Deltares

Enabling Delta Life

Development of 1D2D3D flow solver D-FLOW Flexible Mesh

3TU.AMI, 13-11-2014

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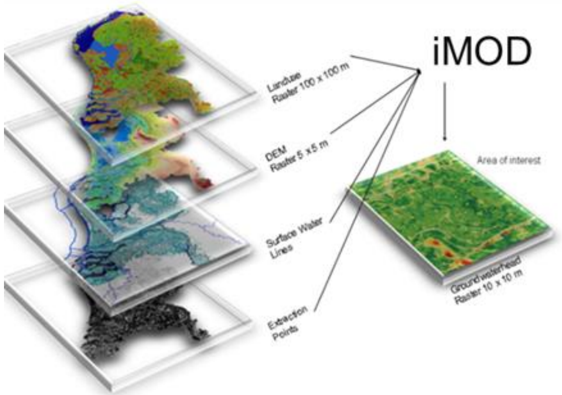
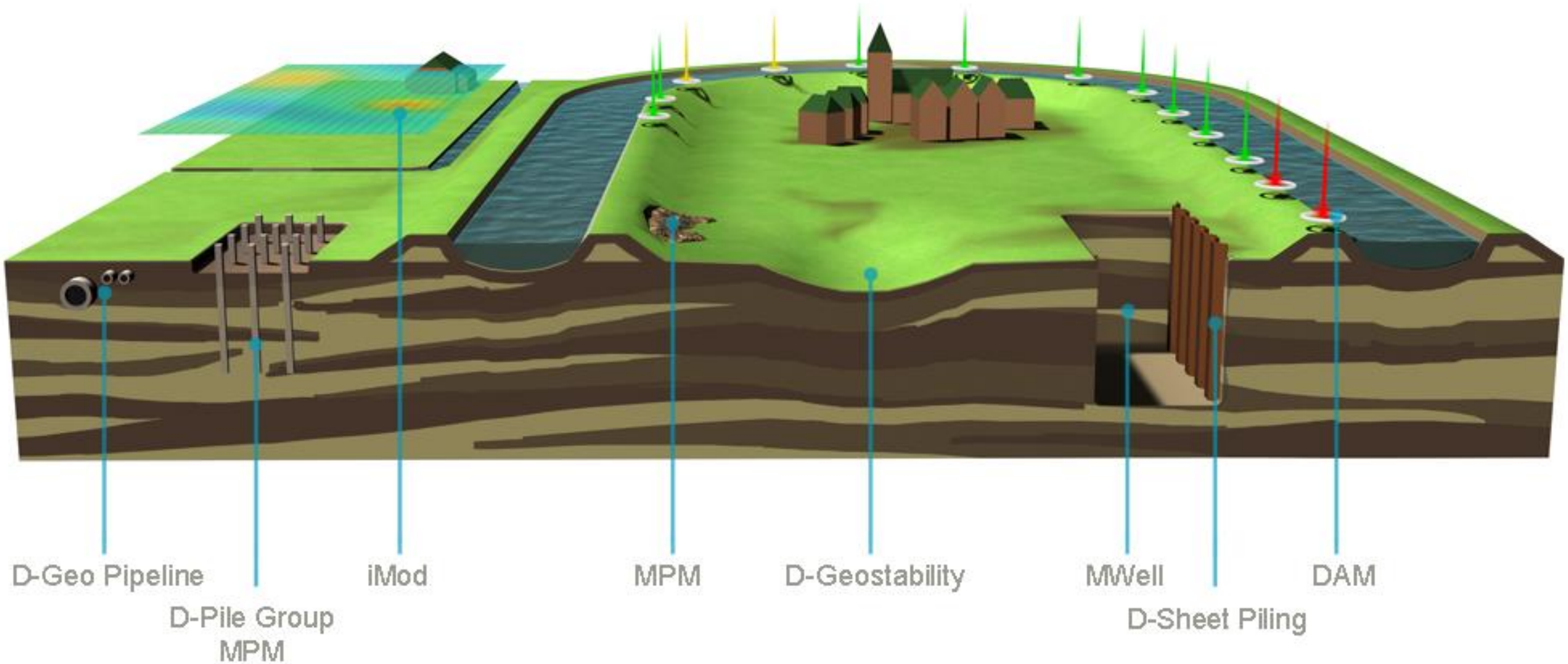
Deltares: Water & Soil   Delft & Utrecht   800

Next Generation Geo Software



NEXT GENERATION GEO SOFTWARE



Next Generation Hydro Software

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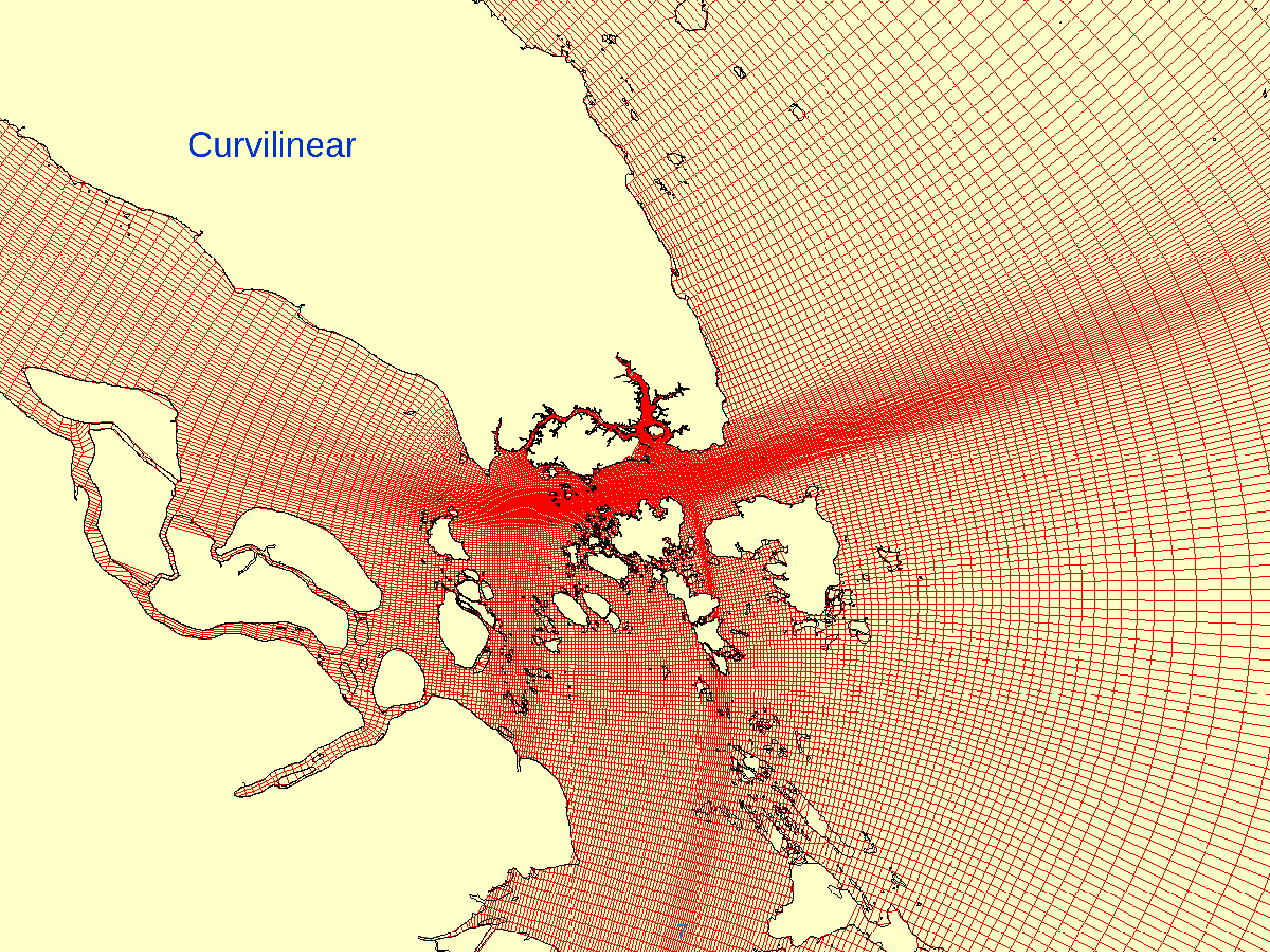
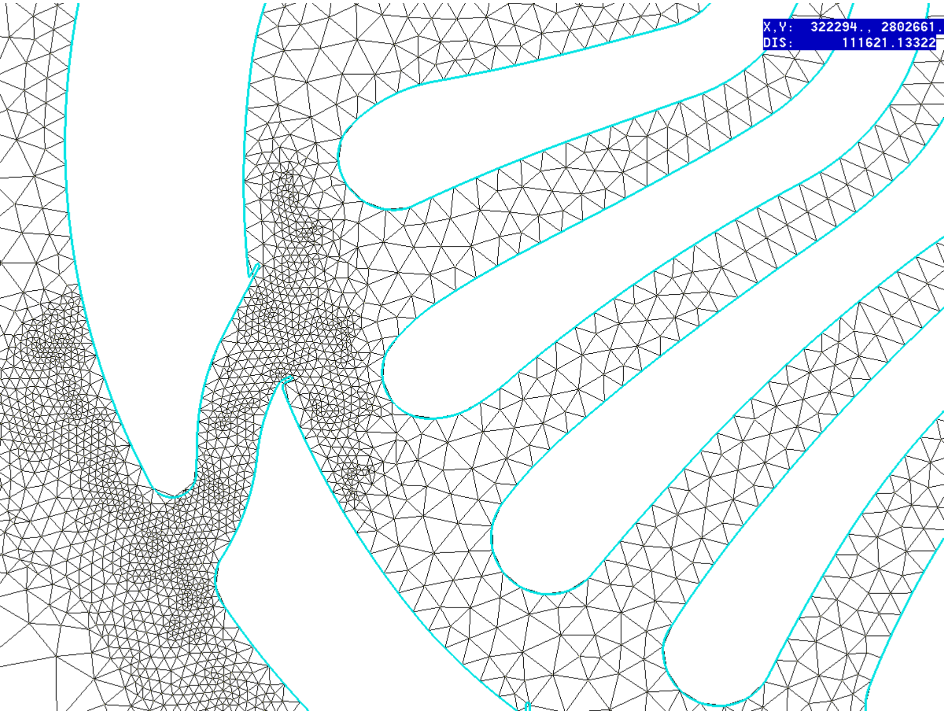
Sobek1D-2D

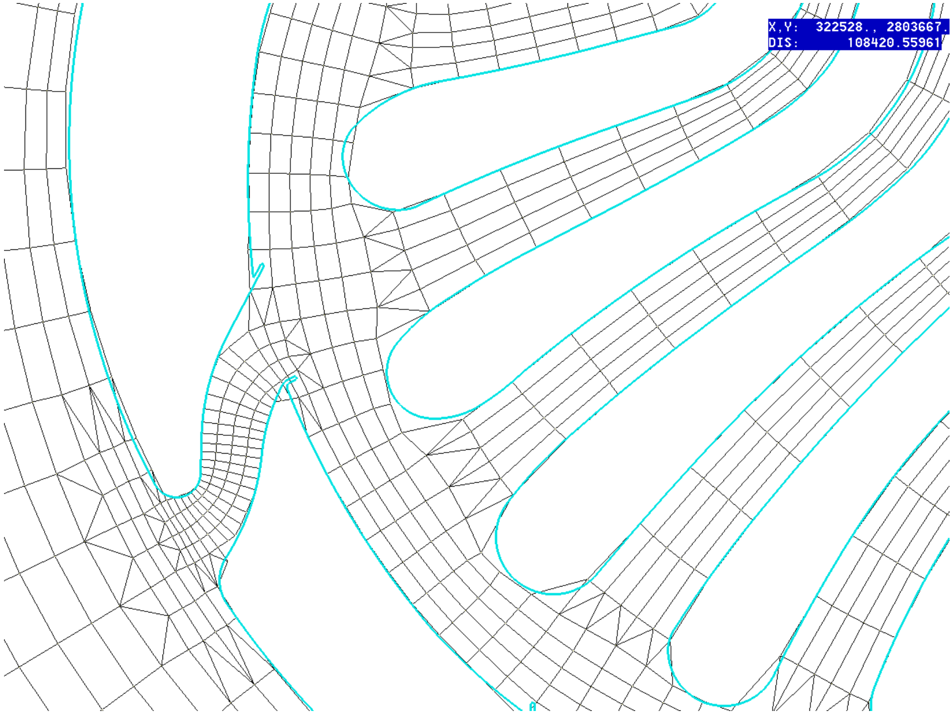

Delft-3D

Curvilinear



Flexibility : Curvilinear + occasional triangle





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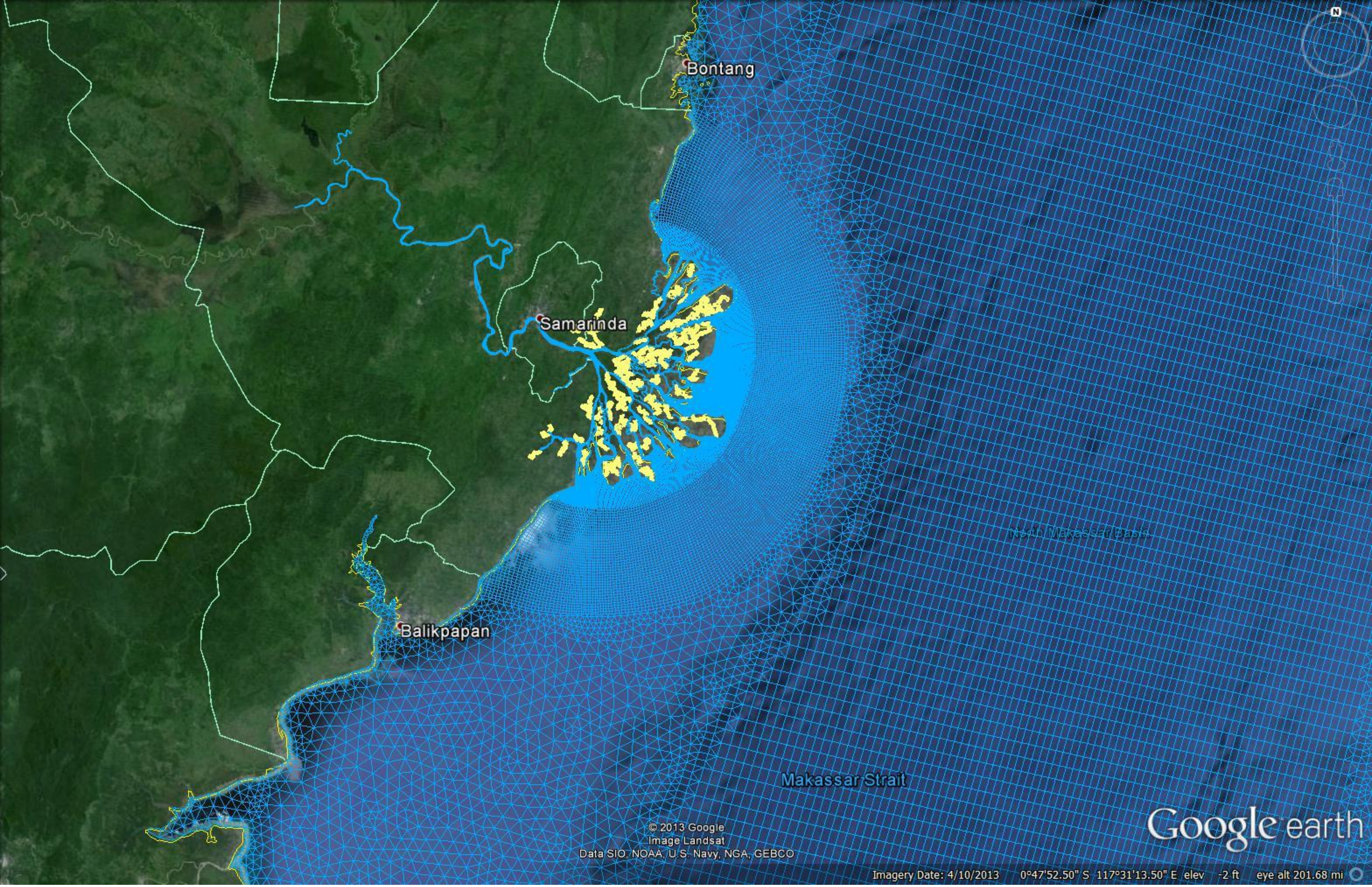
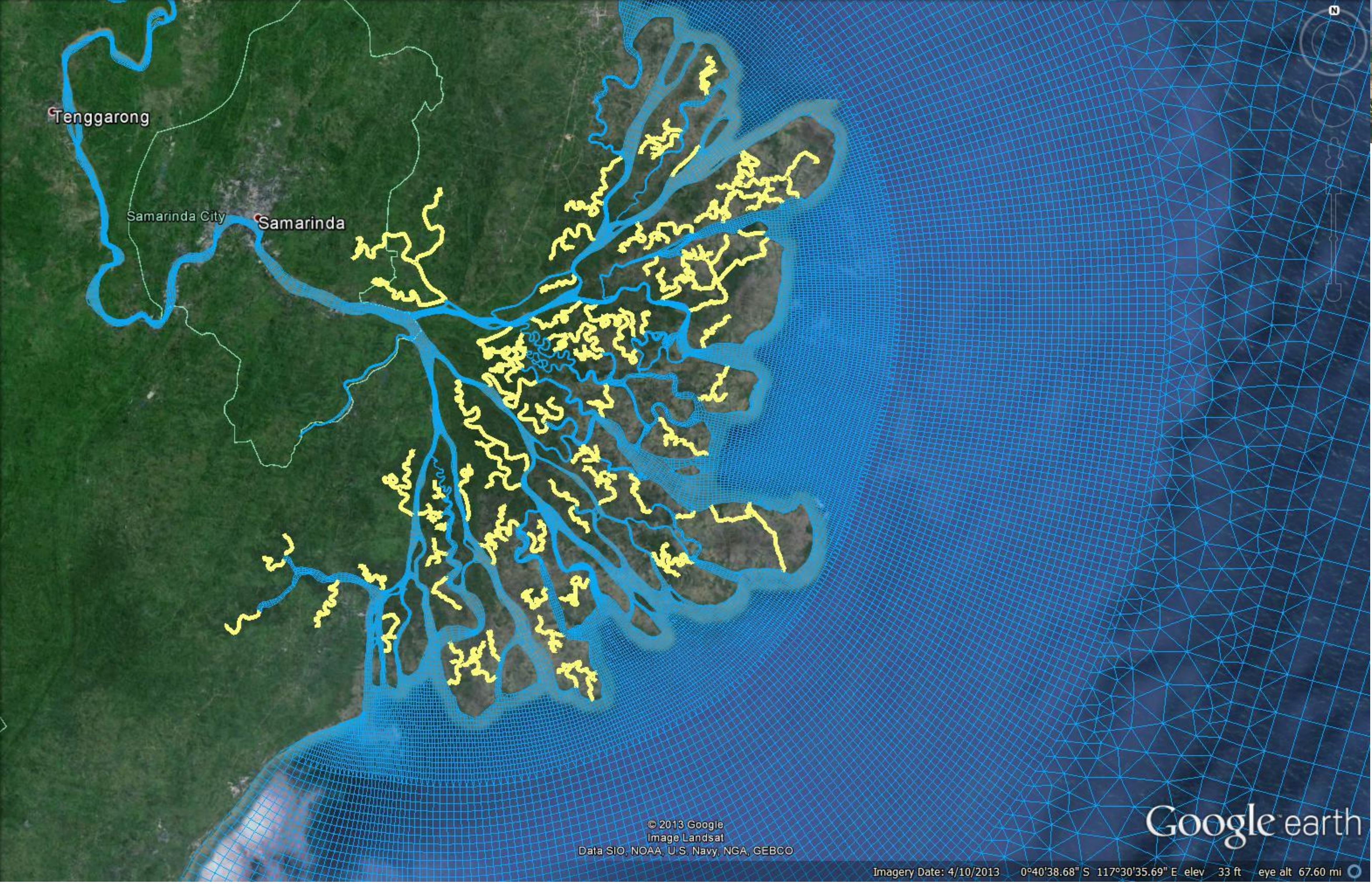
Philippine Sea
Paracel Islands
Spratly Islands
Thailand
Bangkok
Cambodia
Malaysia
Kuala Lumpur
Singapore
Bandar Seri Begawan
Celebes Sea
Indonesia
Makassar Strait
Java Sea
Flores Sea
Banda Sea
Timor-Leste
Arafura Sea
Papua New Guinea
Palau
Guam
Christmas Island
Flying Fish Cove
Cocos (Keeling) Islands
Ashmore and Cartier Islands
Timor Sea
US Dept of State Geographer
Image Landsat
© 2013 Mapabc.com
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Imagery Date: 4/10/2013
1°08'23.28" S 119°55'37.54" E elev -593 ft
eye alt 4186.37 mi


