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AERONAUTICAL RESEARCH LABORATORY

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Flight Mechanics Technical Memorandum 418

PREDICTIONS OF THE STEADY STATE BEHAVIOUR OF AN UNDERWATER TOWED SOUND GENERATOR

by

C. Jermey

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SUMMARY

An underwater towed sound generator, used in sonar research work, was found to be unstable when under tow. Wind tunnel tests were therefore carried out on a model of the vehicle to assess the effectiveness of various modifications designed to improve its stability.

Fluid dynamic data from these tests has been incorporated into a computer model of the towed vehicle and cable. This document describes and presents predictions obtained from the computer model for a range of configurational and operational variables.

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POSTAL ADDRESS: **Director, Aeronautical Research Laboratory, P.O. Box 4331, Melbourne, Victoria, 3001, Australia**

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1. INTRODUCTION

An underwater towed sound generator, used in sonar research work, was found to be unstable when under tow. A model of the vehicle was therefore tested in a wind tunnel to establish the fluid dynamic characteristics of the vehicle and to assess various modifications intended to increase its stability. This work was reported in reference 1. The data measured in the wind tunnel, when combined with the other known characteristics of the vehicle and tow cable, is sufficient to enable predictions to be made of the behaviour of such vehicles when under steady tow.

This report presents a computer model of the underwater towed vehicle and cable system which was developed to use the wind tunnel measured data. The model predicts the important parameters of the towed system for a range of conceptual configurations and operational variables. Results are presented for two configurations which were shown by the wind tunnel tests to be suitably stable.

2. CONFIGURATIONS SELECTED FOR STUDY

The two configurations for which predictions are presented are shown in figure 1. They consist of the original vehicle body, nose and strongback fitted with either of the two tail units shown. (The tail units are referred to as "tail 1" and "tail 3" to match the nomenclature used in reference 1). The use of a cut-down strongback as indicated in figure 1 is also considered and is commented on later.

Details of the tow cable configuration are shown in figure 2; this is the existing tow cable with no modifications. The arrangement of clip-on discs and fairings is designed to suppress cable strumming (a lateral vibration caused by vortex shedding), and they cover the entire submerged length of the cable.

3. THE PREDICTION PROGRAM

A listing of the prediction program is given in Appendix 1. The program is written in FORTRAN 77 and incorporates all input data and options within itself. Thus successive runs for differing configurations require program statements to be edited and the program recompiled between each run. This is not a serious handicap since a single run is sufficient to provide all the relevant data for one vehicle configuration (see Appendix 2 which gives a sample of the program output).

The assumption is made that for reasons of symmetry the underwater vehicle will, if stable, tow with negligible sideslip and with the strongback on the top. The program therefore considers only forces and moments in the vertical plane. The program first determines the incidence at which the vehicle will tow by calculating all relevant forces (weight, buoyancy, fluid dynamic forces and tow cable tension) and then searching for the incidence at which all forces and moments sum to zero. If this is not achieved within an incidence range of -30^{o} to 30^{o} the program prints "vehicle is unstable". Although this is not necessarily true it does imply that stability, if it is achieved, is at an undesirably high angle of incidence where no measured data is available and where asymmetric shedding of body vortices could lead to dynamic stability problems.

Once the incidence of the towed vehicle is determined the program predicts the tension and shape of the tow cable by considering it in one metre lengths, each length taken to be a rigid section freely pin jointed to its immediate neighbours. For each section of cable the program calculates all relevant forces, performs a force balance, and thus determines the progression of tension and angle along the entire cable.

4. GENERATION OF INPUT DATA FOR THE PROGRAM

The input data for the program consist of all the parameters of the tow system which are pertinent to its behaviour under tow. With the exception of the vehicle fluid dynamic characteristics these quantities are listed in table 1. Where possible these quantities have been directly measured. Otherwise they have been calculated from realistic starting assumptions (eg vehicle mass and buoyancy data are based on measured results for the existing body and strongback, plus data calculated for the add-on tail units assuming they are fabricated from aluminium alloy). The drag coefficients used for the tow cable were estimated from data in reference 2.

The fluid dynamic characteristics of the vehicles were derived from wind tunnel test data (see reference 1) and are input to the program as constants in fourth order polynomials fitted to the measured data.

5. PREDICTIONS

All the predictions given here apply only to a system in a steady state. No attempt has been made to model the inevitable launch and deployment transients, and therefore the program can give no information on whether these transients will damp out and allow the system to reach a steady state. However, for the relatively simple shapes and low attitudes considered here there is no reason to suspect any significant dynamic instabilities to occur.

5.1 Sideslip angle of vehicle

In the sideslip plane, gravity and buoyancy forces have no effect and therefore only the fluid dynamic forces need be considered. Since both vehicles are symmetric and statically stable it follows that if a steady state is reached (see earlier comment), it will be at a sideslip angle of zero and with the strongback on the top of the vehicle. In practice, of course, sideslip angles will fluctuate over a small range, the size of the fluctuation depending on turbulence in the water, off-axis loads from the tow cable and the size of the fluid-dynamic stabilising moments. For both vehicles studied here the fluid dynamic stability in the sideslip plane (see ref 1) is sufficient to ensure that sideslip angles remain small. The use of a cut-down strongback would further enhance this stability.

5.2 Incidence angle of vehicle

The incidence angle of the vehicle under tow will depend on gravity, buoyancy and tow cable forces, as well as the fluid dynamic forces. Predictions of this angle for a range of tow speeds and tow attachment points are given in figure 3. Ideally, the vehicle should tow at a low angle throughout the speed range, and it suggested that a limit of $\pm 20^{o}$ should be safely allowable (at angles of 30^{o} and greater asymmetric growth and shedding of body vortices could introduce some dynamic instability). Accepting this limitation, figure 3 shows that the vehicle incidence is very sensitive to tow attachment point and that to achieve acceptable angles throughout the speed range requires the tow attachment to be within about 0.1m of the optimum point.

An optimum tow attachment point on the strongback (ie a point for which the incidence stays close to zero throughout the speed range) may be defined as the point for which the vehicle incidence is within -2^{o} to $+2^{o}$ when fully submerged and at rest. Figures 3a and b appear to indicate that this can be approximated by supporting on the strongback at a point above the CG, but figure 3c is included to show that this is not necessarily so. Figure 3c shows results for a vehicle fitted with nearly 50 kg of ballast in the nose, which shifts the centre of mass to about 0.13m ahead of the centre of buoyancy. The optimum support point for this configuration is a point nearly 0.1m ahead of the CG.

Reference 1 shows that the use of a cut-down strongback has only a very small effect on the incidence plane fluid dynamic characteristics. Figure 3 can therefore also be used for corresponding configurations with a cut-down external strongback, where the removed portion is replaced with an internal strongback of roughly equivalent mass and displacement.

5.3 Tow Cable Behaviour

Factors influencing the behaviour of the tow cable are the loads exerted by the towed vehicle plus the gravity, buoyancy and fluid dynamic forces distributed over the whole length of submerged cable. Predictions of cable trajectory, tension and total length are plotted against depth in figures 4, 5 and 6 for varying tow speeds. Note that the depth scale reads from the towed vehicle (depth = 0) up towards the surface. The predictions thus show the cable characteristics along the full length of submerged cable up to a maximum depth of 140m, and can be simply truncated at any intermediate point for shallower towing depths. The predictions are given for a near optimum towline attachment position (which, for these configurations, is at the CG of the towed vehicle), and for two other acceptable positions at the highest tow speed to give an indication of the effect of varying the tow attachment position.

As expected, the tow cable conditions are very similar for both vehicles considered, and, as long as the vehicle remains stable, are not particularly sensitive to changes in tow attachment position. At low speeds (up to 3 m/s) the cable tension is dominated by the unbuoyed weight of the vehicle. At higher speeds, and for deep towing, the maximum cable tension is increasingly dependent on the drag of the cable itself. It is only at high speeds (4 to 5 m/s) and shallow depths (up to 50m) that the maximum cable tension is significantly dependent on the fluid dynamic characteristics of the vehicle. It is therefore reasonable to expect that for normal (low speed) towing conditions the predictions would be little changed by the use of a cut-down strongback on the towed vehicle.

6. CONCLUDING REMARKS

(1) Both of the vehicles studied here can be arranged to tow in a stable manner throughout the desired range of speeds and depths.

(2) For optimum behaviour of the vehicle under tow (ie attitude remaining close to zero throughout the speed range) the tow cable should be attached at a position which causes the vehicle attitude to lie within the range of about -2^{o} to $+2^{o}$ when the vehicle is at rest and fully submerged. (Note that unless the centre of mass and the centre of buoyancy of the vehicle are coincident, then the vehicle attitude in air will not be the same as in water).

(3) If the tow cable cannot be attached at the optimum position then the selected attachment point should be acceptable if the vehicle attitude lies within a range of -20^{o} to $+20^{o}$ when at rest and submerged.

(4) For moderate changes in the vehicle fluid dynamic characteristics (eg a shape change to nose, strongback or tail), the tow cable conditions should not change significantly as long as the tow cable is correctly attached and the vehicle remains stable under tow.

