasures operations because they are so hard to detect. One of the burial mechanisms which would occur in some important locations is burial by mobile underwater sand dunes (also called sand waves). In this report a new mathematical model is presented for this process and it is shown that the factors which are most critical for the time taken for a mine to become buried are firstly current strength, secondly dune size and thirdly the initial location of a mine in relation to crests and troughs of a sand dune field. As current strength increases the time taken for a mine to become buried decreases sharply. On the other hand the time till burial increases as a dune's size increases, and as a mine's initial distance downstream from a dune's crest increases.

A Mathematical Model for Mine Burial by Mobile Underwater Sand Dunes

P.J. Mulhearn

(DSTO-TR-0290)

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