Celebes Sea
Pulau Tarakan
East Kalimantan
Borneo
West Kalimantan
Indonesia
Central Kalimantan
Makassar Strait
Gorontalo
North Sulawesi
Gulf of Tomini
Molucca Sea
Sulawesi (Celebes)
South Sulawesi
Gulf of Boni
Java Sea
Banda Sea
Semarang
© 2013 MapIt
© 2013 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Imagery Date: 4/10/2013 1°30'23.23" S 118°50'32.19" E elev -6151 ft eye alt 1009.76 mi

Deltares


Bontang
Samarinda
Balikpapan
Makassar Strait
© 2013 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Imagery Date: 4/10/2013 0°47'52.50" S 117°31'13.50" E elev -2 ft eye alt 201.68 mi

Deltares


Tenggarong
Samarinda City
Samarinda
© 2013 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Imagery Date: 4/10/2013 0°40'38.68" S 117°30'35.69" E elev 33 ft eye alt 67.60 mi
Google earth

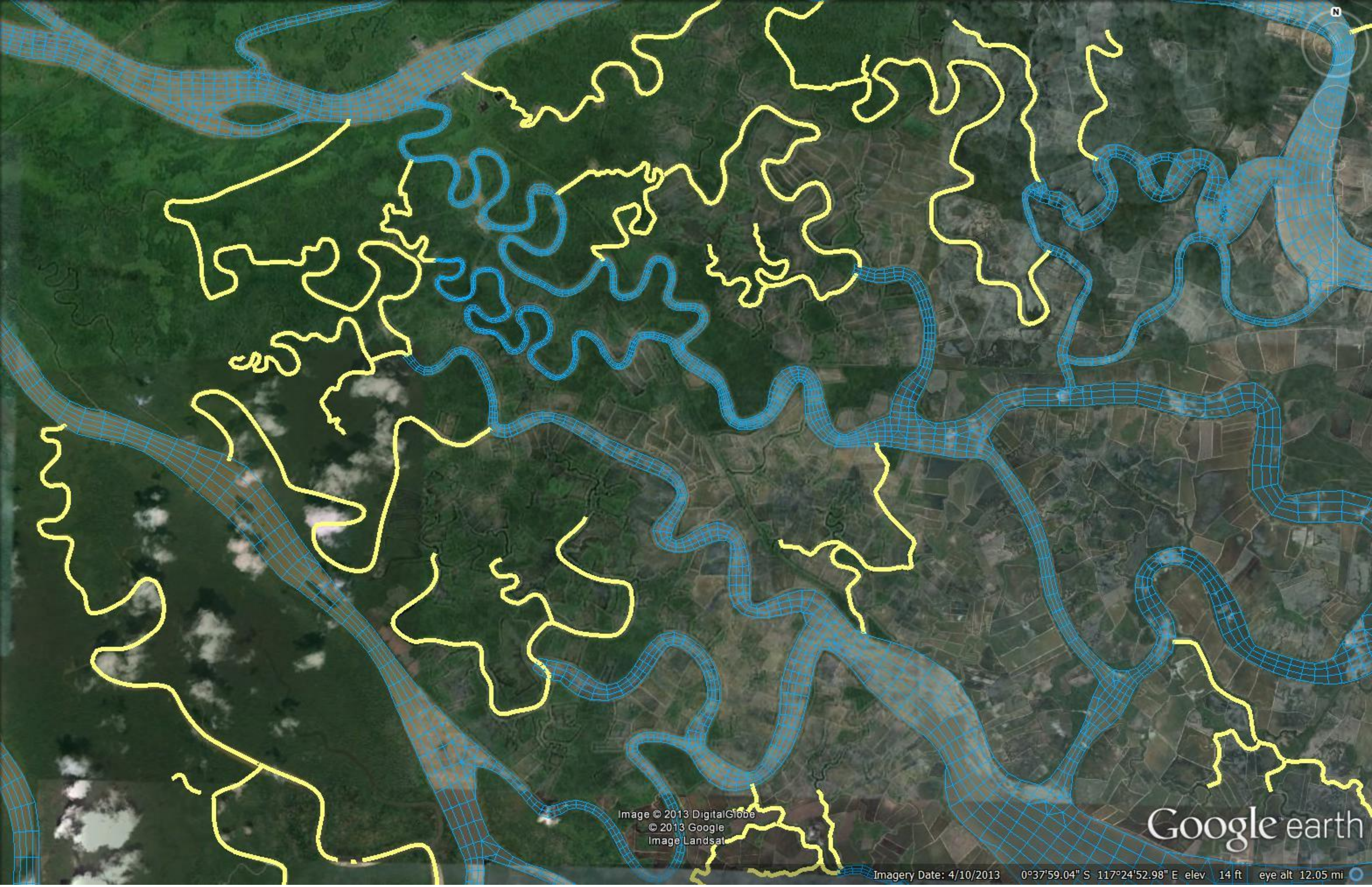


Image © 2013 DigitalGlobe
© 2013 Google
Image Landsat
Google earth
Imagery Date: 4/10/2013 0°37'59.04" S 117°24'52.98" E elev 14 ft eye alt 12.05 mi

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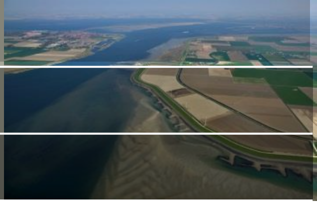
Free surface flows: a niche market

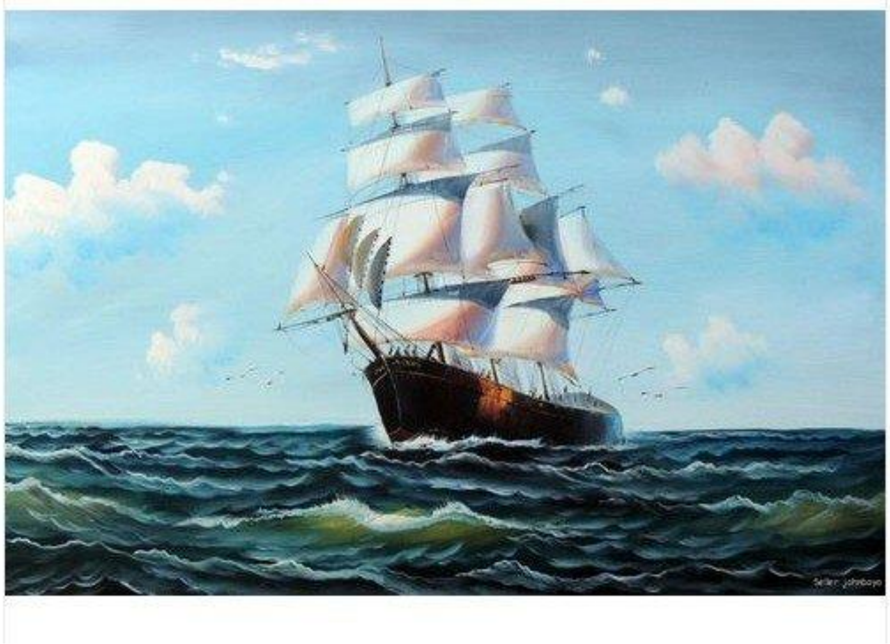


Mostly based upon hydrostatic pressure assumption

Horizontal scale >> Vertical scale

Wave propagation speed may be large

Flow speed and Wave speed, depth 5 km



0-2 m/s => Advection maybe explicit

221 m/s => Pressures allways implicit

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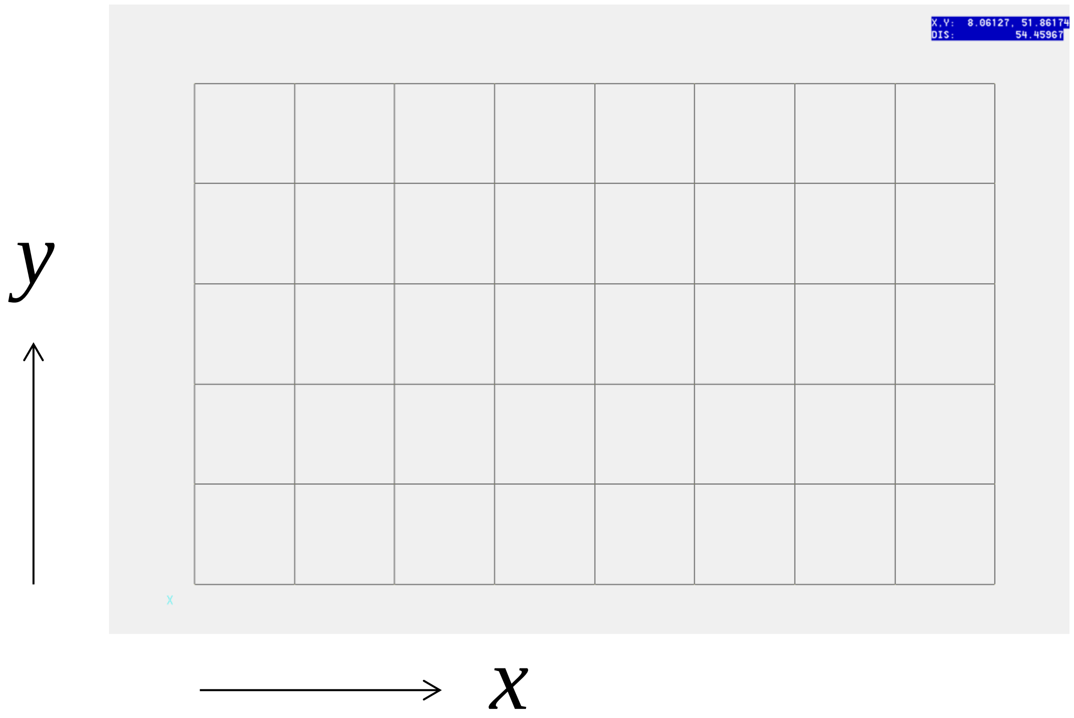
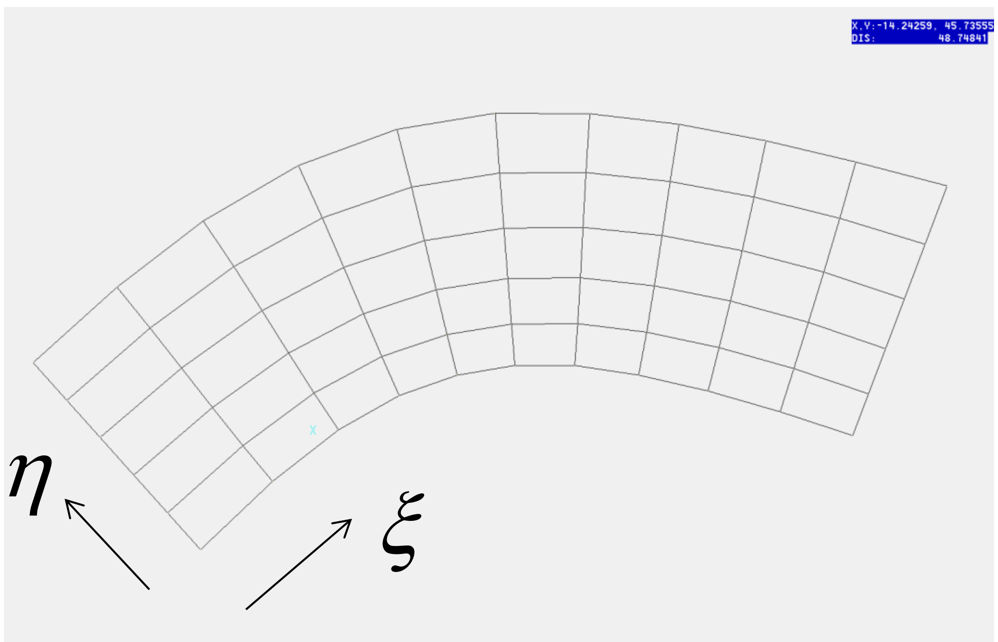
Advection & pressure rectilinear coordinates

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + g\frac{\partial \zeta}{\partial x} .. =$$



Momentum equation orthogonal curvilinear coor.

$$\frac{\partial U}{\partial t}+\frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial U}{\partial \xi}+\frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial U}{\partial \eta}+\frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta}-\frac{VV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi}+\frac{g}{\sqrt{G_{\xi\xi}}}\frac{\partial \zeta}{\partial \xi}..=$$



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Momentum equation non orthogonal coordinates

$$
\frac{\partial U}{\partial t} + V^2 \left(\frac{\sqrt{G_{\eta\eta}}}{J} \right)_\xi + \left(\frac{\sqrt{G_{\xi\xi}}}{\sqrt{G_{\eta\eta}}} \right) UV \left(\frac{\sqrt{G_{\xi\xi}}}{J} \right)_\eta
$$