(5) The disks which are part of the anti-strumming attachments to the tow cable make the cable a potentially high-drag component of the towed system. This is not a problem at low speeds (up to 3 m/s) or for shallow depths (up to 50m), but could become very significant at higher speeds and greater depths.

REFERENCES

No	Author	Title
1	Jermey, C.	"Fluid dynamic characteristics of an underwater towed sound generator". ARL-FLIGHT-MECH-TM 420 (in publication).
2.	Hoerner, S.F.	"Fluid dynamic drag". Hoerner Fluid Dynamics, 1965

APPENDIX 1. LISTING OF THE PREDICTION PROGRAM

```
c           Program name is TOW2. FOR
c
c       This program predicts the trim incidence and tow cable trajectory
c       for an underwater towed low frequency sound generator
c       (with 4 cylindrical fins type tail)
c
            DIMENSION ctens(14),posx(14),posy(14),length(14)
c
            REAL mass,nor0,nor1,nor2,nor3,nor4,norfor,mres,length
c
            INTEGER dirm,dirml
c
            common dens,vel
            common/hydfor/nor0,nor1,nor2,nor3,nor4,ax0,ax1,ax2,ax3,ax4,
           +xcp0,xcp1,xcp2,xcp3,xcp4,refa,refl
            common/towfor/weight,bouyf,norfor,axfor,xcg,xbouy,xcp,xtow,ztow
            common/cable/tax,tnor,alph,cdcnor,cdcax,crefa,effcwt
c
c   set the fluid constants
c     dens=fluid density(kg/m**3)
      dens=1025.0
c
c   set the vehicle constants
c   refl=ref. length=vehicle diam(m)
c   refa=ref.area=vehicle cross sectional area (m**2)
c   mass=vehicle mass(kg)
c   disp=vehicle displacement(m**3)
c   bouyf=bouyancy force on vehicle(n)
c   xcg=vehicle cg position aft of nose(m)
c   xbouy=centre of bouyancy position aft of nose(m)
c   ztow=distance from vehicle axis to tow attachment point(m)
      refl=0.450
      refa=3.1416*(refl**2)/4.0
      mass=330.3
      weight=9.807*mass
      disp=0.1584
      bouyf=9.807*dens*disp
      xcg=1.239
      xbouy=1.244
      ztow=0.305
c
c   set the hydrodynamic constants - these are the constants in the
c   following equations:
c   normal force coeff(+ve upwards)
c     cnor=nor0 + nor1*inc + nor2*inc**2 + nor3*inc**3 + nor4*inc**4
c   axial force coeff(+ve backwards)
c     cax= ax0 + ax1*inc + ax2*inc**2 + ax3*inc**3 + ax4*inc**4
c   centre of pressure of normal force(calibers aft of nose)
c     xcp= xcp0 + xcp1*inc + xcp2*inc**2 + xcp3*inc**3 + xcp4*inc**4
c   WHERE: inc= incidence (radians)
```

```
         nor0=0.030
         nor1=12.676
         nor2=0.334
         nor3=-9.981
         nor4=-2.748
         ax0=0.500
         ax1=-0.078
         ax2=1.424
         ax3=0.251
         ax4=-4.592
         xcp0=4.232
         xcp1=0.010
         xcp2=-1.088
         xcp3=-0.139
         xcp4=-1.153
c
c   set the cable constants
c     cdcax=drag coeff of cable(per metre) for flow along cable
c     cdcnor=drag coeff of cable(per metre) for flow normal to cable
c     cdrefa=ref area for cable drag =frontal area of bare cable/m(m**2)
c     cmass=cable mass/m(kg)
c     cdisp=cable displacement/m(m**3)
c     effcwt=effective cable weight/m after allowing for bouyancy(n)
         cdcax=0.24
         cdcnor=0.16
         crefa=0.016
         cmass=0.763
         cdisp=0.000468
         effcwt=(cmass-cdisp*dens)*9.807
c
c   set initial values of variables
c     vel=tow speed(m/s)
c     xtow=towline attachment position aft of nose(m)
         vel=5.0
         xtow=xcg-0.5
c
c   set up output headings
      write(6,2000)
2000format('0',35x,'UNDERWATER SOUND GENERATOR TOWING',
    1'CHARACTERISTICS',//)
c
c   set an initial guess for incidence angle and incidence step
c     alph=incidence angle(radians), nose up is +ve
c     dalph=incidence step(radians) to be used to refine guessed alph
20    alph=-30.0/57.296
      dalph=10.0/57.296
c
c   set misc indicators
c     dirm=1 for +ve pitching moment,=-1 for -ve
c     dirml=the previous (last) value of dirm
         dirm=1
         dirml=1
c
c   calculate the hydrodynamic forces on the vehicle
```

```
10      call hydfor(alph,norfor,axfor,xcp)
c
c  calculate towing forces(normal and axial) and resultant moment on
c  vehicle
        call towfor(alph,tnor,tax,mres)
c
c  adjust incidence appropriately as determined by unbalanced moment
        dirml=dirm
        if(mres.gt.0)then
            dirm=1
        else
            dirm=-1
        end if
        if(dirm.ne.dirml)dalph=-dalph/10.0
c  if close to stable trim (dalph.1t.0.1 deg) jump out of incidence
c  adjusting loop
        if(abs(dalph).1t.0.001)go to 100
        alph=alph+dalph
c  if unstable for alph between -30 deg and +30 deg, jump out of
c  loop and write appropriate message
        if(abs(alph).gt.0.55)go to 110
        go to 10
c
c  printout final prediction
c    jump to here if unstable
110     write(6,1010)vel,(xcg-xtow)
1010    format(' ','for tow speed ',f4.1,' m/s and tow position ',f5.2,
     1' m ahead of cg, vehicle is unstable')
        go to 120
c    jump to here if stable
100     alphd=alph*57.296
        write(6,1000)vel,(xcg-xtow),alphd
1000    format(' ','for tow speed',f4.1,' m/s and tow position ',f5.2,
     1' m ahead of cg, vehicle trim angle is ',f6.1,' deg')
c    now calculate and print out the cable trajectory
        call cable(length,ctens,posx,posy)
        write(6,1020)length
        write(6,1030)ctens
        write(6,1040)posx
        write(6,1050)posy
1020    format(' ','     cable length (m)        ',14f7.1)
1030    format(' ','     cable tension (n)       ',14f7.0)
1040    format(' ','     horizontal position (m) ',14f7.1)
1050    format(' ','     vertical position (m)   ',14f7.1,/)
120     continue
c
c    now set new tow speed and/or tow position and repeat calculations.
c    if all speeds and tow positions completed, go to STOP
      vel=vel-1.0
      if(vel.1t.0.0)then
        write(6,*)
        write(6,*)
        write(6,*)
        vel=5.0
```

```
         xtow=xtow+0.1
         if(xtow.gt.(xcg+0.51))go to 200
         go to 20
      else
         go to 20
      end if
c
c
200   STOP
      END


      SUBROUTINE HYDFOR(alph,norfor,axfor,xcp)
c
c  This subroutine calculated the hydrodynamic forces acting on the
c  towed body from curves of coefficients versus incidence
c
c    alph=incidence of vehicle(radians), +ve is nose up
c    norfor=normal force on vehicle(n), +ve is up
c    axfor=axial force on vehicle(n), +ve is backward
c    xcp=centre of pressure of normal force(cal), +ve is behind nose
c
         real nor0,nor1,nor2,nor3,nor4,norfor,norfcf
c
         common dens,vel
         common/hydfor/nor0,nor1,nor2,nor3,nor4,ax0,ax1,ax2,ax3,ax4,
        +xcp0,xcp1,xcp2,xcp3,xcp4,refa,refl
c
         dynp=0.5*dens*(vel**2)
         norfcf=nor0+nor1*alph+nor2*(alph**2)+nor3*(alph**3)+nor4*(alph**4)
         norfor=norfcf*dynp*refa
         axfcf=ax0+ax1*alph+ax2*(alph**2)+ax3*(alph**3)+ax4*(alph**4)
         axfor=axfcf*dynp*refa
         xcpcal=xcp0+xcp1*alph+xcp2*(alph**2)+xcp3*(alph**3)+xcp4*(alph**4)
         xcp=xcpcal*refl
         RETURN
         END


         SUBROUTINE TOWFOR(alph,tnor,tax,mres)

c
c  This subroutine calculates the tow cable forces on the towed body
c  and also the resultant pitching moment on the vehicle
c
c    alph=incidence of vehicle(radians), +ve is nose up
c    tnor=cable force normal to vehicle axis(n), +ve is up
c    tax=cable force parallel to vehicle axis(n), +ve is forward
c    mres=pitching moment on vehicle(n.m), +ve is nose up
c
         common/towfor/weight,bouyf,norfor,axfor,xcg,xbouy,xcp,xtow,ztow
c
         real norfor,mres
c
```