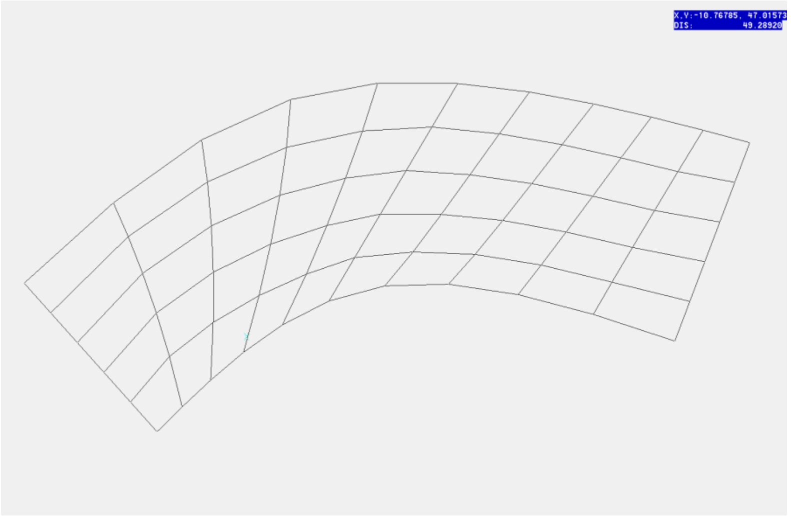
$$
+ \frac{1}{J^2} \left(+ \sqrt{G_{\eta\eta}}\, y_\eta U \frac{\partial \left[x_\xi U \right]}{\partial \xi} + \sqrt{G_{\xi\xi}}\, y_\eta V \frac{\partial \left[x_\xi U \right]}{\partial \eta} \right)
$$

$$
+ \frac{1}{J^2} \left(+ \sqrt{G_{\xi\xi}}\, y_\eta U \frac{\partial \left[x_\eta V \right]}{\partial \xi} + \frac{G_{\xi\xi}}{\sqrt{G_{\eta\eta}}} y_\eta V \frac{\partial \left[x_\eta V \right]}{\partial \eta} \right)
$$

$$
+ \frac{1}{J^2} \left(- \sqrt{G_{\eta\eta}}\, x_\eta U \frac{\partial \left[y_\xi U \right]}{\partial \xi} - \sqrt{G_{\xi\xi}}\, x_\eta V \frac{\partial \left[y_\xi U \right]}{\partial \eta} \right)
$$

$$
+ \frac{1}{J^2} \left(- \sqrt{G_{\xi\xi}}\, x_\eta U \frac{\partial \left[y_\eta V \right]}{\partial \xi} - \frac{G_{\xi\xi}}{\sqrt{G_{\eta\eta}}} x_\eta V \frac{\partial \left[y_\eta V \right]}{\partial \eta} \right) + \ldots =
$$

$$
+ \frac{g}{J} \left(\sqrt{G_{\eta\eta}} \frac{\partial \zeta}{\partial \xi} - \frac{\left(x_\xi x_\eta + y_\xi y_\eta \right)}{\sqrt{G_{\eta\eta}}} \frac{\partial \zeta}{\partial \eta} \right)
$$



$$
J = x_\xi y_\eta - y_\xi x_\eta
$$

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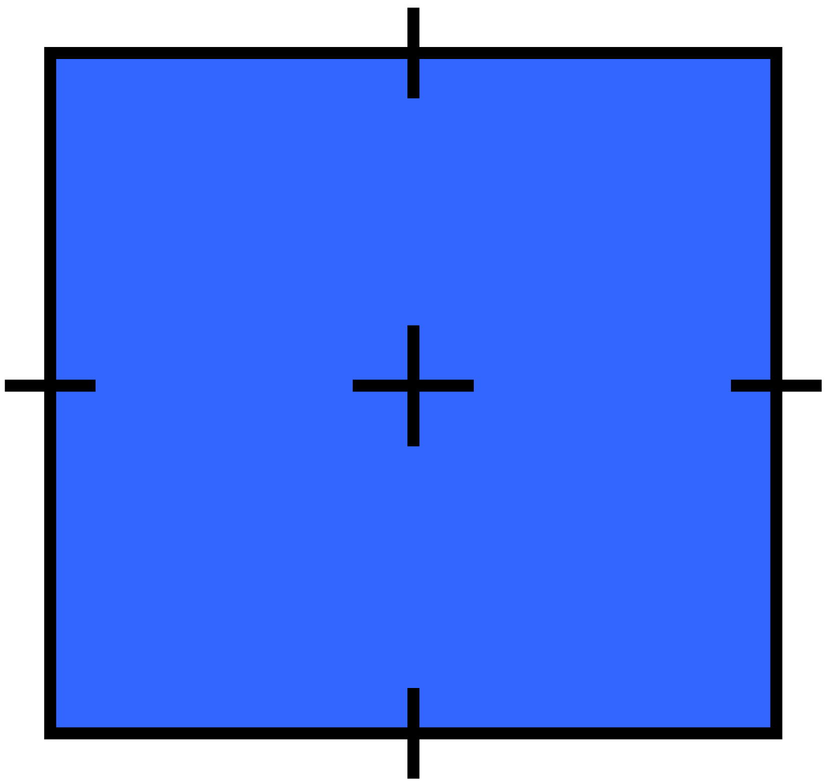
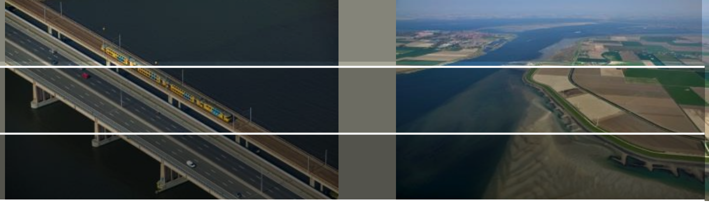
Staggered approach



Pressures / concentrations in cell centres

Velocities at cell faces



Finite volume approach

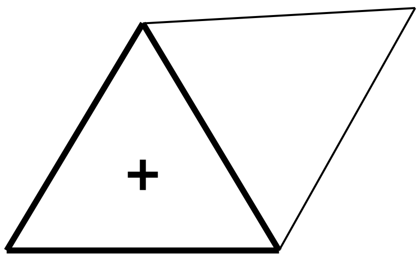
Conservation of:

$$\frac{\partial V}{\partial t} = \sum_{in\zeta} Q - \sum_{out\zeta} Q$$

Volume

$$\frac{\partial Vc}{\partial t} = \sum_{in\zeta} Qc_{in} - \sum_{out\zeta} Qc_{out}$$

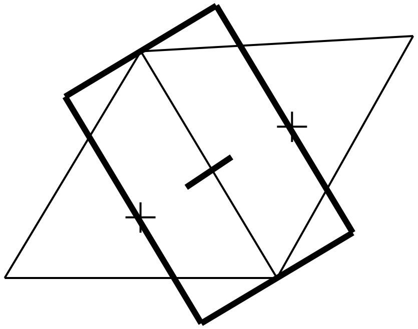
Mass



Cell center

$$\frac{\partial V_u \rho u}{\partial t} = \sum_{inu} Q\rho_{in}u_{in} - \sum_{outu} Q\rho_{out}u_{out} + \sum F_u$$

Momentum



Cell face

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Time integration 2D, teta scheme

$$\frac{u^{n+1}-u^{n}}{\Delta t}+\frac{g}{\Delta x}\left\{\theta\left(\zeta_2^{n+1}-\zeta_1^{n+1}\right)+\left(1-\theta\right)\left(\zeta_2^{n}-\zeta_1^{n}\right)\right\}+bu^{n+1}=d$$

Acceleration + pressure + bedfriction = -advection

Rewrite as: $u^{n+1}=R_u+F_u\left(\zeta_2^{n+1}-\zeta_1^{n+1}\right)$

Substitue in: $A_\zeta\frac{\zeta^{n+1}-\zeta^{n}}{\Delta t}+\theta\left(A_{u2}u_2^{n+1}-A_{u1}u_1^{n+1}\right)+\left(1-\theta\right)\left(A_{u2}u_2^{n}-A_{u1}u_1^{n}\right)=Q_\zeta$

Solve sparse pressure matrix.

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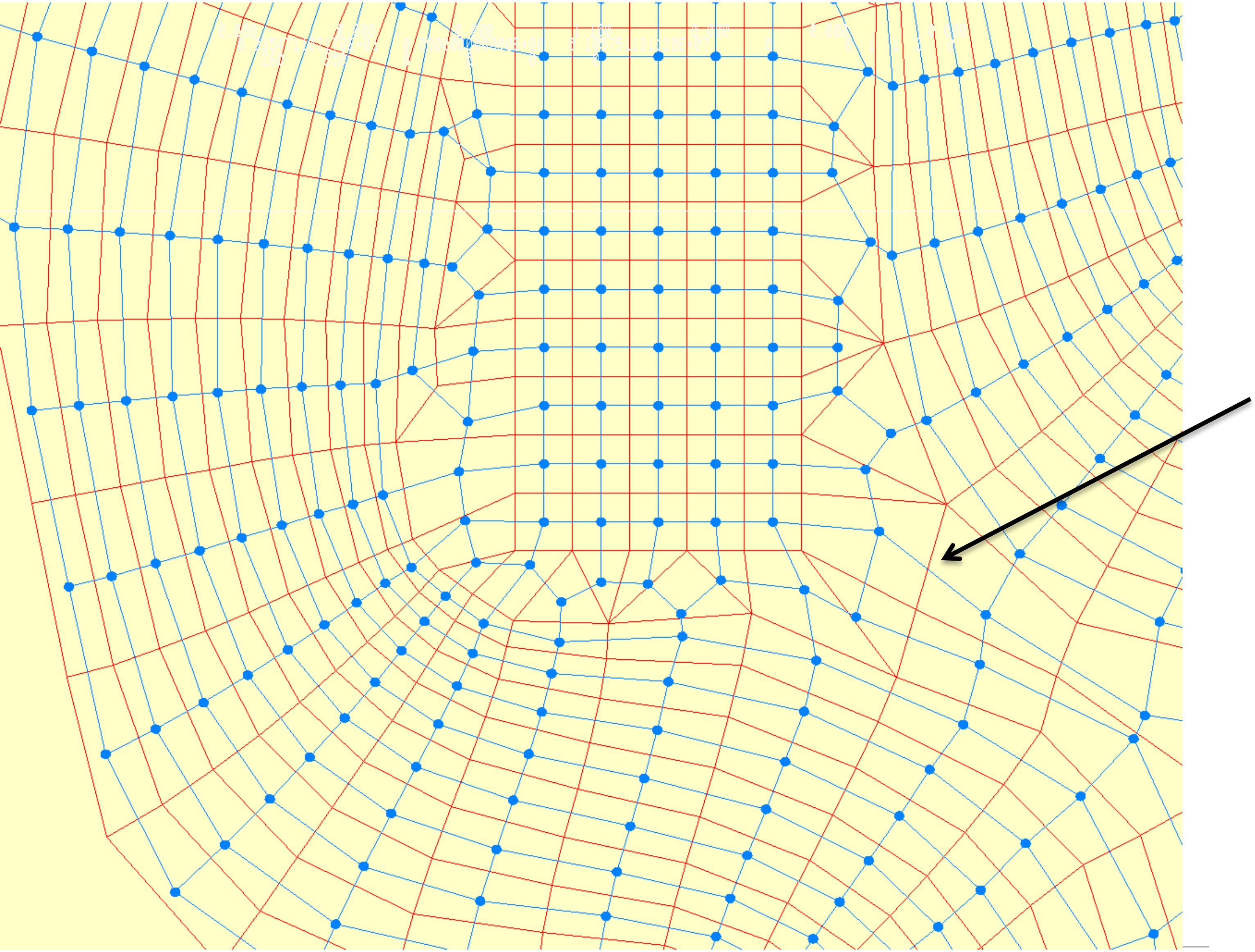
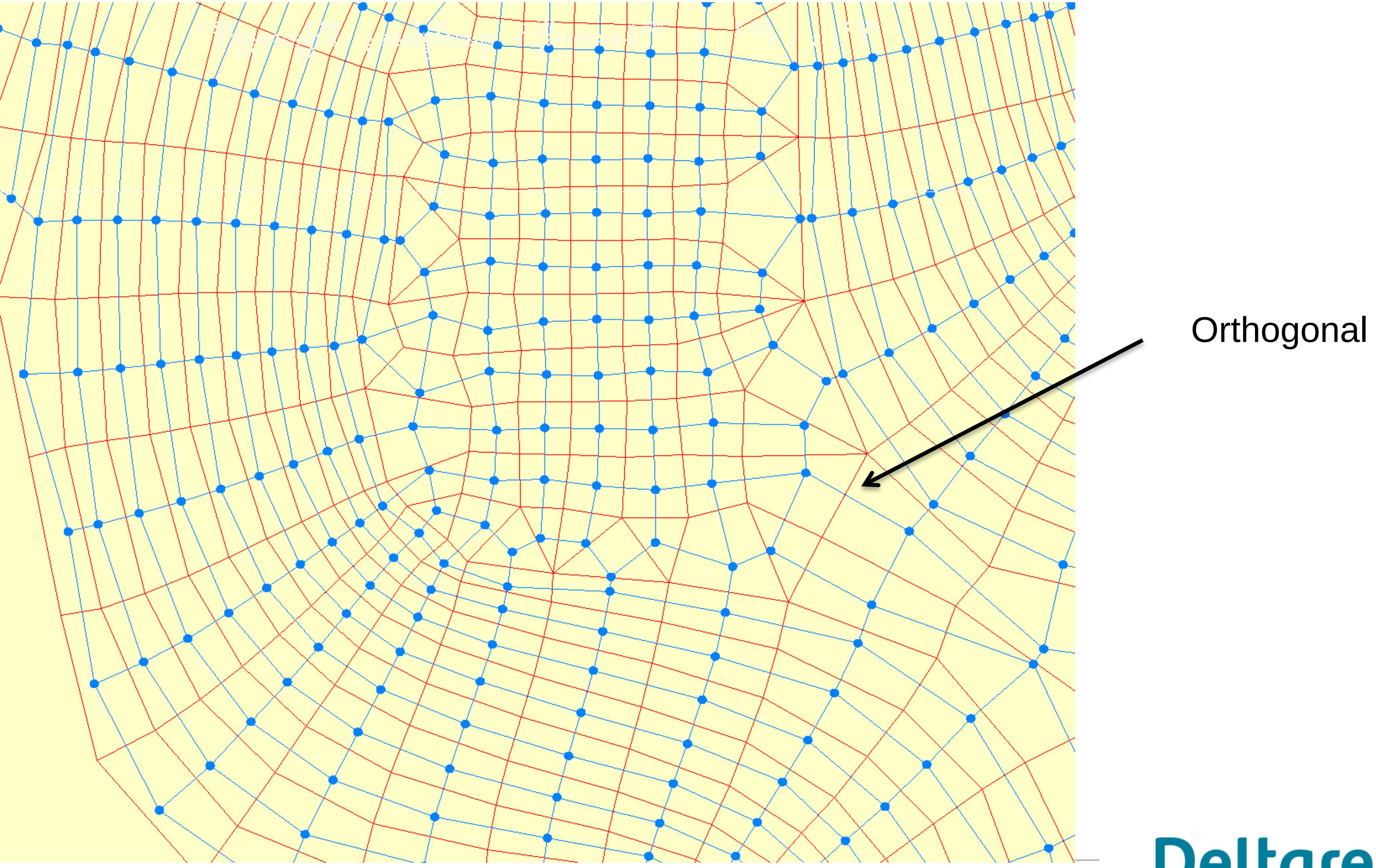
Not Orthogonal



Orthogonal !



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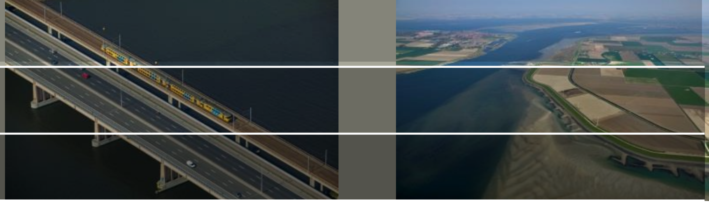
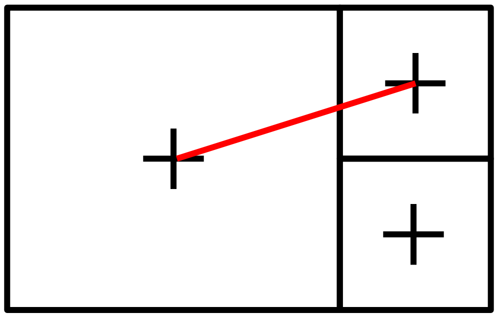
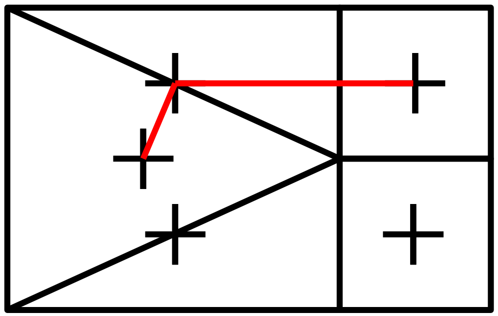


Orthogonal grid refinement

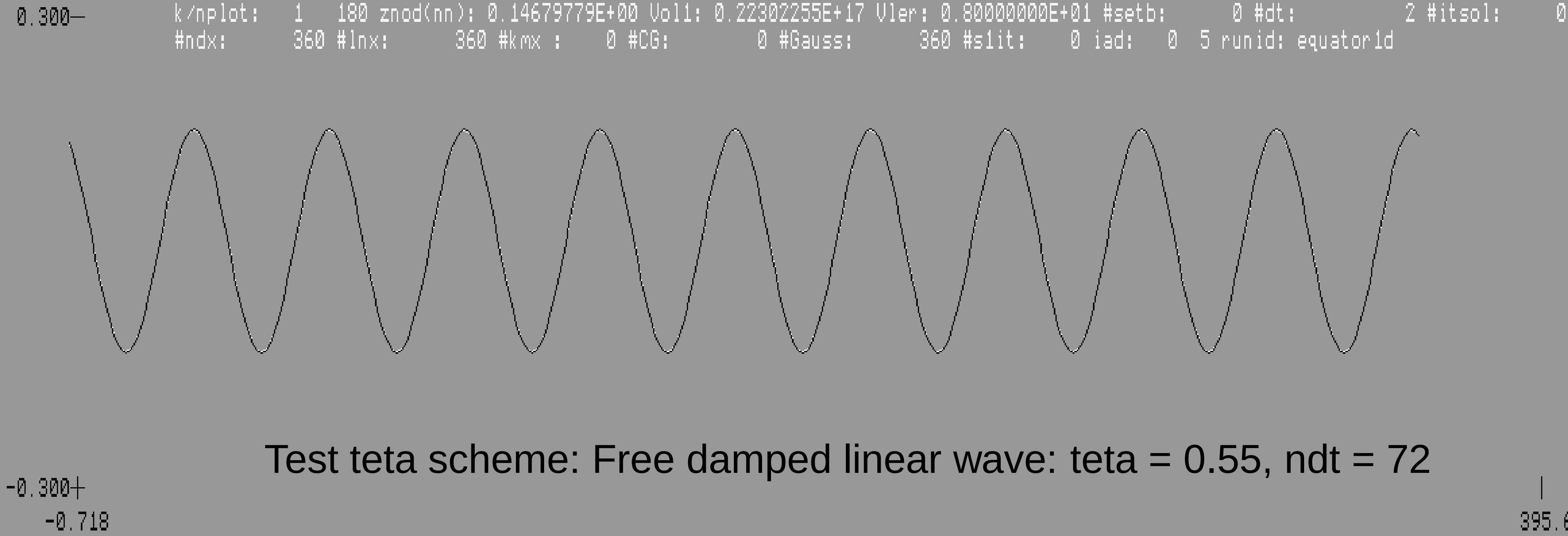


Non orthogonal



Orthogonal

19920831_002000 dt: 600.000 Avg.dt:600.000 CPU/step: 0.000 Tot: 0.0 Sol/Rest:.00E+00 Samer: 0.00000000E+00 Samtot:0.00000000E+0
k/nplot: 1 180 znod(nn): 0.14679779E+00 Vol1: 0.22302255E+17 Vler: 0.80000000E+01 #setb: 0 #dt: 2 #itsol: 0
#ndx: 360 #lnx: 360 #kmx : 0 #CG: 0 #Gauss: 360 #slit: 0 iad: 0 5 runid: equator1d



Test teta scheme: Free damped linear wave: teta = 0.55, ndt = 72

Forced amplitude = 0.000000 (m), ndx = 36 , ndt = 72, cfl = 0.500019

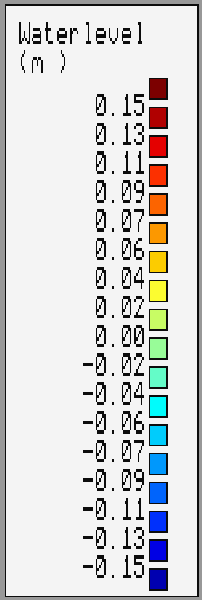
Free amplitude = 0.149214 (m), ndx = 36 , ndt = 30, cfl = 1.193663

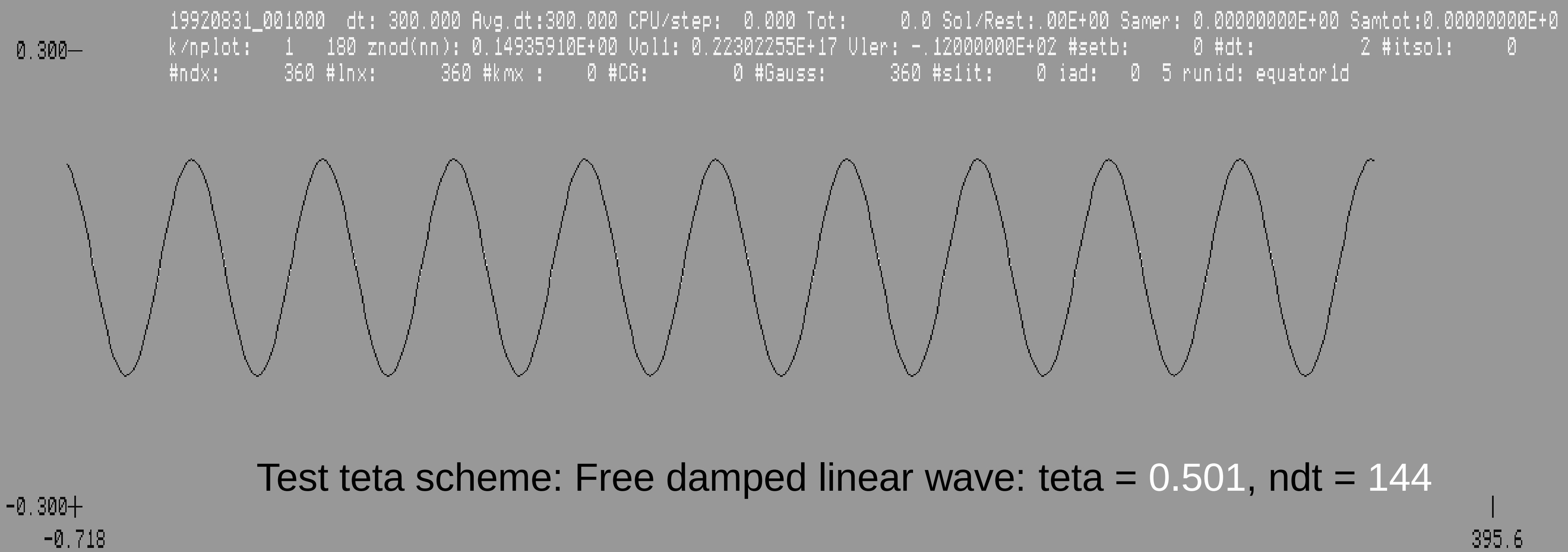
Total amplitude = 0.149214 (m)

Computed amplitude = 0.148455 (m), comp/analytic= 0.995

Teta = 0.55000 , Manlin = 4.00000 , Umod = 0.00477

Nforced = 0.03 , Nfree = 0.07 , Dept = 5000.00





Test teta scheme: Free damped linear wave: teta = 0.501, ndt = 144

Forced amplitude = 0.000000 (m), ndx = 36 , ndt = 144, cfl = 0.250010

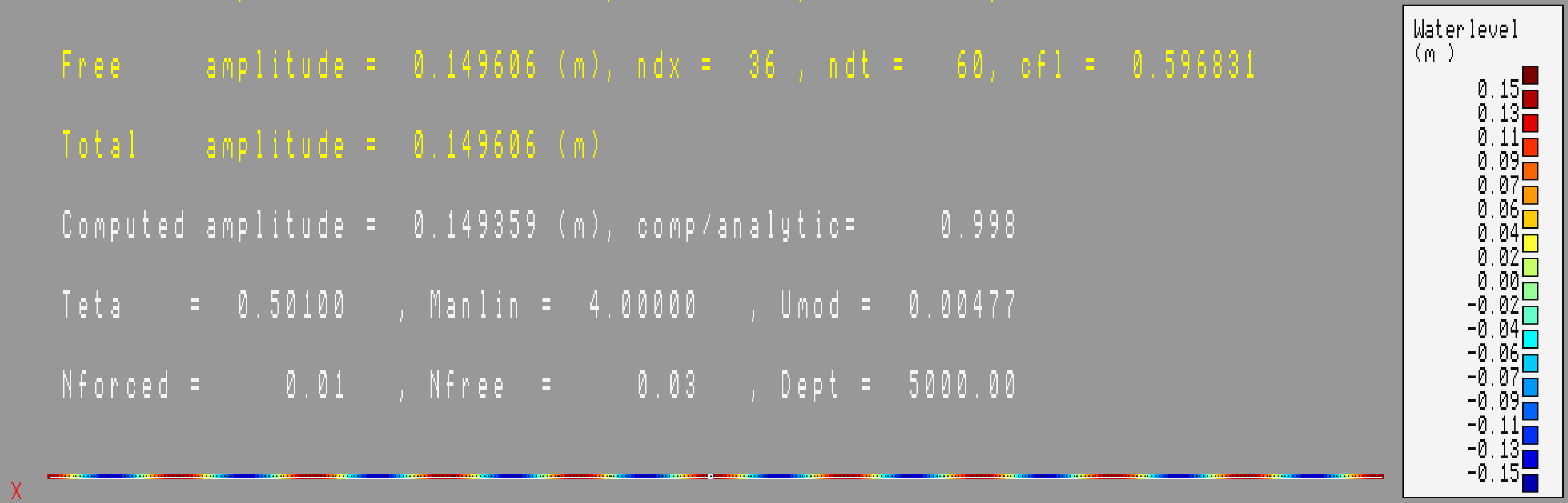
Free amplitude = 0.149606 (m), ndx = 36 , ndt = 60, cfl = 0.596831

Total amplitude = 0.149606 (m)

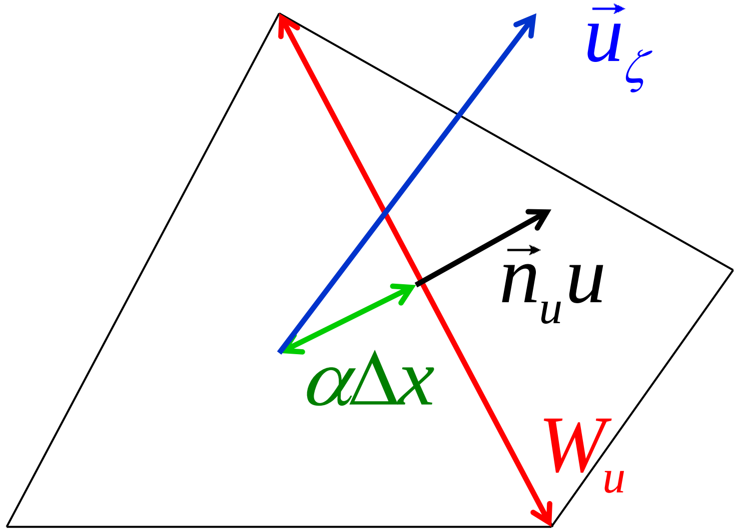
Computed amplitude = 0.149359 (m), comp/analytic= 0.998

Teta = 0.50100 , Manlin = 4.00000 , Umod = 0.00477

Nforced = 0.01 , Nfree = 0.03 , Dept = 5000.00



Faces to center and centers to face



$$\overrightarrow{u_\zeta} = \frac{1}{A_\zeta} \sum^{faces} \alpha \Delta x W_u \overrightarrow{n_u u}$$

$$V_u = \alpha V_L + (1 - \alpha) V_R$$

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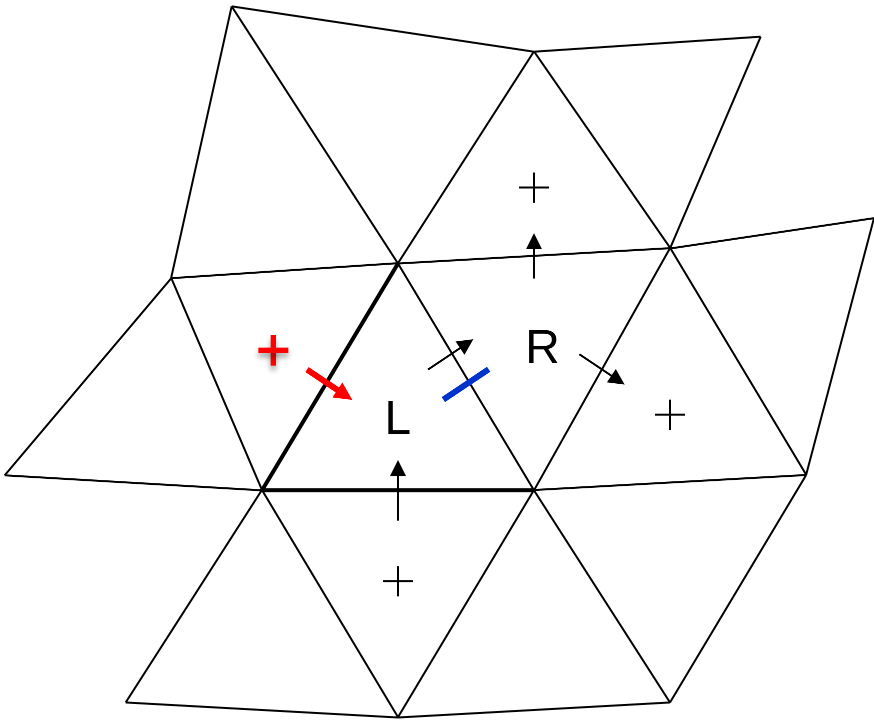
Momentum advection ~ Kramer Stelling

Advection term gets contributions assembled at Left and Right nodes

$$\frac{1}{V_u}\left\{\begin{array}{l} \alpha \left(\sum\limits_{inL} Q(u_{in}-u)-\sum\limits_{outL} Q(u_{out}-u)\right)+ \\ (1-\alpha)\left(\sum\limits_{inR} Q(u_{in}-u)-\sum\limits_{outR} Q(u_{out}-u)\right) \end{array}\right\}$$

$$V_u = \alpha V_L + (1-\alpha)V_R$$

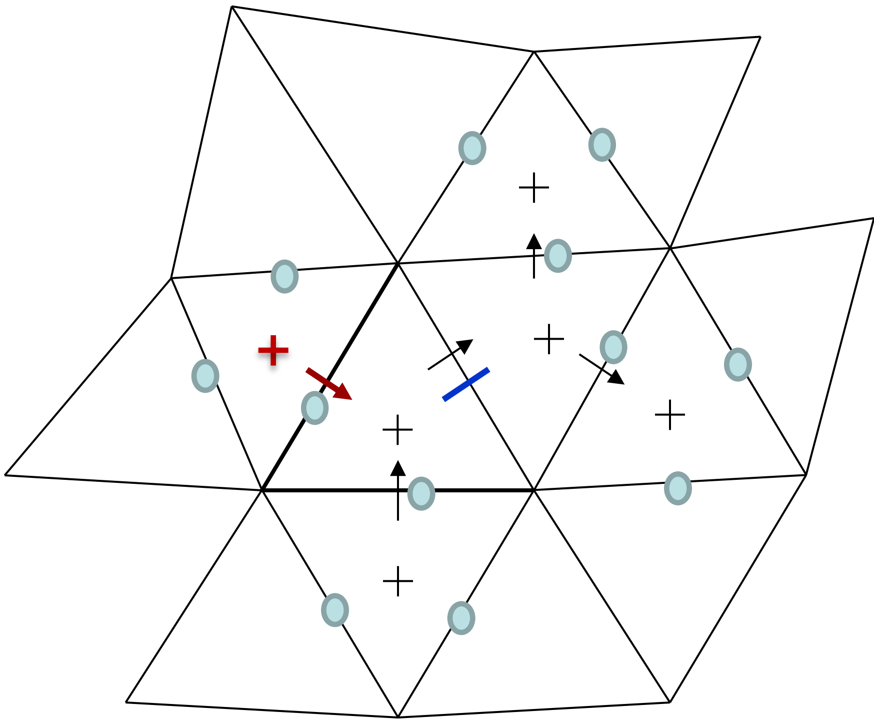


Momentum advection

Velocity points involved in first order

$$\frac{1}{V_u}\left\{\begin{array}{l}\alpha\left(\sum_{inL} Q(u_{in}-u)-\sum_{outL} Q(u_{out}-u)\right)+\\(1-\alpha)\left(\sum_{inR} Q(u_{in}-u)-\sum_{outR} Q(u_{out}-u)\right)\end{array}\right\}$$