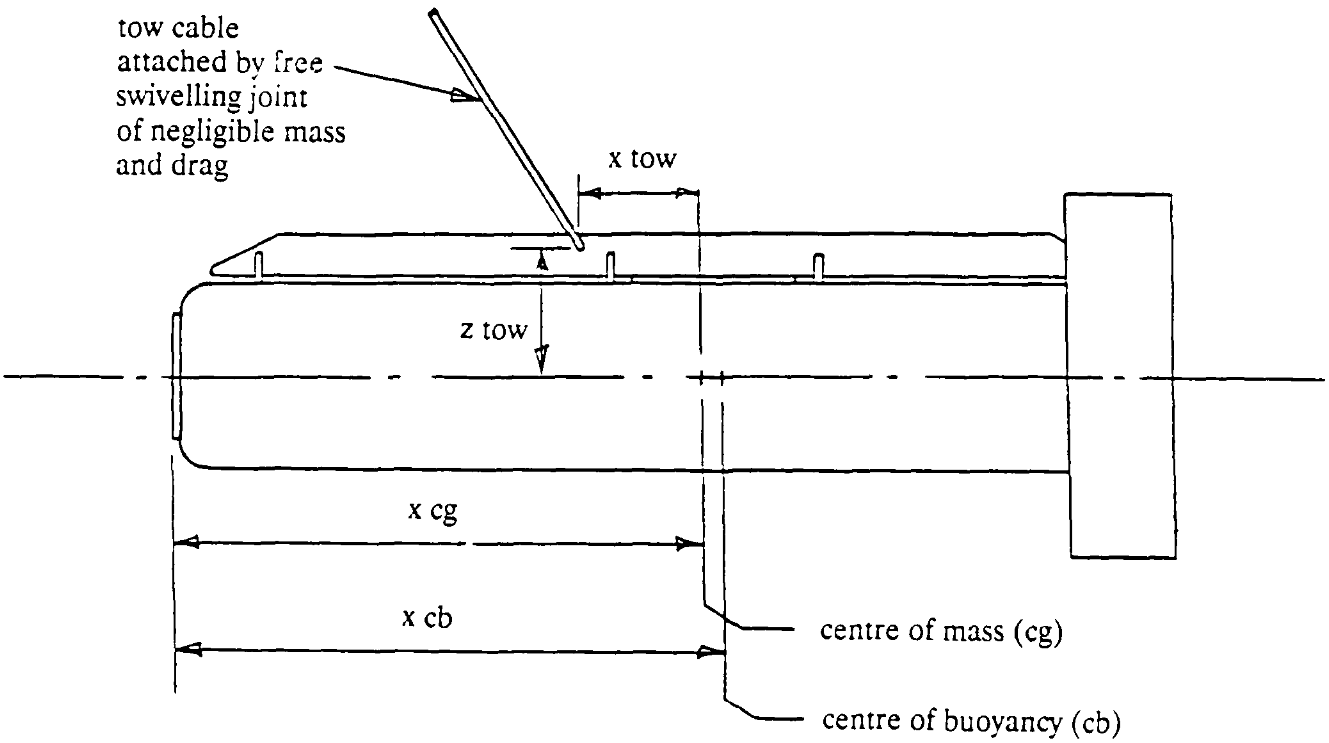
```
      tnor=(weight-bouyf)*cos(alph)-norfor
      tax=(weight-bouyf)*sin(alph)+axfor
      mres=(weight*xcg-bouyf*xbouy)*cos(alph)-norfor*xcp-tnor*xtow-
     1tax*ztow
      RETURN
      END


      SUBROUTINE CABLE(length,ctens,posx,posy)
c
c  This subroutine calculates the tension and shape of the first
c  2000 metres of tow cable from the towed body by considering the
c  cable to be made up of 2000 pin-jointed rigid sections, each section
c  one metre long
c
c   length=length of cable(m), measured from vehicle attachment point
c   ctens=cable tension(n), at points defined by 'length'
c   posx=horizontal distance(m), from attachment point, +ve is forward
c   posy=vertical distance(m), from attachment point, +ve is up
c
      dimension ctens(14),posx(14),posy(14),length(14)
c
      common dens,vel
      common/cable/tax,tnor,alph,cdcnor,cdcax,crefa,effcwt
c
      real length
c
c  set up initial values at cable attachment point
      xold=0.0
      yold=0.0
      told=sqrt(tax**2+tnor**2)
      ang1=atan(tnor/tax)
      if(tax.1t.0.0)ang1=ang1+3.1416
      angold=alph+ang1
      ystore=9.6
      j=0
c
c  now calculate cable characteristics at each metre for 2000 metres
      do 10 i=1,2000
      xnew=xold+cos(angold)
      ynew=yold+sin(angold)
      fnor=cdcnor*crefa*0.5*dens*(vel*sin(angold))**2
      fax=cdcax*crefa*0.5*dens*(vel*cos(angold))**2
      wnor=effcwt*cos(angold)
      wax=effcwt*sin(angold)
      tnewax=told+fax+wax
      tnewnr+wnor-fnor
      tnew=sqrt(tnewax**2+tnewnr**2)
      angnew=angold+atan(tnewnr/tnewax)
c  store variables for output at 10 metre depth increments
      if(ynew.ge.ystore) then
         j=j+1
         if(j.eq.15) go to 20
         length(j)=i
```

```
            ctens(j) = tnew
            posx(j) = xnew
            posy(j) = ynew
            ystore = ystore + 10.0
         end if
         xold = xnew
         yold = ynew
         told = tnew
         angold = angnew
10       continue
20       RETURN
         END
```