$$V_u=\alpha V_L+(1-\alpha)V_R$$



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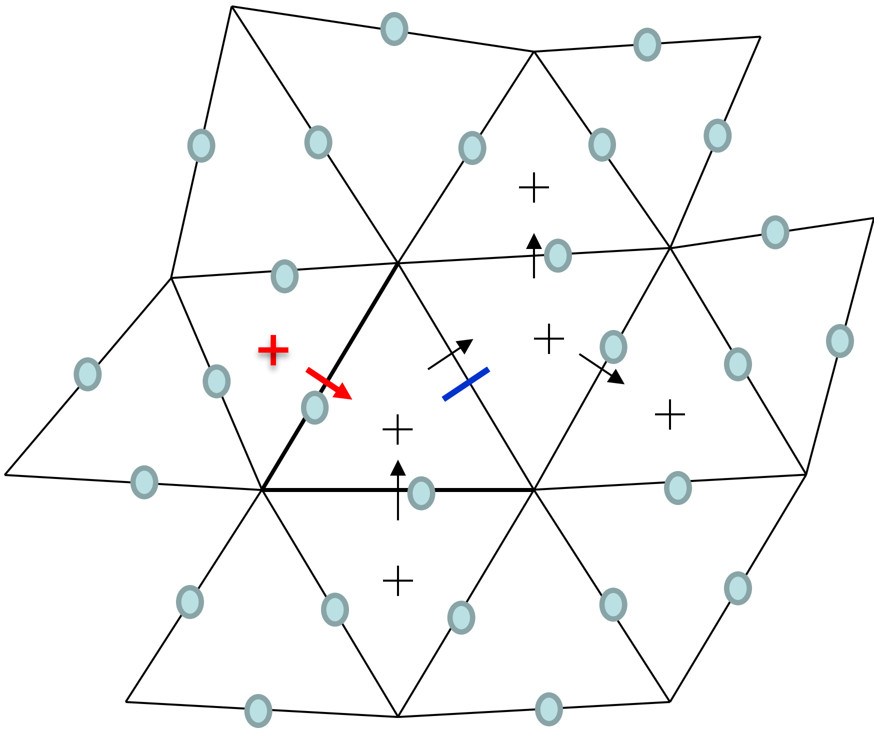
Momentum advection

Velocity points involved in limited higher order

$$\frac{1}{V_u}\left\{\begin{array}{l}\alpha\left(\sum_{inL} Q(u_{in}-u)-\sum_{outL} Q(u_{out}-u)\right)+\\(1-\alpha)\left(\sum_{inR} Q(u_{in}-u)-\sum_{outR} Q(u_{out}-u)\right)\end{array}\right\}$$

$$V_u=\alpha V_L+(1-\alpha)V_R$$



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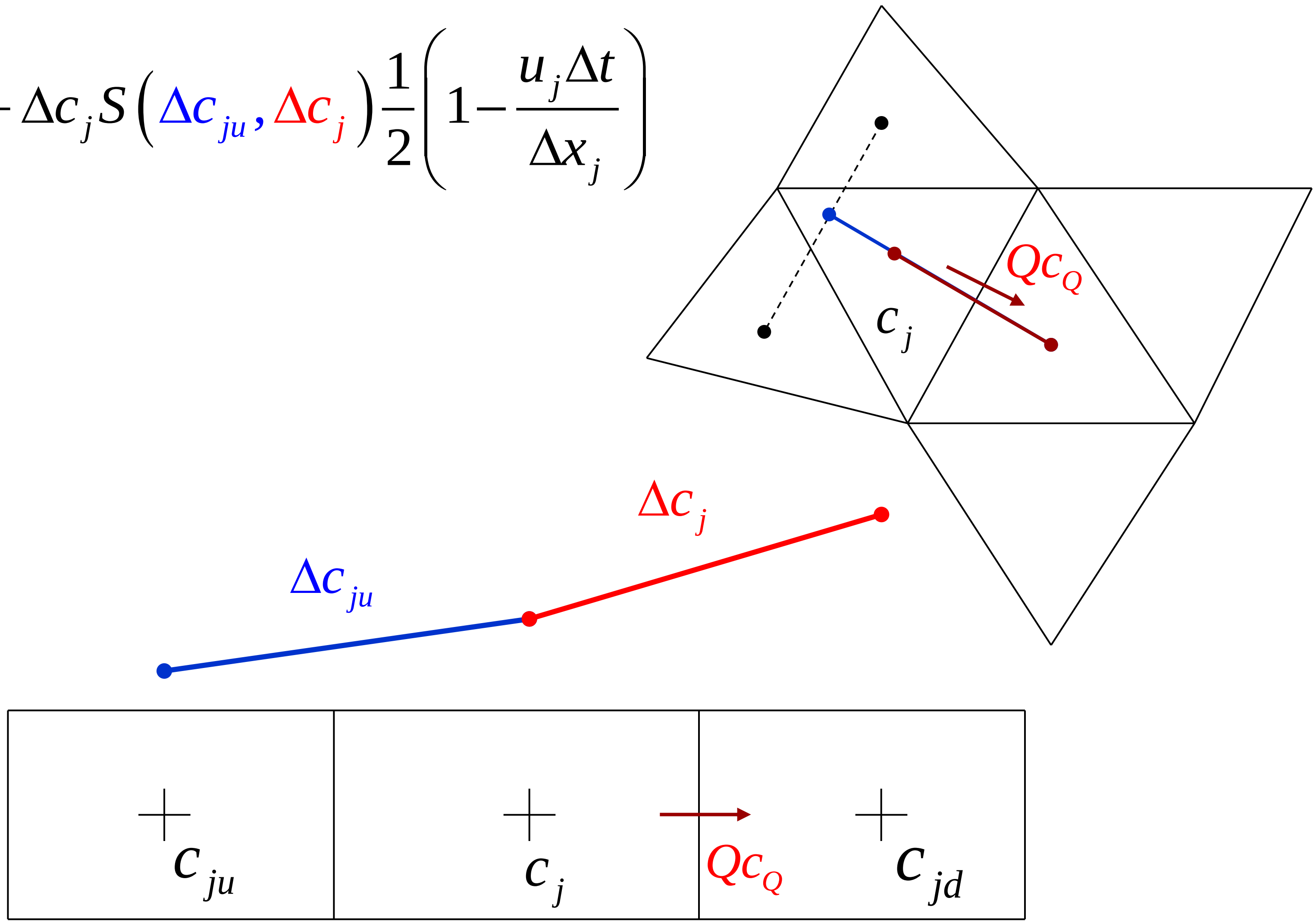
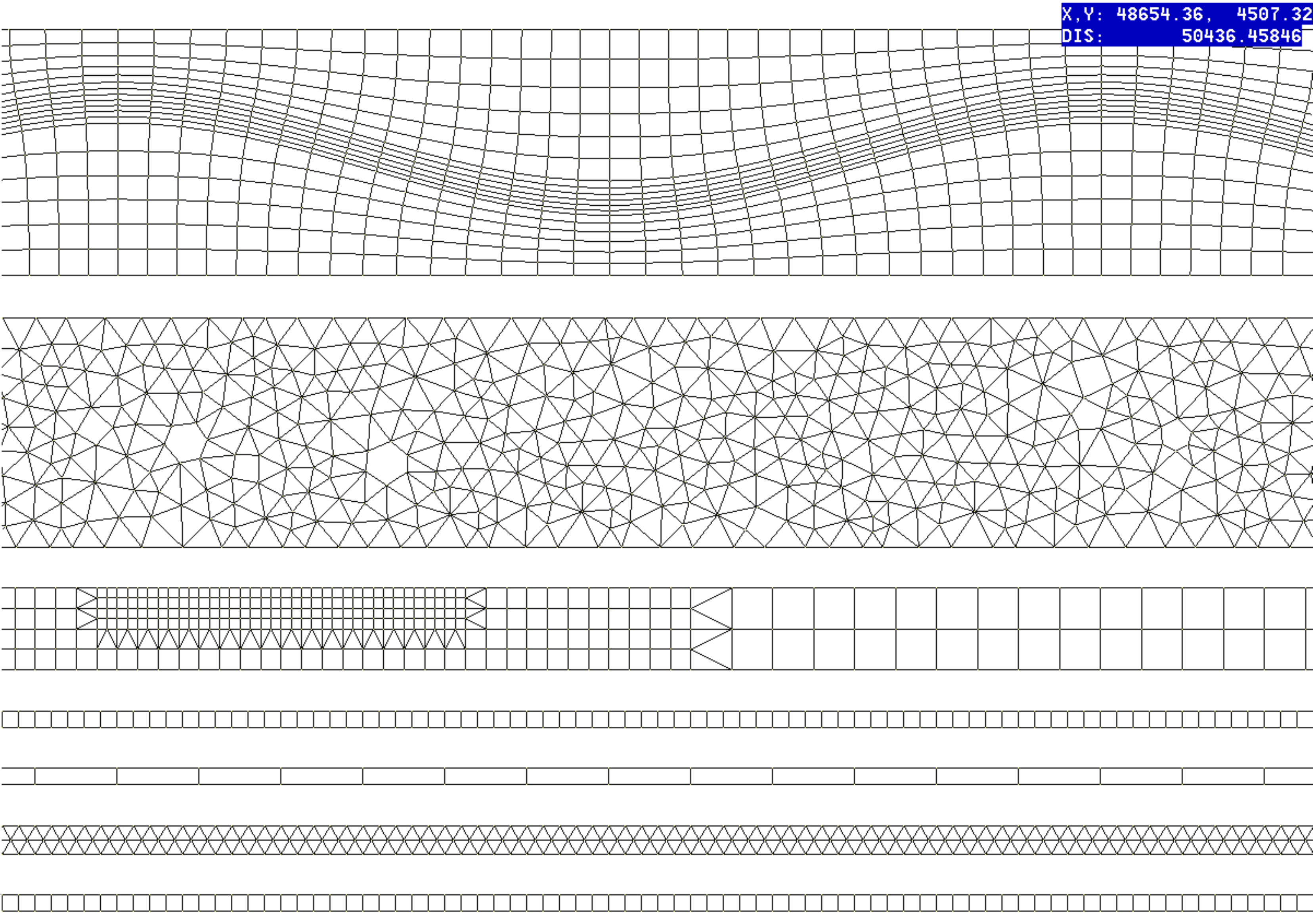
Higher order slope limiter

$$c_Q = c_j + \Delta c_j S\left(\Delta c_{ju}, \Delta c_j\right)\frac{1}{2}\left(1 - \frac{u_j \Delta t}{\Delta x_j}\right)$$

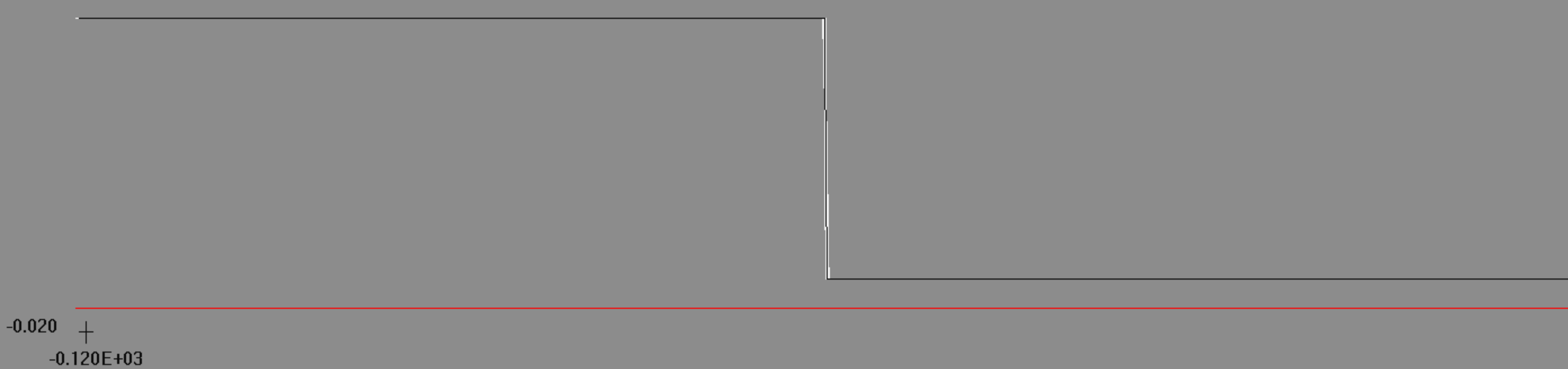


Dambreak test grids



20061225_000000 dt: 1.000 Avg.dt: 1.000 CPU/step: 0.000 Tot: 0.0 Sol/Rest:.00E+00 Samer: 0.00000000E+00 Samtot:0.0000
k/nplot: 1 7849 znod(nn): 0.20000000E+01 Vol1: 0.00000000E+00 Vler: 0.00000000E+00 #setb: 0 #dt: 0 #itsol:
#ndx: 15698 #lnx: 24619 #kmx : 0 #CG: 4670 #Gauss: 11028 #slit: 0 iad: 34 5 runid: wetbed