APPENDIX 2. SAMPLE OUTPUT FROM THE PREDICTION PROGRAM

```
                        UNDERWATER SOUND GENERATOR TOWING CHARACTERISTICS

for tow speed  5.0 m/s and tow position  0.50 m ahead of cg, vehicle trim angle is    0.9 deg
      cable length (m)            14.3   29.0   46.3   64.0   84.0  104.0  125.0  146.0  169.0  191.0  215.0  238.0  263.3  287.3
      cable tension (n)          1937.  2394.  2967.  3612.  4360.  5131.  5957.  6798.  7730.  8631.  9623. 10540. 11627. 12617.
      horizontal position (m)      9.7   21.2   34.9   49.9   67.0   84.4  102.9  121.5  142.1  161.8  181.5  204.4  227.1  249.3
      vertical position (m)       10.1   19.7   29.8   39.7   50.1   60.0   70.0   79.6   90.0   99.6  109.9  119.6  130.0  139.8

for tow speed  4.0 m/s and tow position  0.50 m ahead of cg, vehicle trim angle is    1.7 deg
      cable length (m)            12.0   25.0   39.0   54.0   69.0   86.0  103.0  120.0  139.0  158.0  177.0  196.0  217.0  237.0
      cable tension (n)          1462.  1654.  1895.  2181.  2488.  2854.  3235.  3627.  4076.  4534.  4998.  5468.  5994.  6500.
      horizontal position (m)      6.6   14.9   24.6   35.7   47.2   60.7   74.5   88.6  104.5  120.6  136.8  153.2  171.4  188.8
      vertical position (m)       10.0   20.1   30.1   40.2   49.8   60.1   70.1   79.6   90.0  100.1  109.9  119.6  130.1  139.9

for tow speed  3.0 m/s and tow position  0.50 m ahead of cg, vehicle trim angle is    3.5 deg
      cable length (m)            11.0   22.0   34.0   46.0   58.0   71.0   85.0   99.0  113.0  128.0  143.0  158.0  174.0  190.0
      cable tension (n)          1211.  1279.  1365.  1461.  1566.  1688.  1829.  1977.  2131.  2302.  2478.  2659.  2855.  3055.
      horizontal position (m)      4.2    9.2   15.4   22.2   29.5   37.9   47.3   57.0   67.0   78.0   89.2  100.6  112.9  125.4
      vertical position (m)       10.1   19.9   30.2   40.1   49.6   59.6   70.0   80.0   89.8  100.0  110.0  119.7  130.0  140.0

for tow speed  2.0 m/s and tow position  0.50 m ahead of cg, vehicle trim angle is    8.2 deg
      cable length (m)            10.0   21.0   31.0   42.0   53.0   64.0   75.0   86.0   97.0  109.0  120.0  132.0  144.0  156.0
      cable tension (n)          1144.  1180.  1214.  1253.  1294.  1336.  1379.  1424.  1470.  1521.  1569.  1623.  1678.  1734.
      horizontal position (m)      2.4    5.5    8.6   12.4   16.5   20.9   25.6   30.5   35.6   41.5   47.0   53.2   59.6   66.1
      vertical position (m)        9.7   20.3   29.8   40.1   50.3   60.4   70.3   80.2   89.9  100.4  109.9  120.2  130.3  140.4

for tow speed  1.0 m/s and tow position  0.50 m ahead of cg, vehicle is unstable
for tow speed  0.0 m/s and tow position  0.50 m ahead of cg, vehicle is unstable

                                                 |
                                                 |

for tow speed  5.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is   -0.5 deg
      cable length (m)            12.0   25.0   39.0   54.0   69.0   86.0  104.0  122.0  141.0  161.0  181.0  202.0  223.0  245.0
      cable tension (n)          2275.  2558.  2921.  3357.  3830.  4398.  5028.  5679.  6385.  7144.  7916.  8738.  9570. 10450.
      horizontal position (m)      6.5   14.7   24.4   35.6   47.3   60.9   75.7   90.9  107.0  124.3  141.7  160.1  178.6  198.1
      vertical position (m)       10.1   20.2   30.2   40.2   49.7   59.8   70.0   79.8   89.7   99.9  109.7  119.8  129.7  139.9

for tow speed  4.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is   -0.3 deg
      cable length (m)            11.0   22.0   34.0   47.0   60.0   74.0   89.0  104.0  119.0  136.0  152.0  169.0  187.0  205.0
      cable tension (n)          1898.  2006.  2150.  2331.  2535.  2776.  3053.  3347.  3654.  4015.  4364.  4745.  5157.  5576.
      horizontal position (m)      4.4    9.7   16.4   24.3   32.8   42.6   53.4   64.7   76.2   89.6  102.4  116.2  131.0  146.3
      vertical position (m)       10.1   19.7   29.7   40.0   49.8   59.9   70.2   80.1   89.7  100.2  109.7  119.7  129.9  139.9

for tow speed  3.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is    0.3 deg
      cable length (m)            10.0   21.0   32.0   43.0   54.0   66.0   78.0   90.0  102.0  115.0  128.0  142.0  155.0  169.0
      cable tension (n)          1659.  1708.  1763.  1826.  1896.  1980.  2071.  2169.  2273.  2392.  2517.  2657.  2791.  2941.
      horizontal position (m)      2.5    6.0   10.1   14.8   19.9   26.0   32.5   39.5   46.7   54.9   63.3   72.7   81.6   91.4
      vertical position (m)        9.7   20.1   30.3   40.3   50.0   60.3   70.4   80.2   89.8   99.9  109.8  120.2  129.6  139.6

for tow speed  2.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is    1.6 deg
      cable length (m)            10.0   20.0   30.0   41.0   51.0   61.0   72.0   82.0   93.0  104.0  114.0  125.0  136.0  147.0
      cable tension (n)          1564.  1594.  1624.  1657.  1689.  1721.  1757.  1791.  1830.  1869.  1905.  1947.  1989.  2032.
      horizontal position (m)      1.2    2.7    4.6    6.9    9.2   11.8   15.0   18.1   21.7   25.5   29.2   33.5   37.9   42.5
      vertical position (m)        9.9   19.8   29.6   40.4   50.1   59.8   70.3   79.8   90.2  100.5  109.8  120.0  130.0  140.0

for tow speed  1.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is    6.4 deg
      cable length (m)            10.0   20.0   30.0   40.0   50.0   60.0   70.0   80.0   90.0  100.0  110.0  120.0  131.0  141.0
      cable tension (n)          1564.  1592.  1620.  1647.  1675.  1703.  1731.  1759.  1787.  1814.  1842.  1870.  1901.  1929.
      horizontal position (m)      0.4    0.9    1.4    2.0    2.7    3.4    4.2    5.1    6.0    7.0    8.1    9.1   10.4   11.6
      vertical position (m)       10.0   20.0   30.0   39.9   49.9   59.9   69.9   79.8   89.8   99.7  109.7  119.6  130.5  140.5

for tow speed  0.0 m/s and tow position  0.10 m ahead of cg, vehicle trim angle is   17.4 deg
      cable length (m)            10.0   20.0   30.0   40.0   50.0   60.0   70.0   80.0   90.0  100.0  110.0  120.0  130.0  140.0
      cable tension (n)          1675.  1703.  1730.  1758.  1786.  1814.  1841.  1869.  1897.  1925.  1953.  1980.  2008.  2036.
      horizontal position (m)      0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
      vertical position (m)       10.0   20.0   30.0   40.0   50.0   60.0   70.0   80.0   90.0  100.0  110.0  120.0  130.0  140.0

                                                 |
                                                 |

for tow speed  5.0 m/s and tow position -0.40 m ahead of cg, vehicle trim angle is   -4.3 deg
      cable length (m)            11.0   21.0   32.0   44.0   55.0   67.0   80.0   92.0  105.0  119.0  132.0  147.0  161.0  176.0
      cable tension (n)          5395.  5492.  5618.  5779.  5947.  6153.  6400.  6648.  6938.  7272.  7608.  7998.  8387.  8819.
      horizontal position (m)      1.6    7.4   12.1   17.7   23.1   29.9   37.5   44.8   53.2   62.5   71.6   82.0   92.1  103.2
      vertical position (m)       10.4   19.6   29.6   40.2   49.6   59.7   70.2   79.7   89.7  100.2  109.6  120.2  129.9  140.0

for tow speed  4.0 m/s and tow position -0.40 m ahead of cg, vehicle trim angle is  -11.5 deg
      cable length (m)            11.0   21.0   32.0   43.0   54.0   65.0   77.0   88.0  100.0  113.0  125.0  138.0  150.0  163.0
      cable tension (n)          4854.  4916.  4993.  5078.  5172.  5275.  5397.  5517.  5657.  5820.  5978.  6159.  6335.  6532.
      horizontal position (m)      3.1    6.7   10.8   15.2   20.0   25.2   31.1   36.8   43.4   50.8   57.9   65.8   73.3   81.7
      vertical position (m)       10.5   19.9   30.1   40.2   50.1   59.8   70.2   79.6   89.7  100.4  110.0  120.3  129.7  139.6

for tow speed  3.0 m/s and tow position -0.40 m ahead of cg, vehicle is unstable
for tow speed  2.0 m/s and tow position -0.40 m ahead of cg, vehicle is unstable
for tow speed  1.0 m/s and tow position -0.40 m ahead of cg, vehicle is unstable
for tow speed  0.0 m/s and tow position -0.40 m ahead of cg, vehicle is unstable


for tow speed  5.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
for tow speed  4.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
for tow speed  3.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
for tow speed  2.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
for tow speed  1.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
for tow speed  0.0 m/s and tow position -0.50 m ahead of cg, vehicle is unstable
```

TABLE 1. INPUT DATA USED IN THE PREDICTION PROGRAM



		with tail 1	with tail 3
Vehicles			
	x_{cg}	1.277 m	1.244 m
	x_{cb}	1.266 m	1.239 m
	mass	340.8 kg	330.3 kg
	displacement	0.162 m^3	0.158 m^3
General			
	tow speed	variable, 0m/s to 5 m/s	
	x_{tow}	variable, 0.5m to -0.5m	
	z_{tow}	0.305 m	
	fluid density	1025 kg/m^3 (sea water)	
Tow cable			
	mass	0.763 kg/m	
	displacement	0.000468 m^3/m	
	drag coeffs	0.24 (for axial flow) 0.16 (for cross flow)	reference length is diam of bare cable (0.016m)

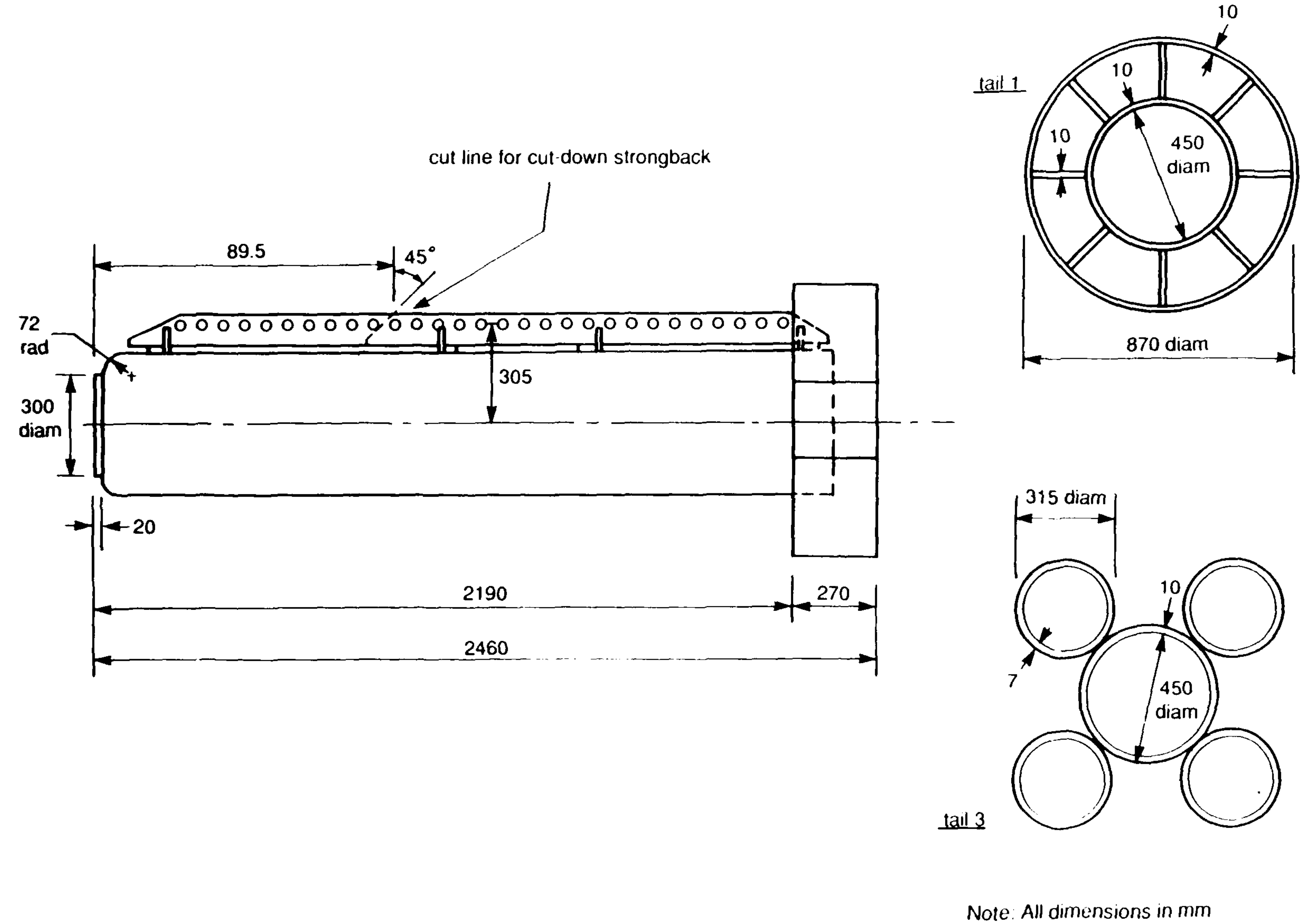
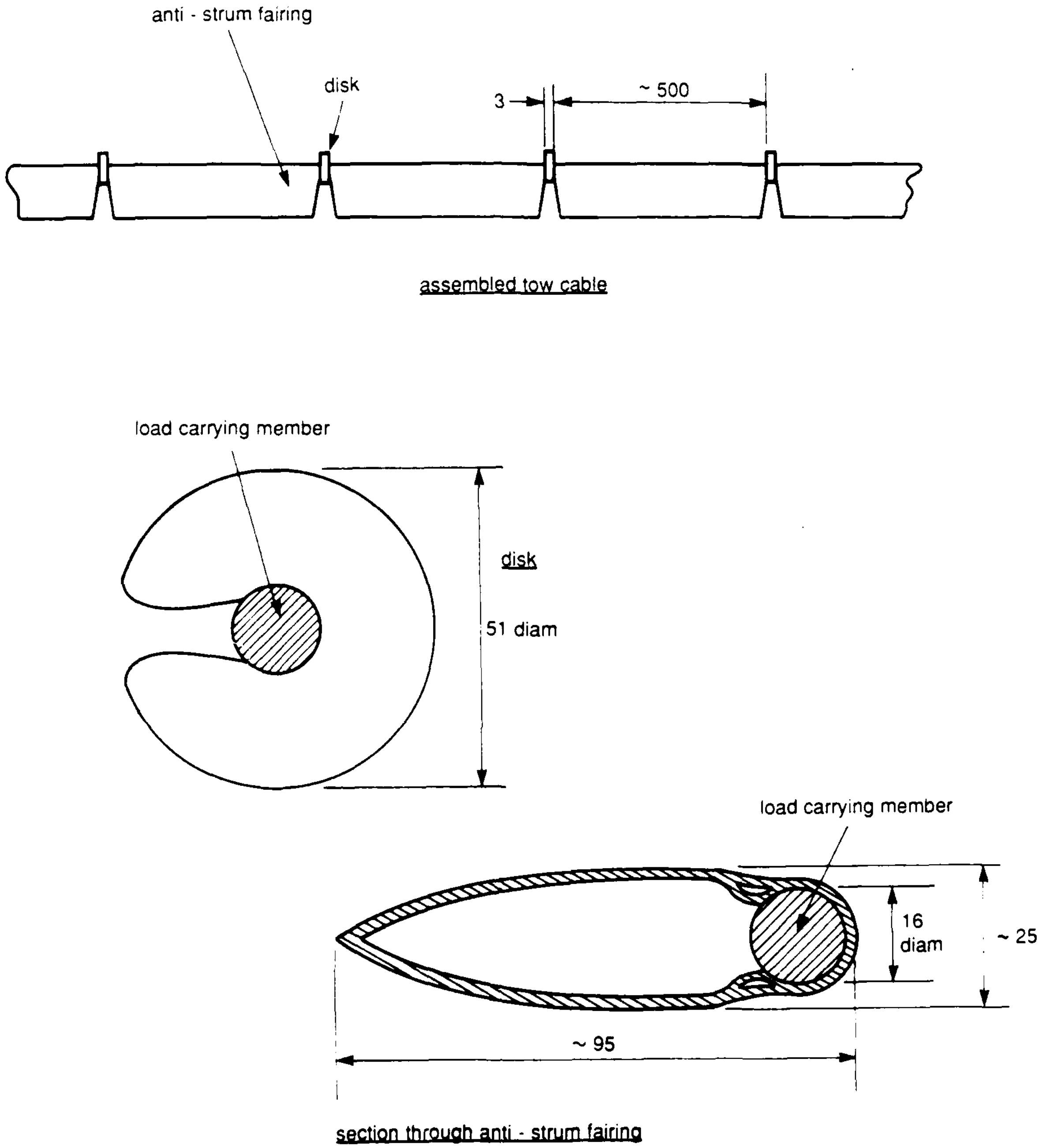
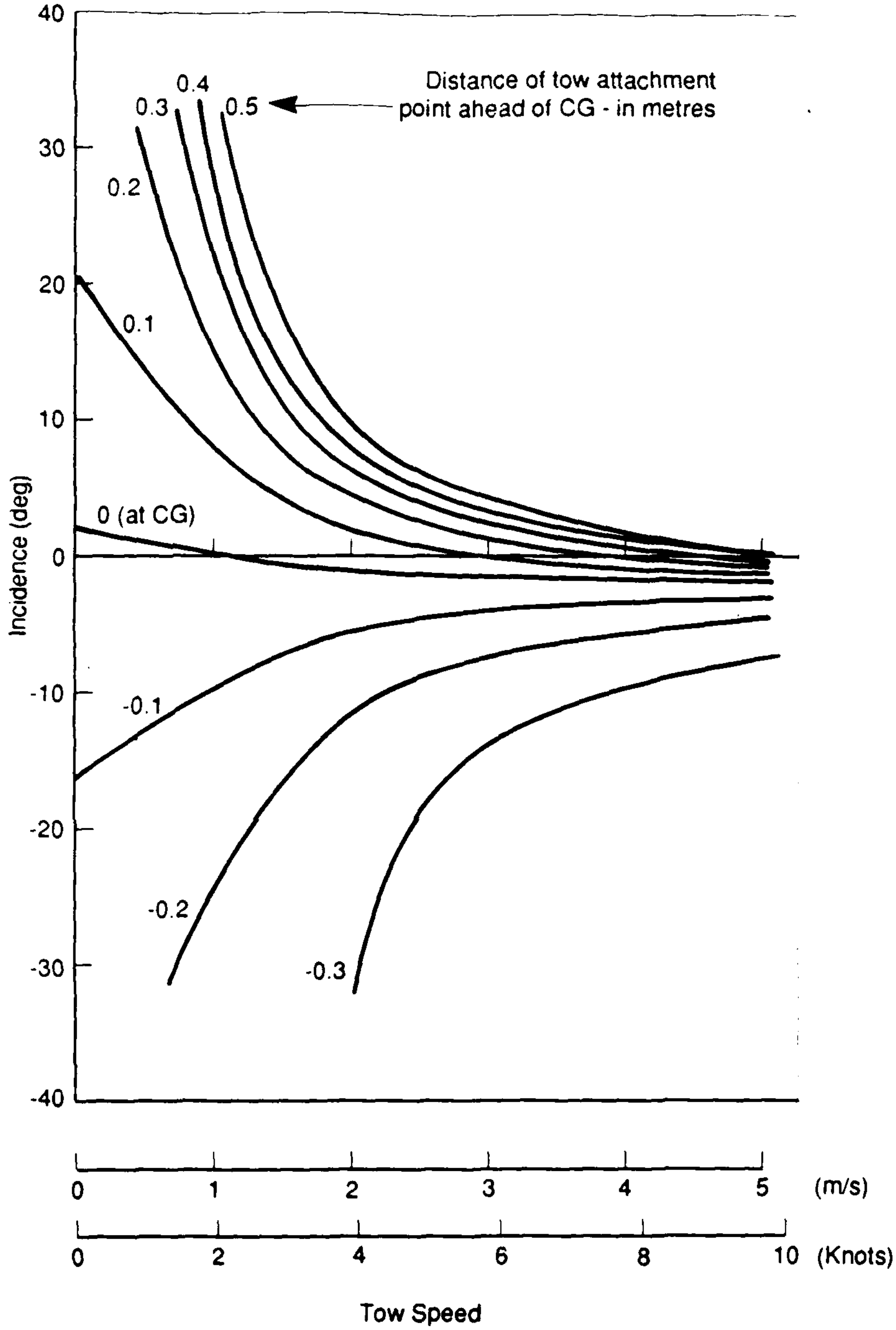