2D

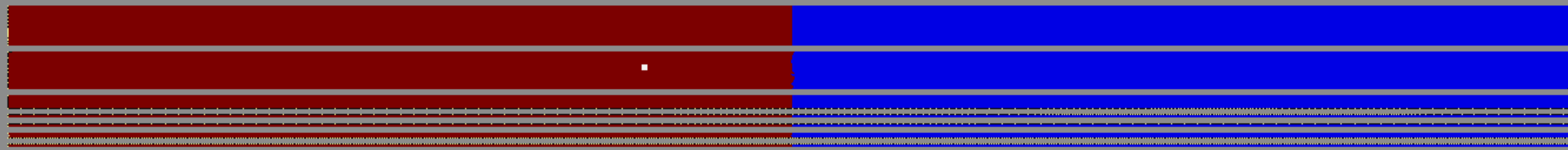


Ave Difference (m) = 0.0004

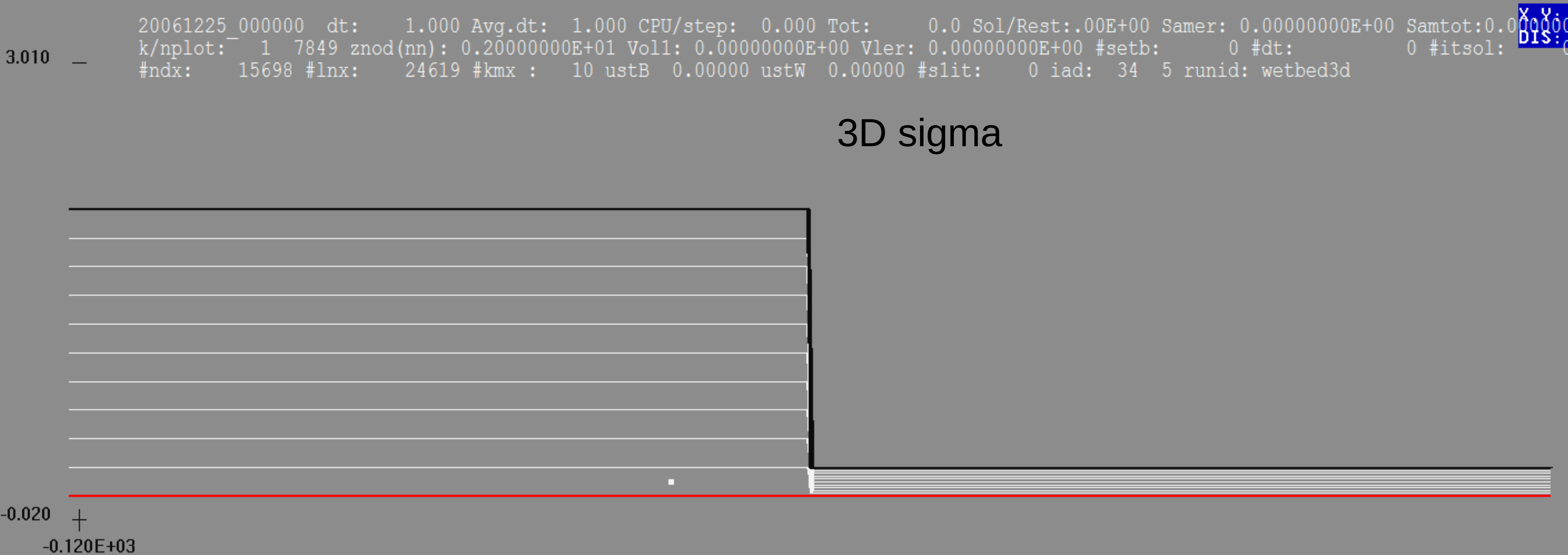
Rms Difference (m) = 0.0169

Max Difference (m) = 0.9419

Cum Difference (m) = 0.0004



3D sigma

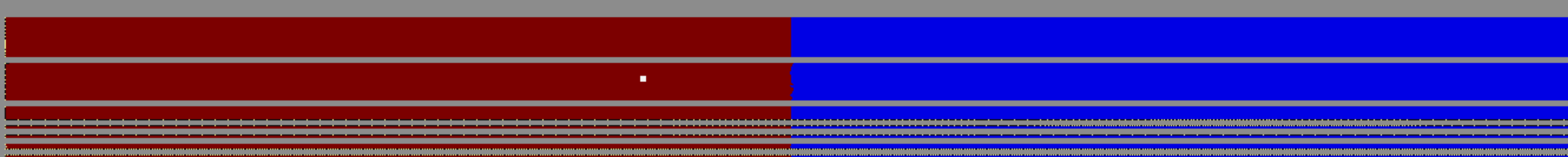


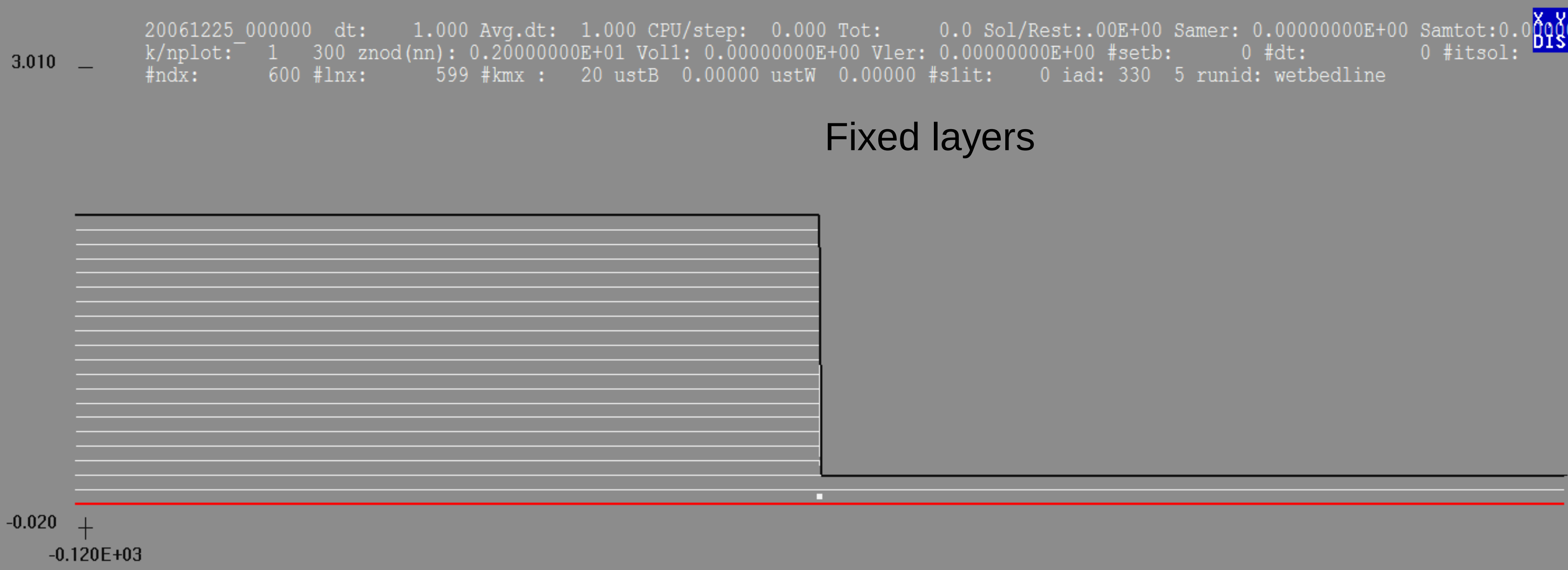
Ave Difference (m) = 0.0004

Rms Difference (m) = 0.0169

Max Difference (m) = 0.9419

Cum Difference (m) = 0.0004





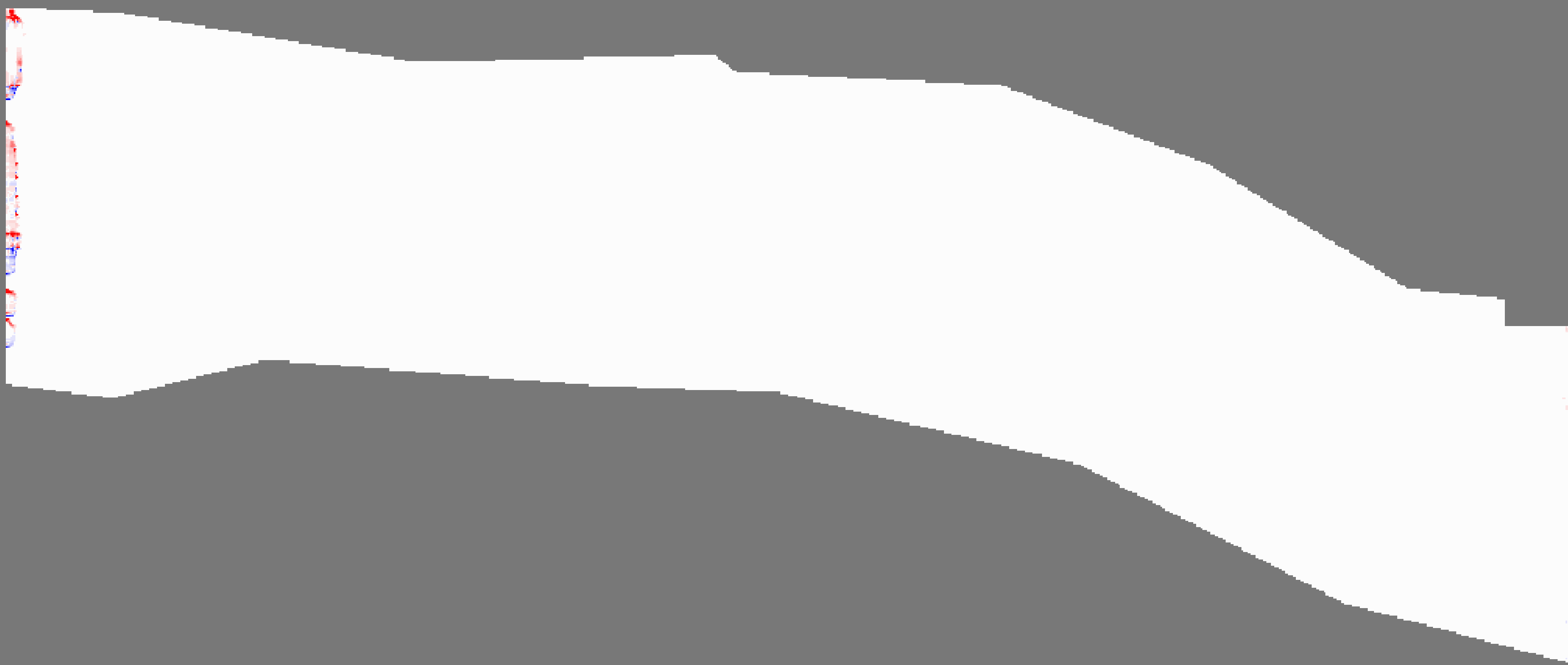
Ave Difference (m) = 0.0000

Rms Difference (m) = 0.0000

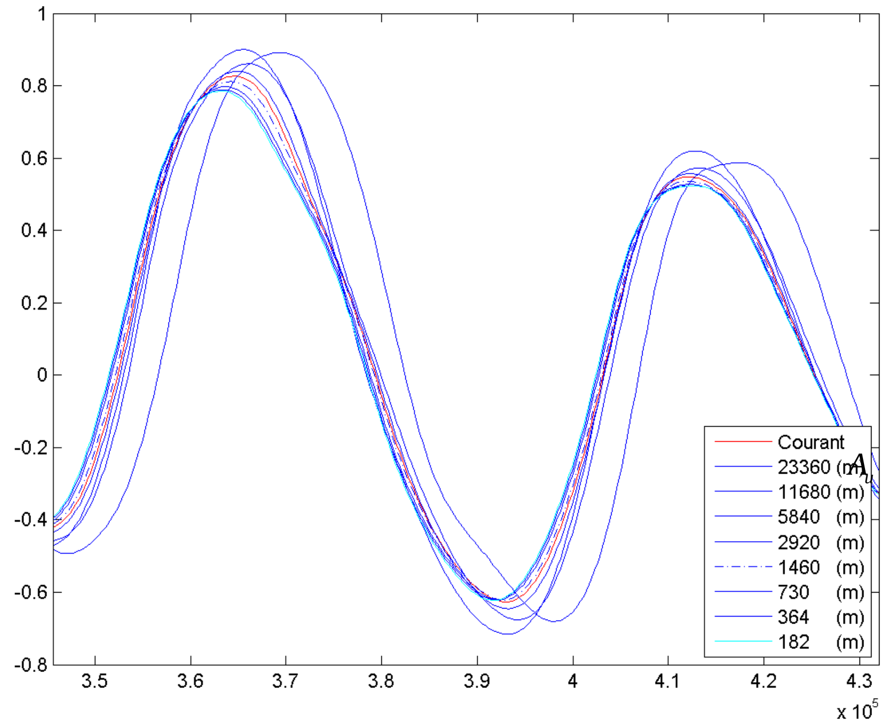
Max Difference (m) = 0.0000

Cum Difference (m) = 0.0000

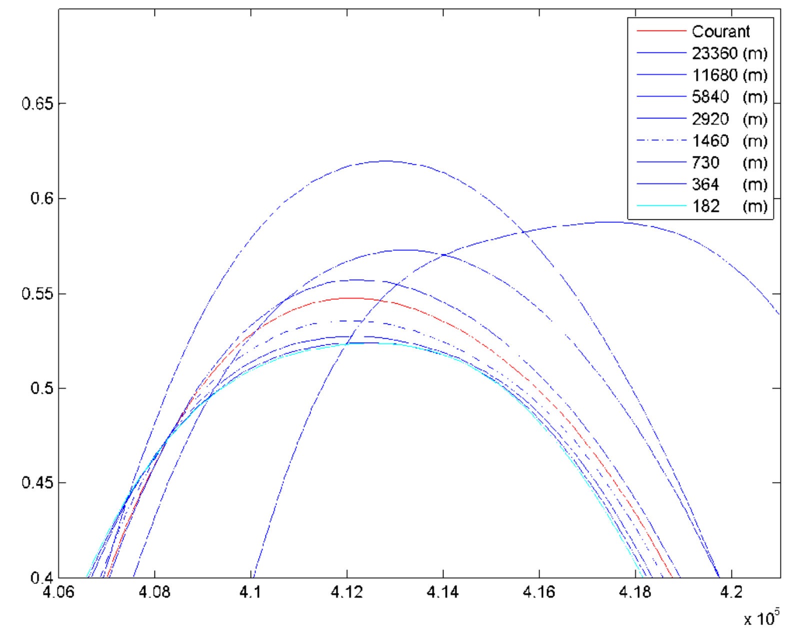
Time S/H/D: 4.000 0.001 0.000 dt: 0.133 Avg.dt: 0.444 CPU/step: 0.047 Tot: 0.3 Sol/Rest: 0.046
k/nplot: 1 100 znod(nn) -999.000000 Vol1: 0.32815816E+06 Vler: -.80945028E-10 #setb: 0 #dt: 8 #itsol: 9
#CG: 9367 #Gauss: 8213 #expl: 0 #wet: 17580 #chkadvd: 789 #nodneg: 0 #slit: 0

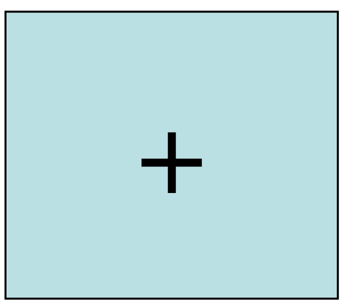


Spatial convergence cell centre bathymetry



$A_u =$





Face area ~ maximum level of adjacent centers

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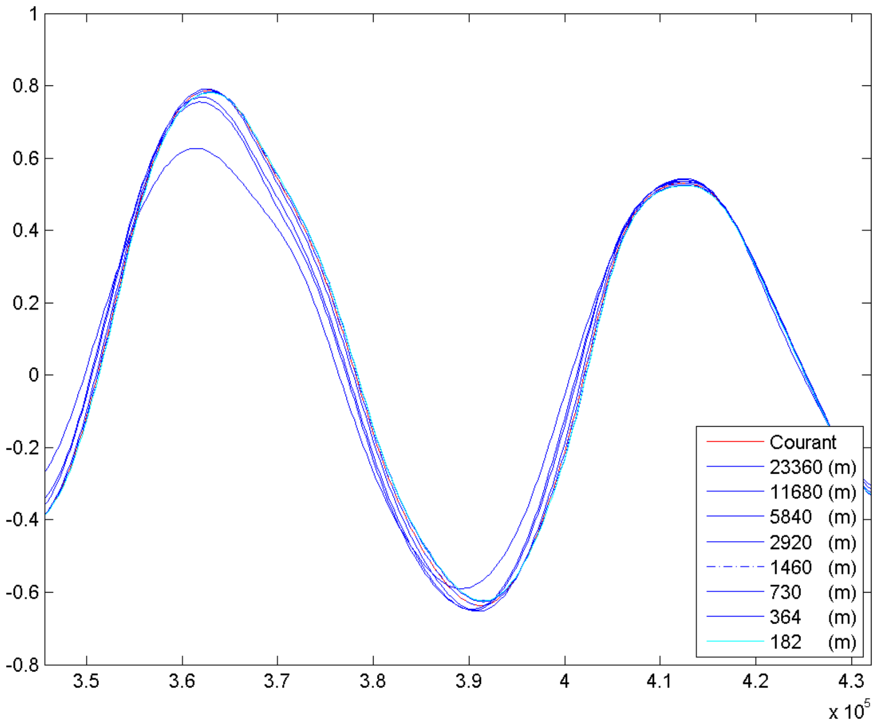
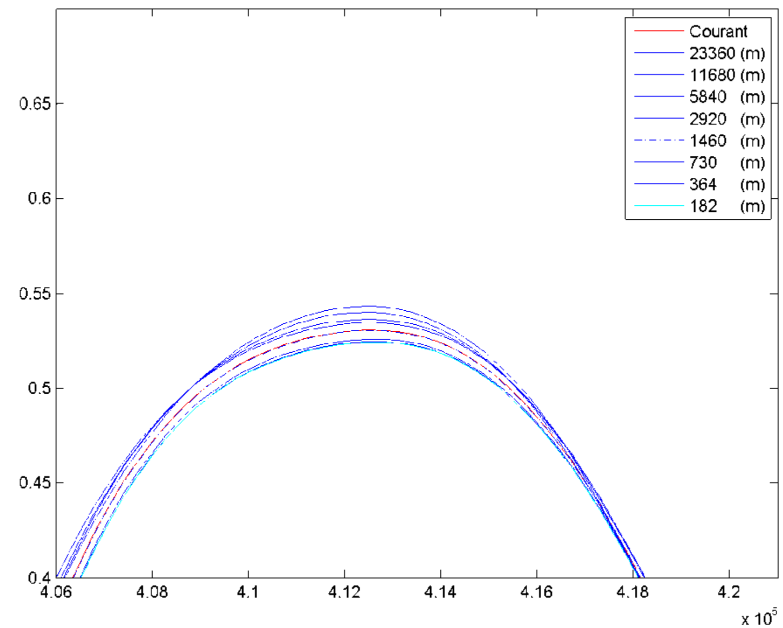
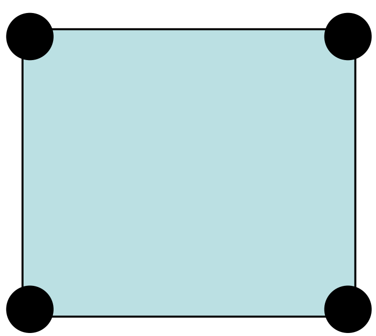
Spatial convergence cell corner bathymetry

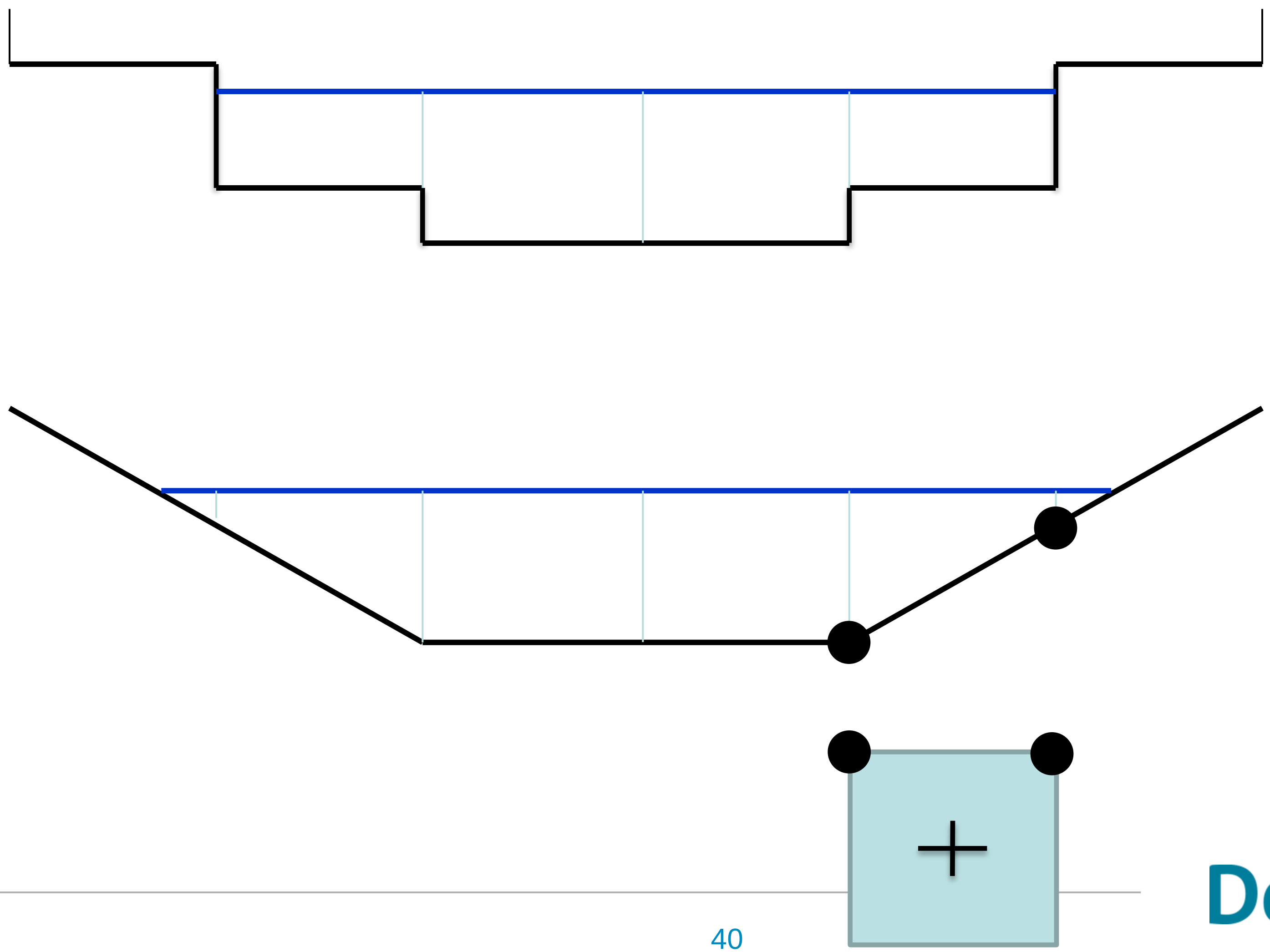


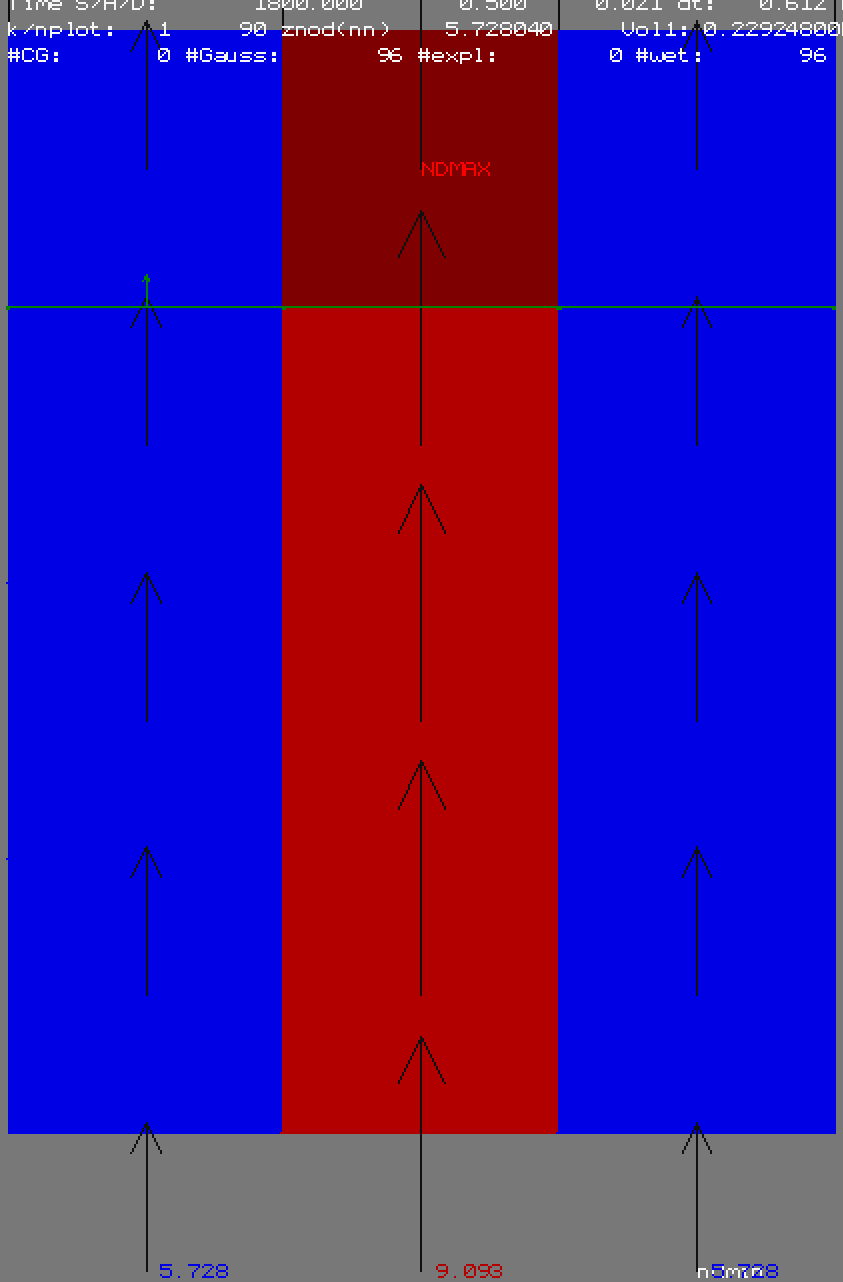




Face area ~ average level of adjacent corners peak flows ~ 6 m/s

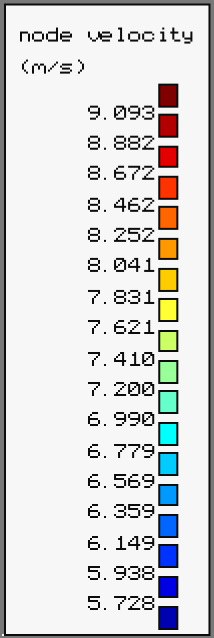
Continuous wet area => more gradual drying&flooding