FIGURE 1: GEOMETRY OF THE TOWED VEHICLES



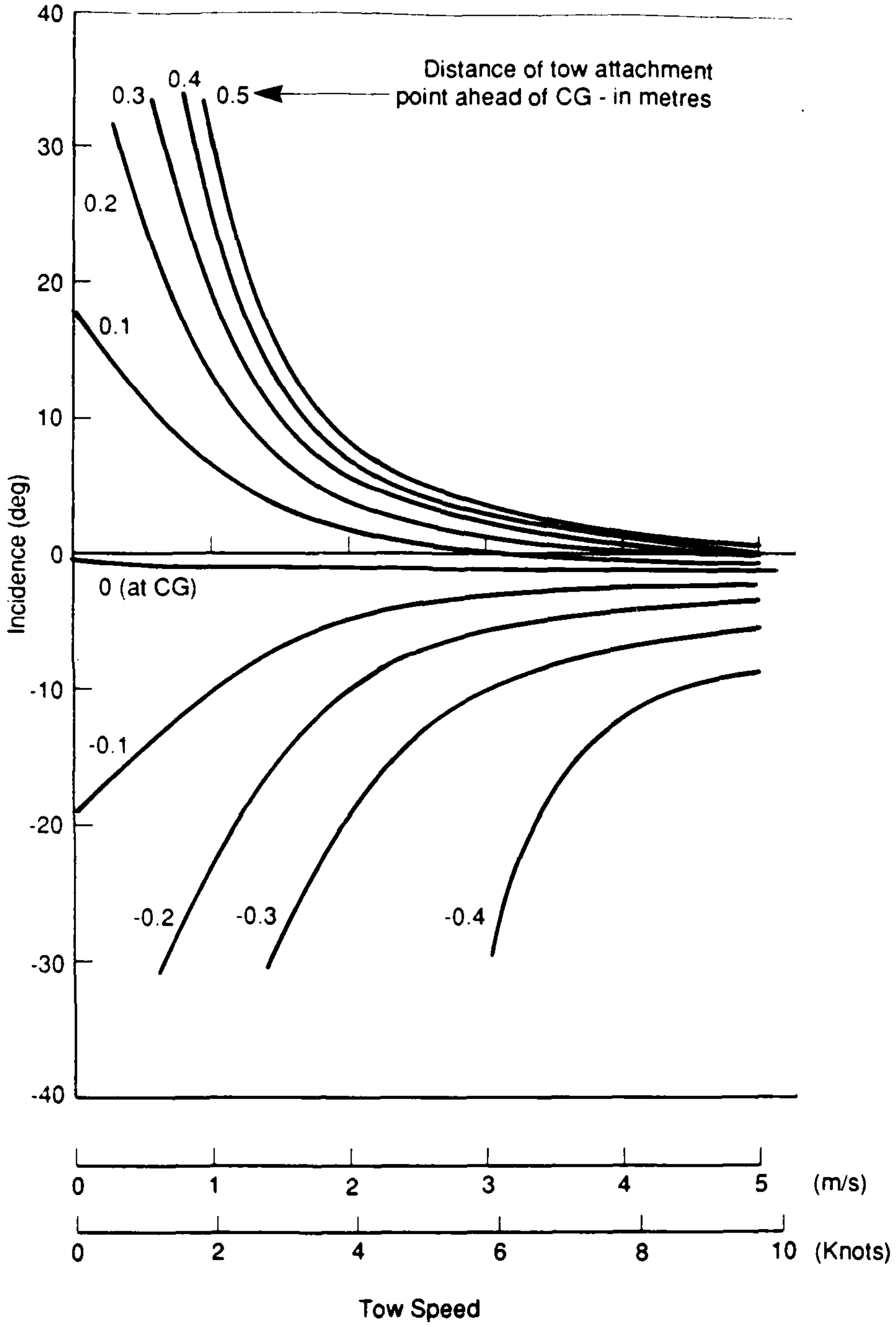
Note: All dimensions in mm

FIGURE 2: GEOMETRY OF THE TOW CABLE



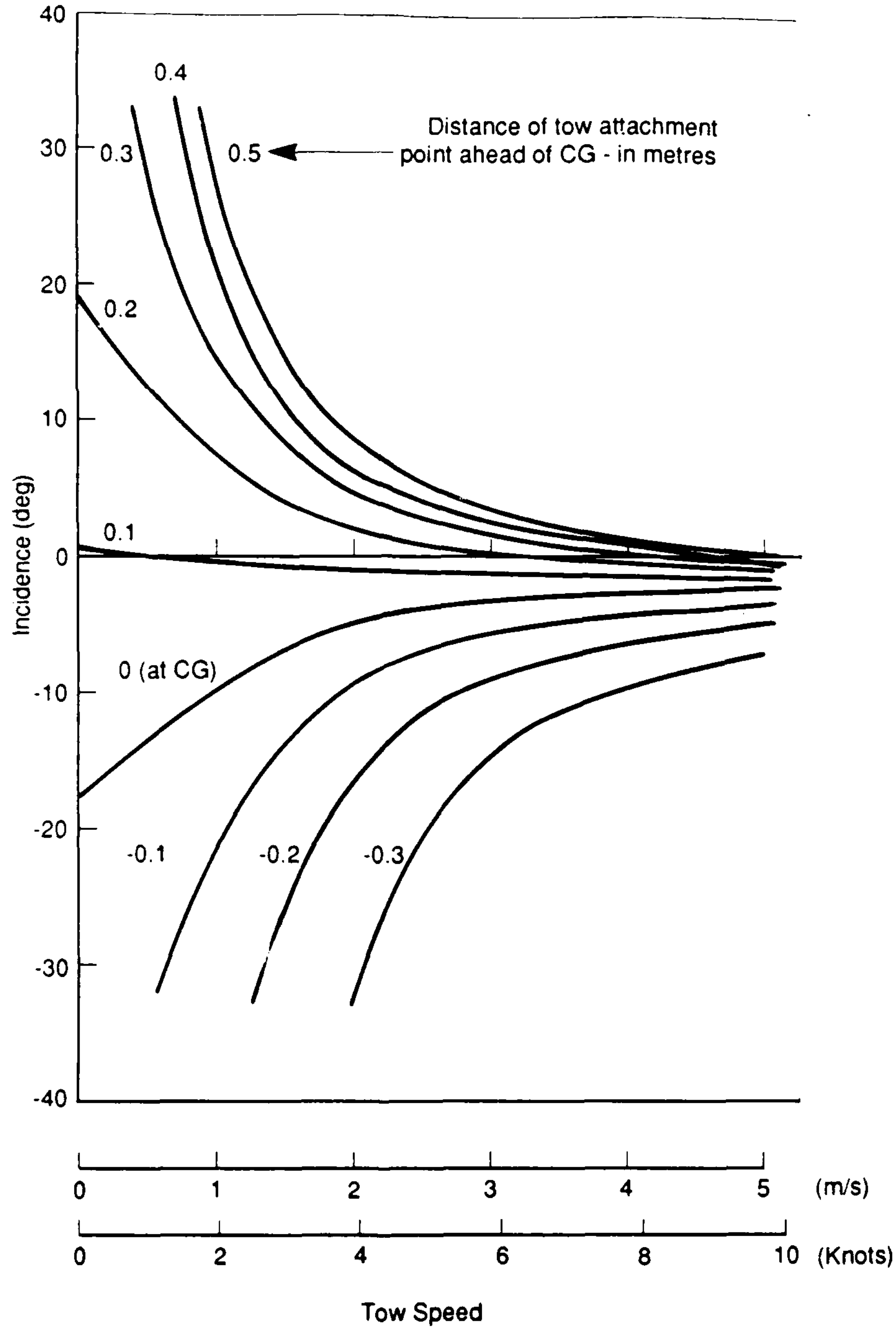
(a) With tail 1

FIGURE 3. INCIDENCE OF THE TOWED VEHICLE



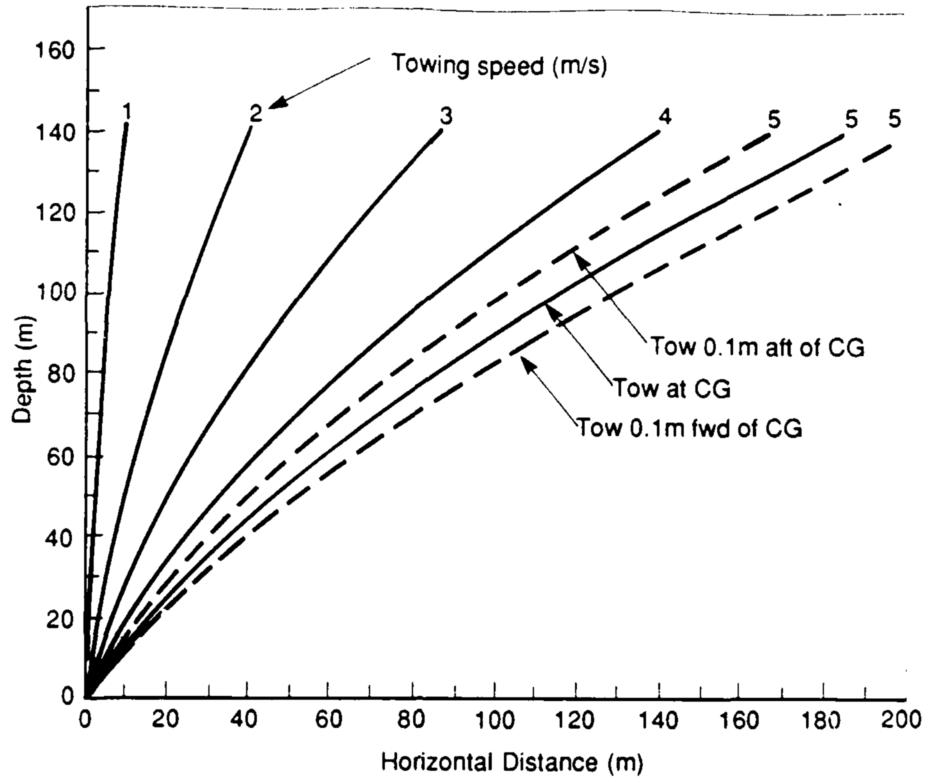
(b) With tail 3

FIGURE 3. (CONT'D): INCIDENCE OF THE TOWED VEHICLE

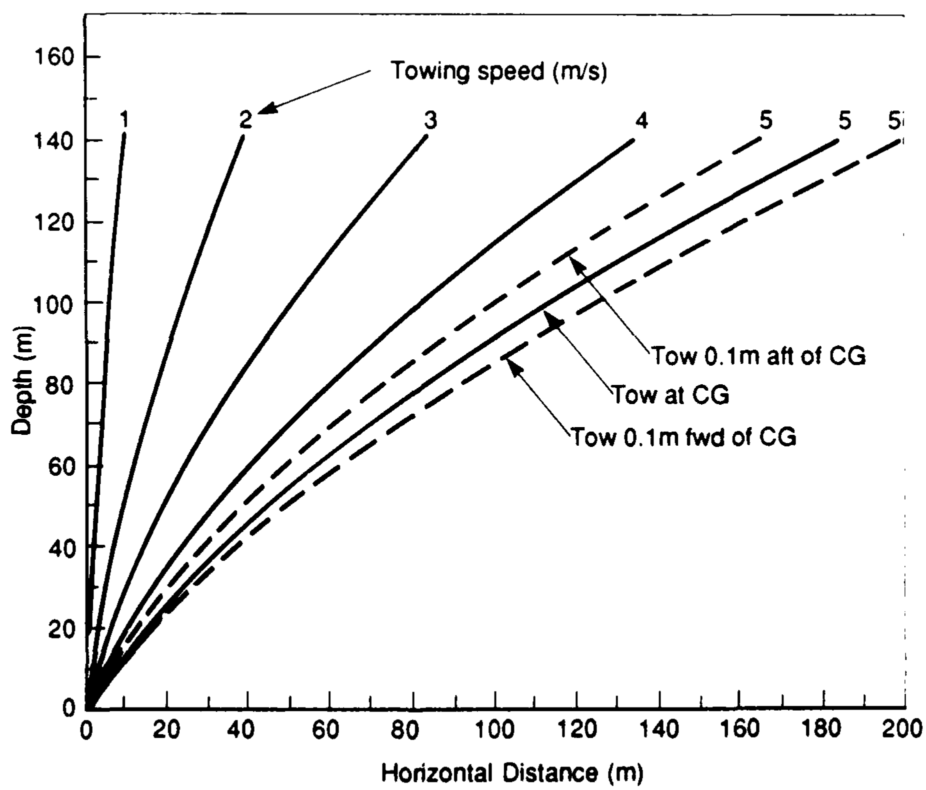


(c) With tail 1 and nose ballast

FIGURE 3. (CONT'D): INCIDENCE OF THE TOWED VEHICLE

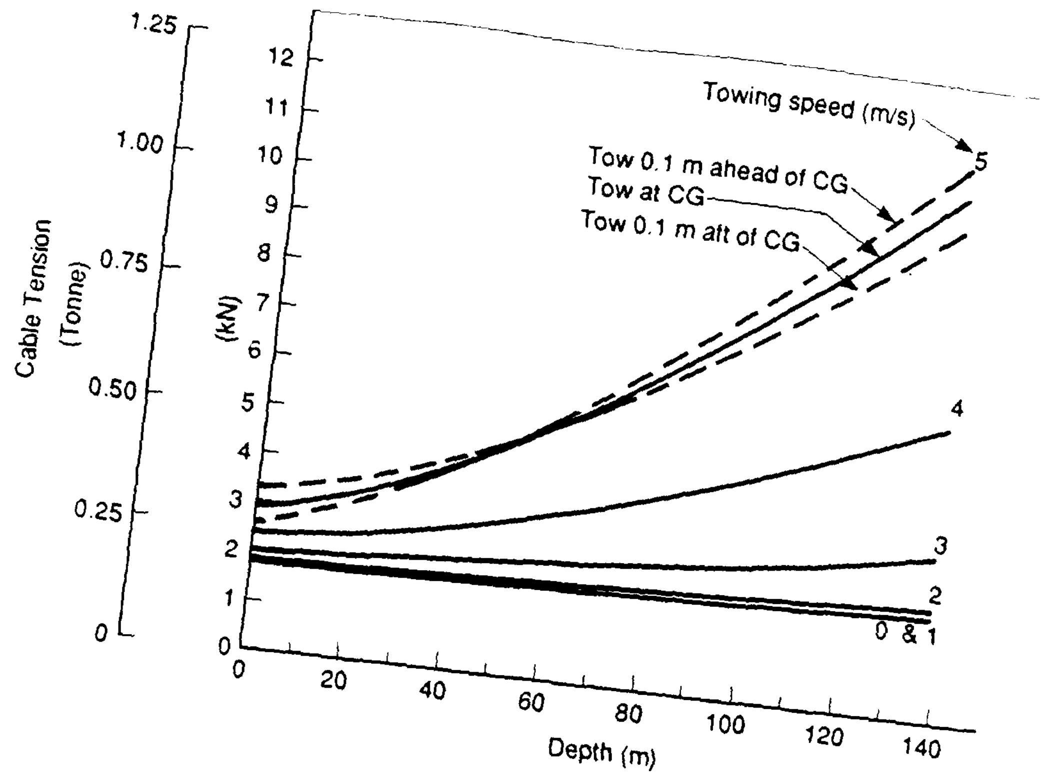


(a) With tail 1

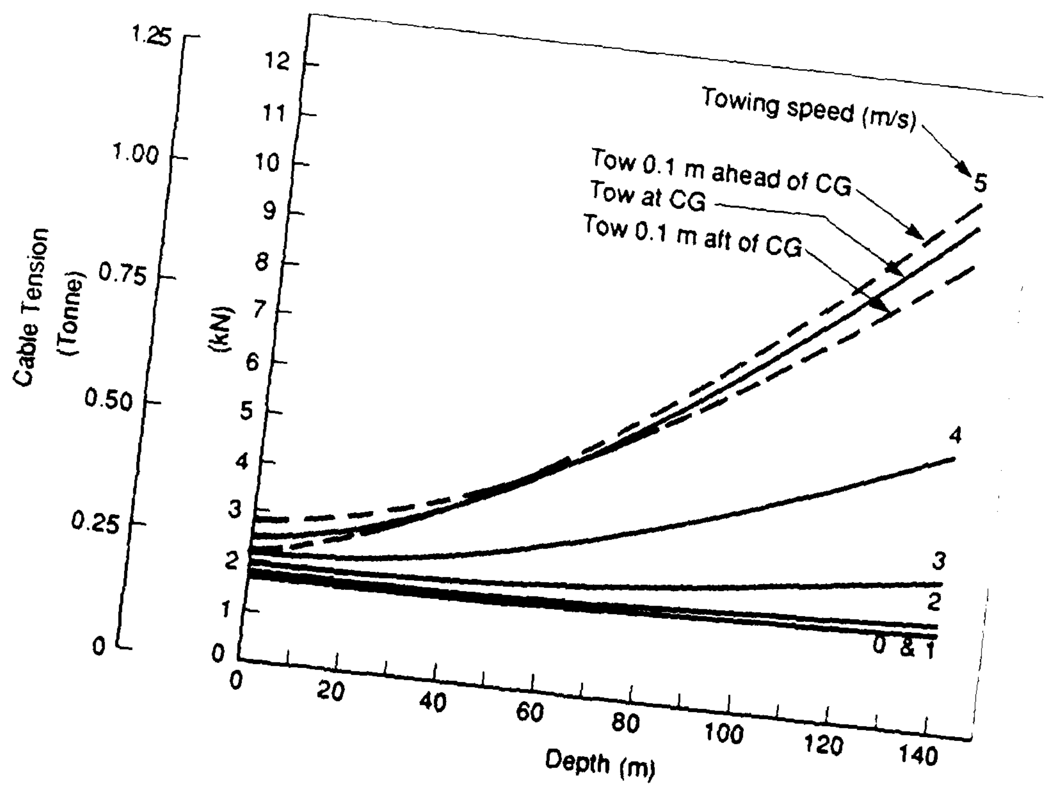


(b) With tail 3

FIGURE 4. TOW CABLE SHAPE

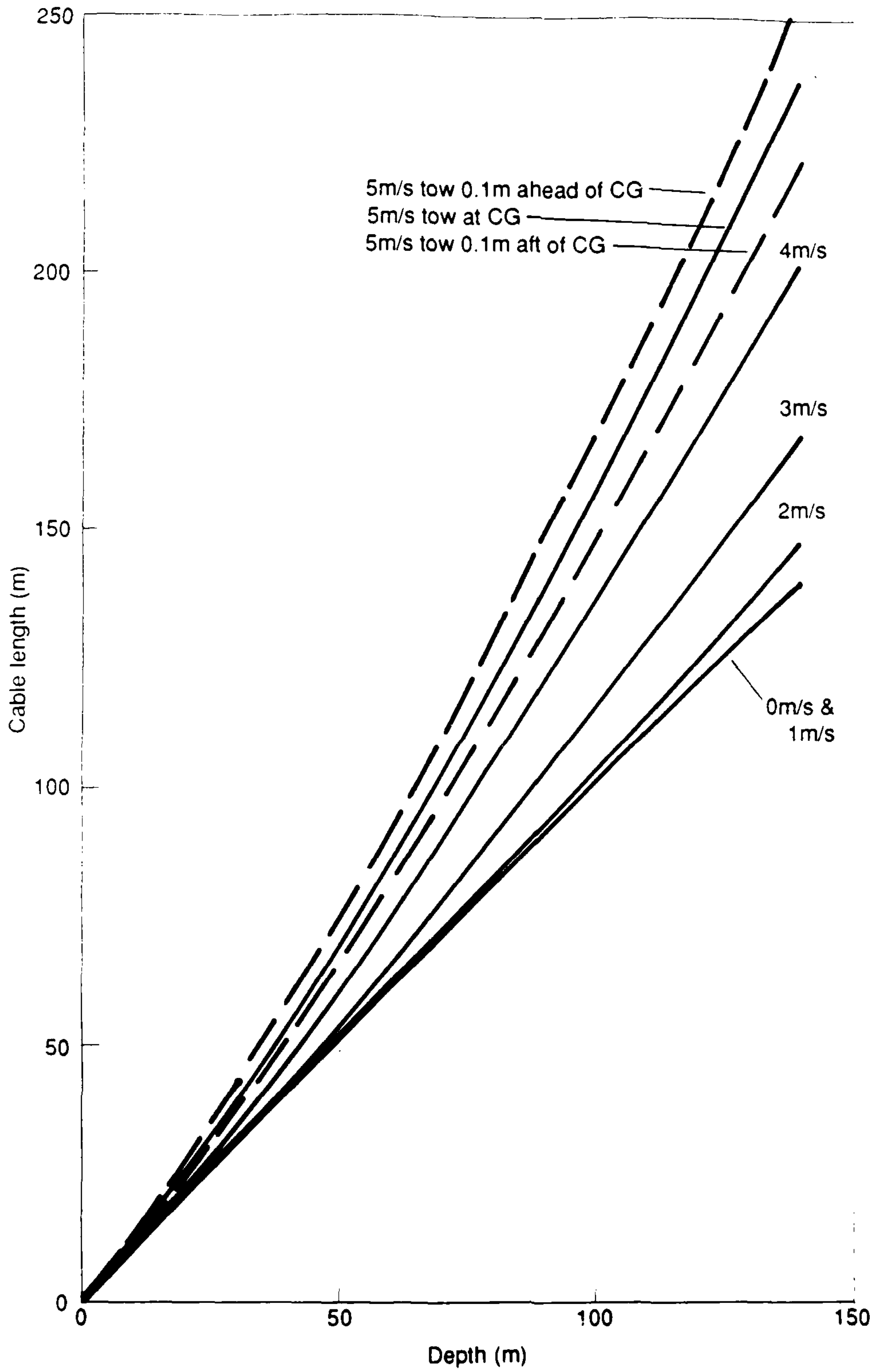


(a) With tail 1



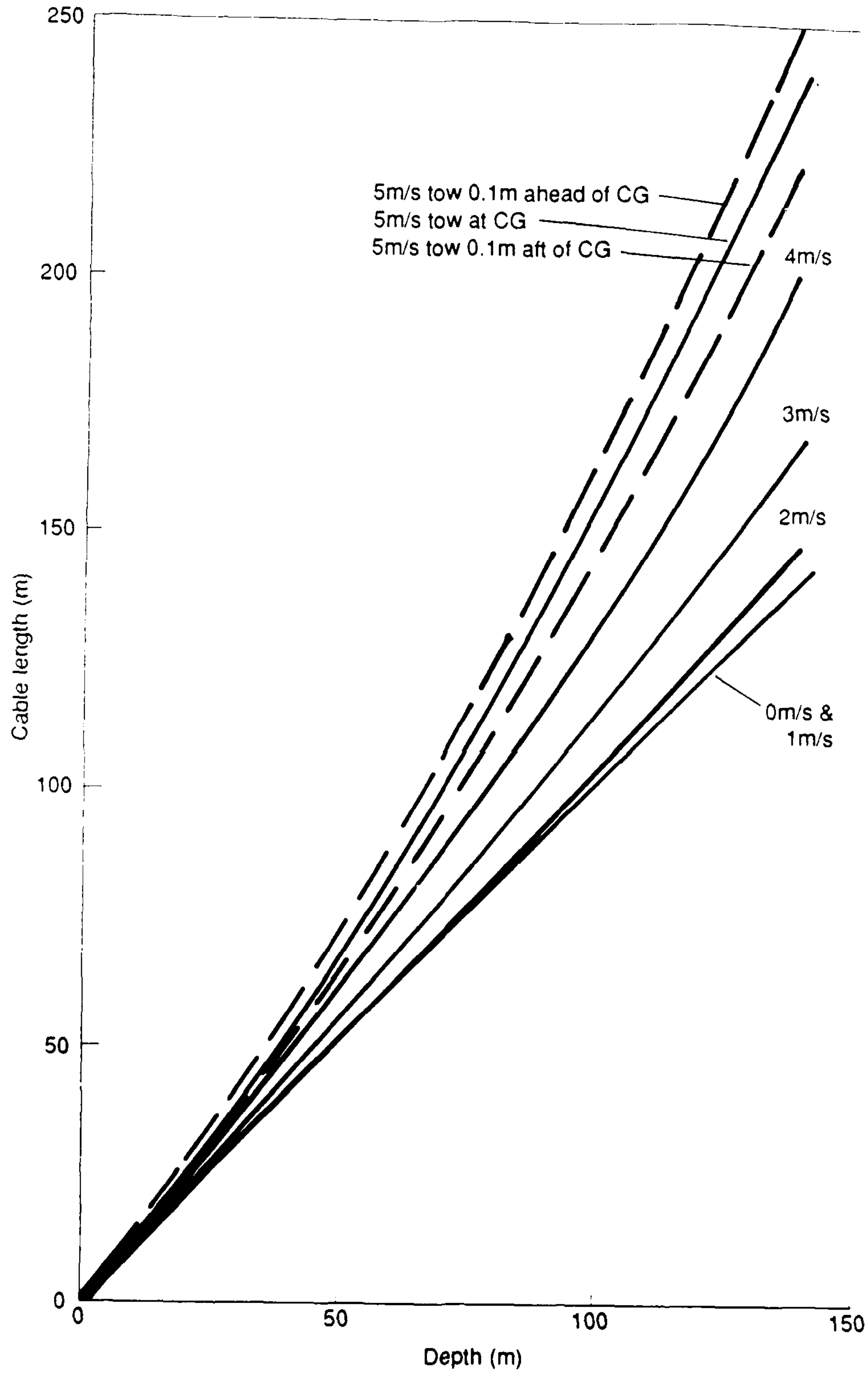
(b) With tail 3

FIGURE 5. TOW CABLE TENSION



a) with tail 1

FIGURE 6. TOW CABLE LENGTH



b) with tail 3

FIGURE 6. TOW CABLE LENGTH

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16. ABSTRACT
An underwater towed sound generator, used in sonar research work, was found to be unstable when under tow. Wind tunnel tests were therefore carried out on a model of the vehicle to assess the effectiveness of various modifications designed to improve its stability.

Fluid dynamic data from these tests has been incorporated into a computer model of the towed vehicle and cable. This document describes and presents predictions obtained from the computer model for a range of configurational and operational variables.

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