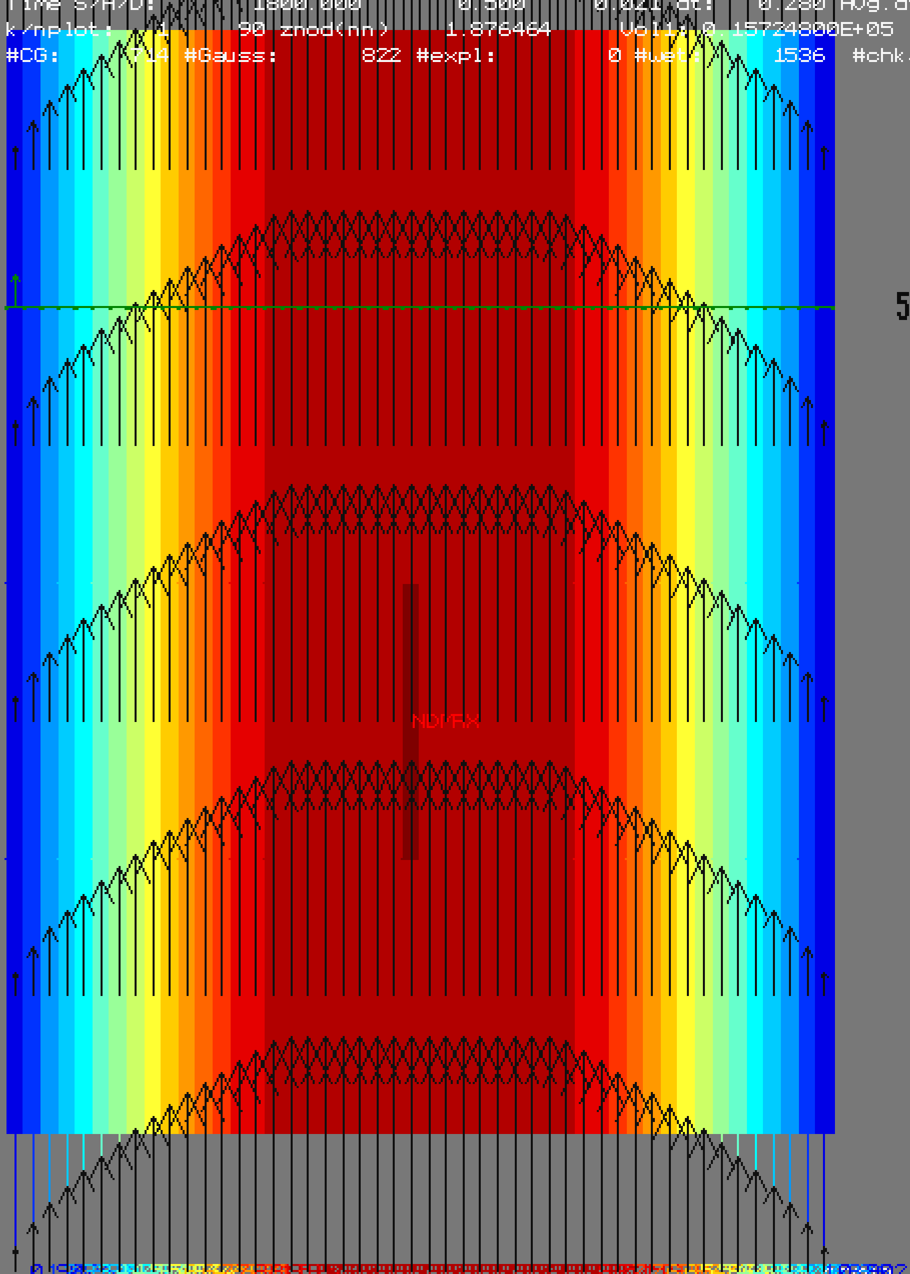


474.264 m3/s

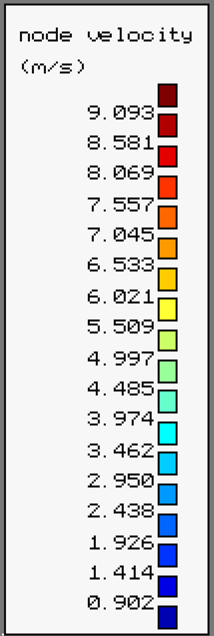
3 cells



Regular 2D bottom friction approach



48 cells
Q=509 m3/s



Subgrid: Analytic Conveyance approach

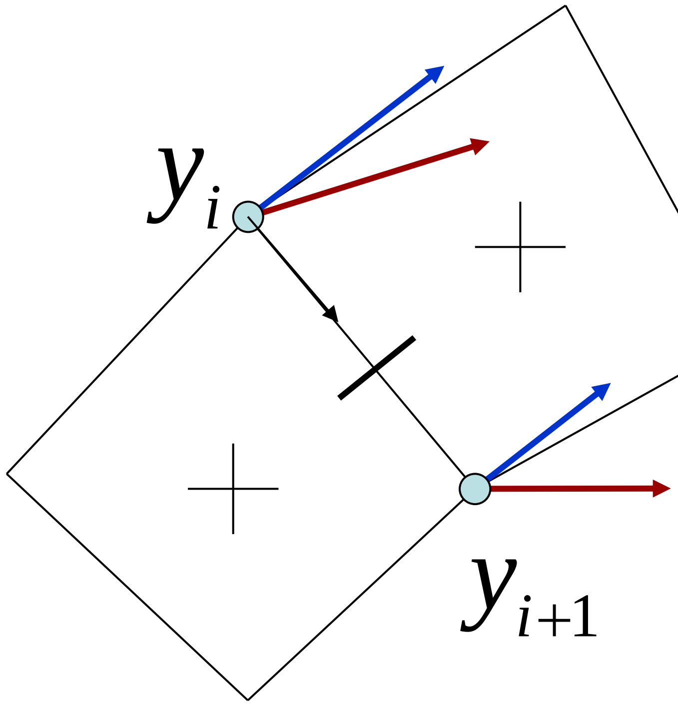
$$friction term: \frac{uU}{HC^2}$$

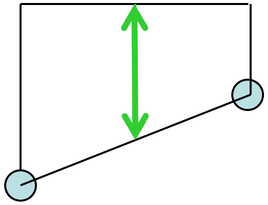
$$u = f(y)$$

$$U = g(y)$$

$$\mathrm{H} = \mathrm{h(y)}$$

$$\mathrm{C} = \mathrm{i(y)}$$

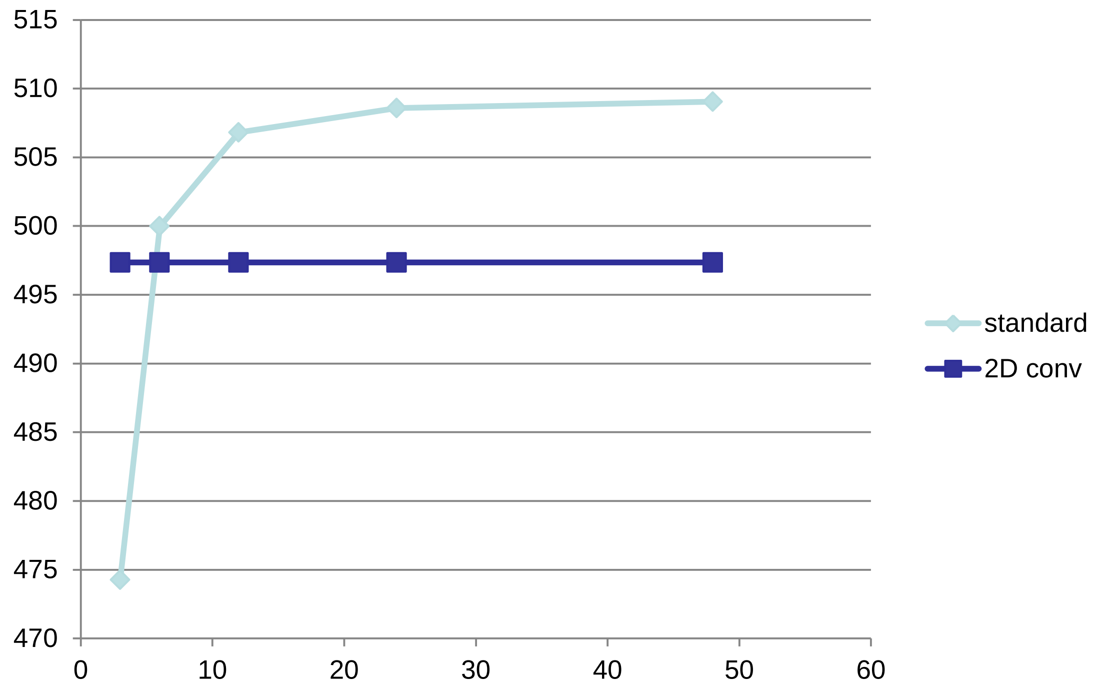




Deltares

Spatial convergence of subgrid approach

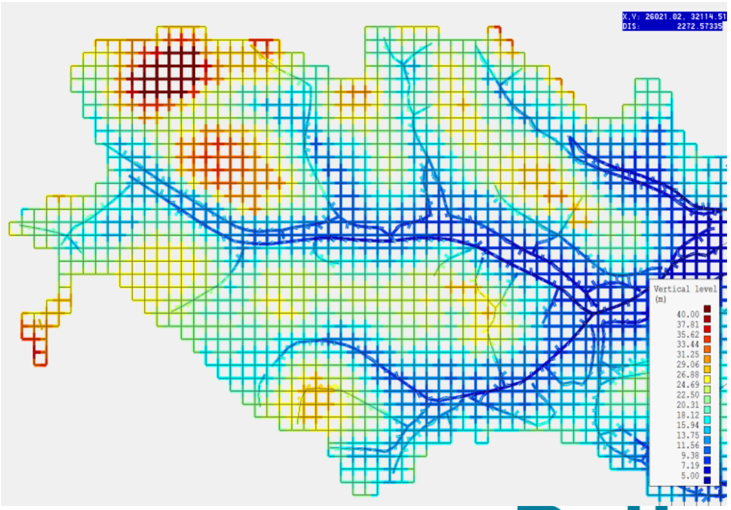
Flooding
Discharge
Capacity
m3/s



Nr of cells in cross-sectional direction.
3, 6, 12, 24 or 48 cells

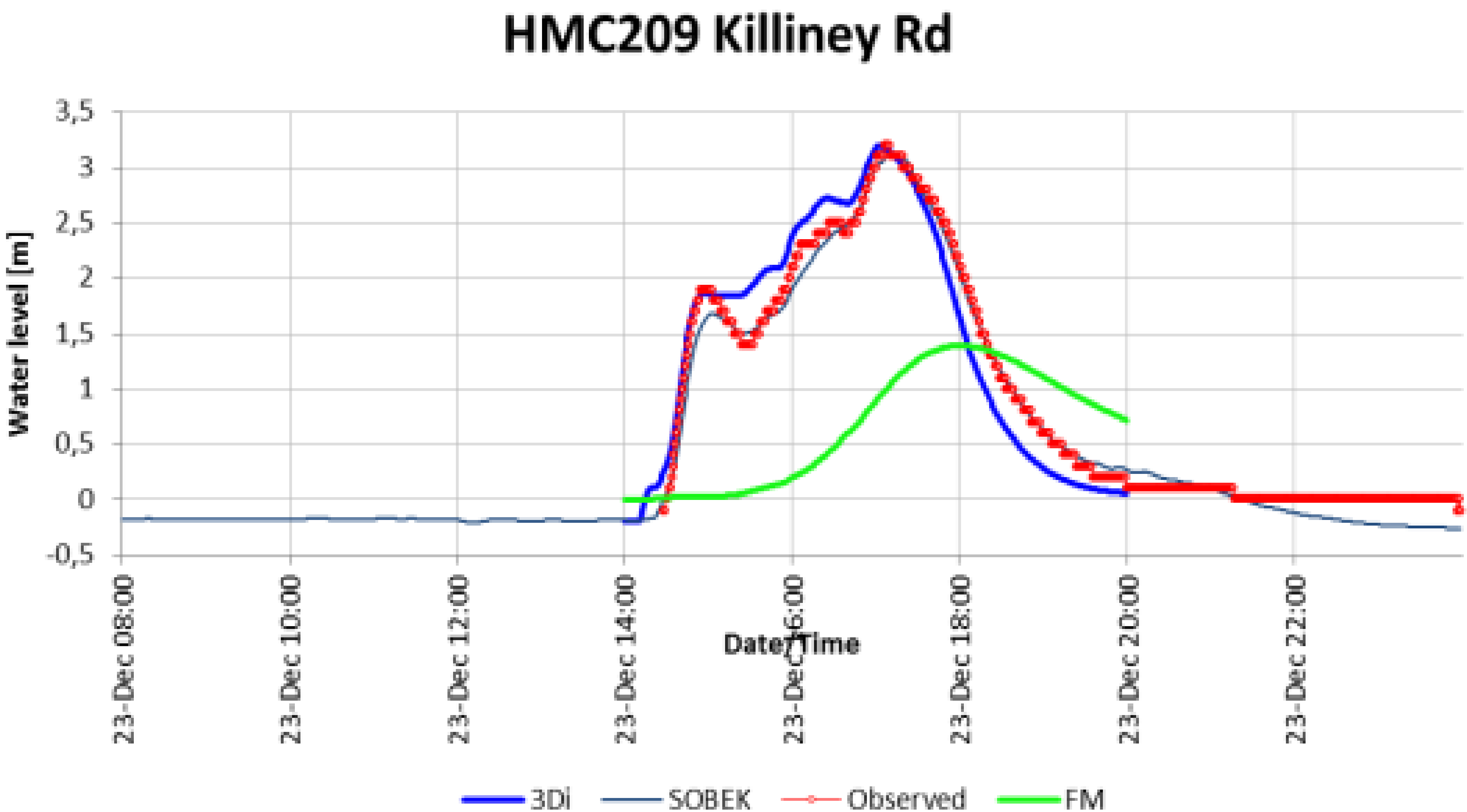
Deltares

Singapore rainfall runoff: Non-linear volumes

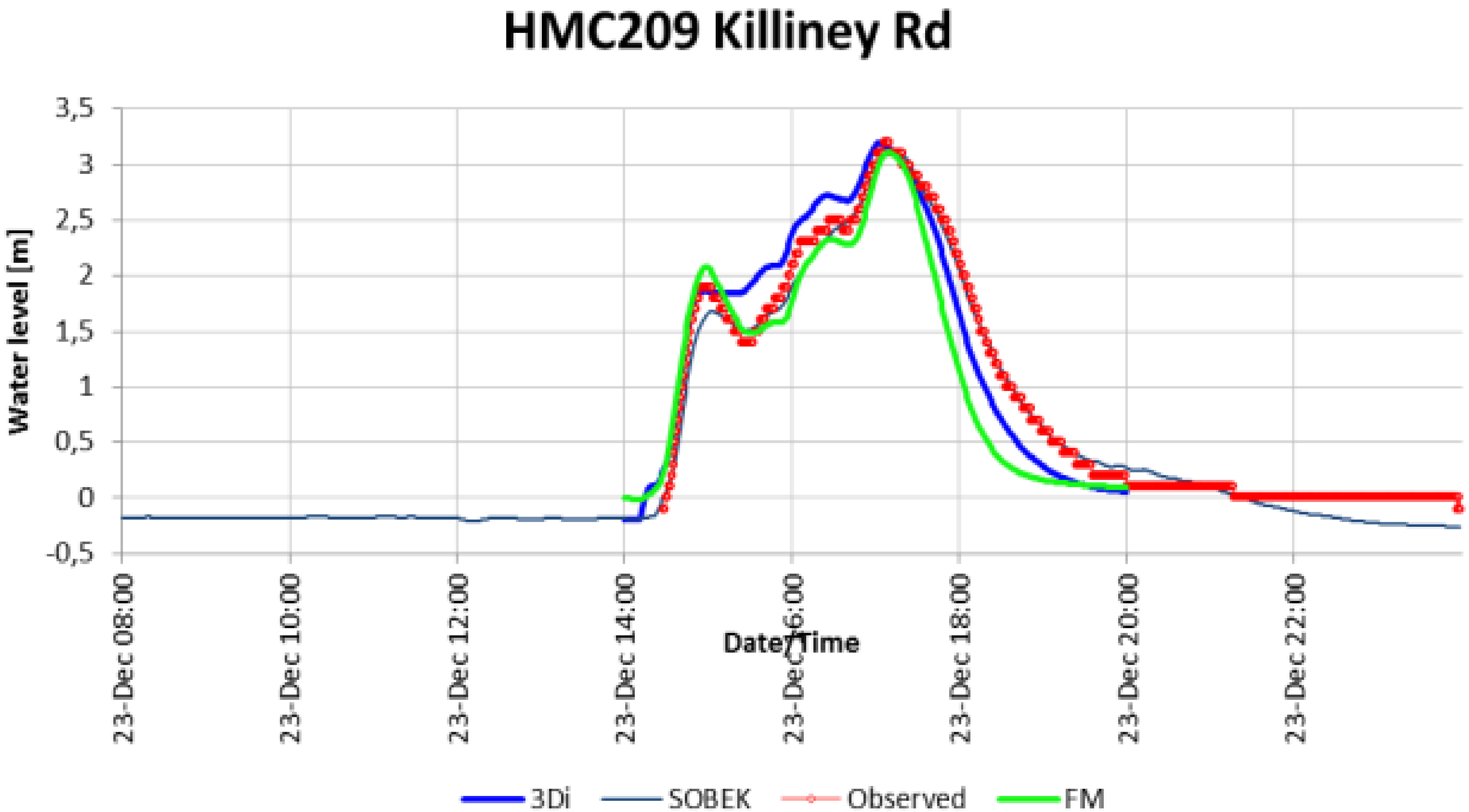


Deltares

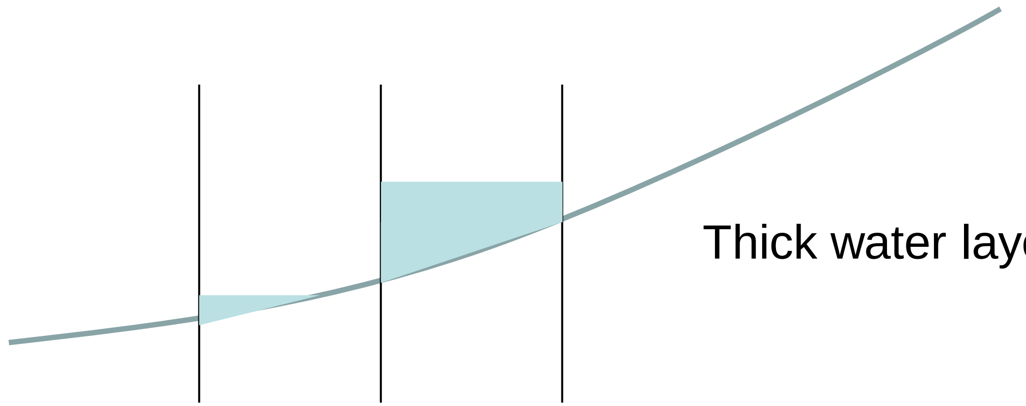
Singapore rainfall runoff: Linear volumes



Singapore rainfall runoff: Non-linear volumes



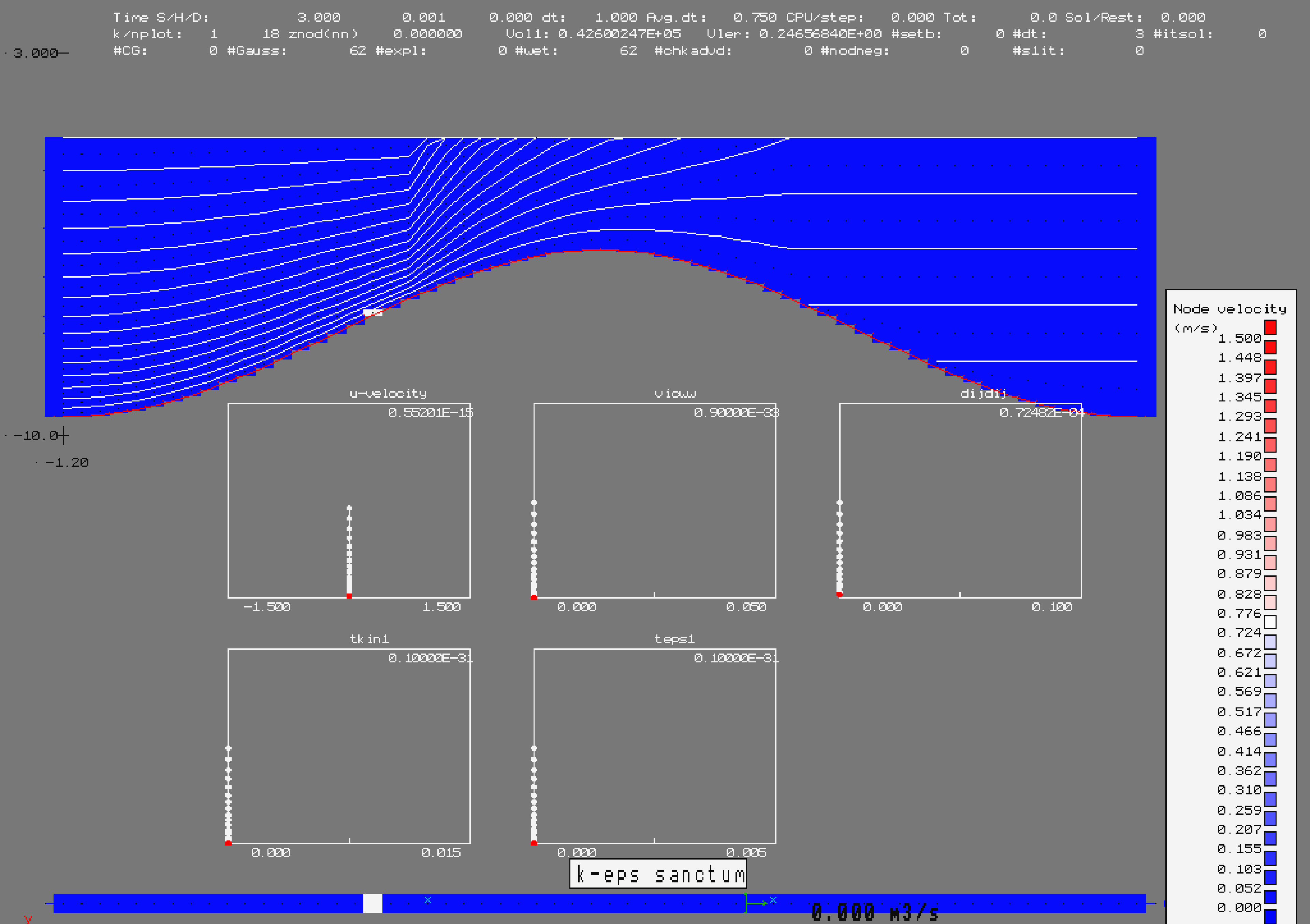
Subgrid 2: non-linear volumes



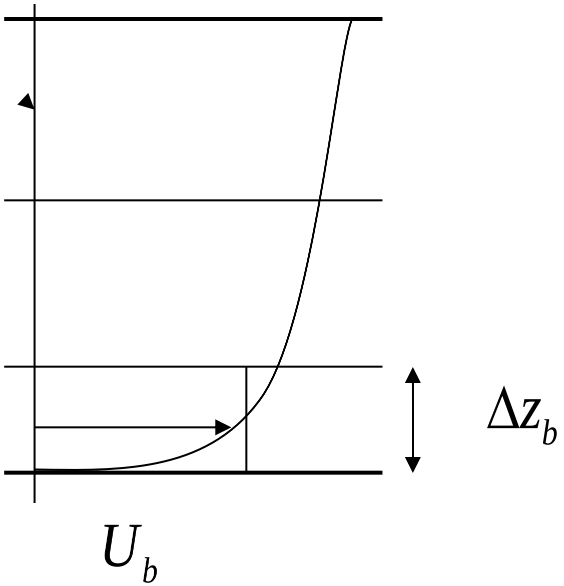
$$V^{p+1} = V^{p} + \left(\zeta^{p+1} - \zeta^{p}\right)\frac{\partial V^{p}}{\partial \zeta}$$

$$V^{p+1} = V^{p} + \left(\zeta^{p+1} - \zeta^{p}\right)A_{\zeta}^{p}$$

$$\frac{V^{p} + \left(\zeta^{p+1} - \zeta^{p}\right)A_{\zeta}^{p} - V^{n}}{\Delta t} + \sum_{out} A_{u}u - \sum_{in} A_{u}u = 0$$


Time S/H/D: 3.000 0.001 0.000 dt: 1.000 Avg.dt: 0.750 CPU/step: 0.000 Tot: 0.0 Sol/Rest: 0.000
k/nplot: 1 18 znod(nn) 0.000000 Vol1: 0.42600247E+05 Vler: 0.24656840E+00 #setb: 0 #dt: 3 #itsol: 0
#CG: 0 #Gauss: 62 #expl: 0 #wet: 62 #chkadvd: 0 #nodneg: 0 #slit: 0
3.000
-10.0
-1.20
u-velocity
0.55201E-15
-1.500
1.500
viqw
0.90000E-33
0.000
0.050
dijdij
0.72482E-04
0.000
0.100
tkin1
0.10000E-31
0.000
0.015
teps1
0.10000E-31
0.000
0.005
k-eps sanctum
0.000 m3/s
Node velocity (m/s)
1.500
1.448
1.397
1.345
1.293
1.241
1.190
1.138
1.086
1.034
0.983
0.931
0.879
0.828
0.776
0.724
0.672
0.621
0.569
0.517
0.466
0.414
0.362
0.310
0.259
0.207
0.155
0.103
0.052
0.000

Epsilon b.c. : Neumann unlike Delft3D
Ustar : Layer integrated unlike Delft3D



$$u_* = \frac{\kappa U_b}{\ln\left(\frac{\Delta z_b}{2 z_0} + 1\right)}, \quad or \quad u_* = \frac{\kappa U_b}{\ln\left(\frac{\Delta z_b}{e z_0} + 1\right)}$$

Mid layer	Layer integrated
Delft3D	DFM

Log profile testcase: slope.mdu

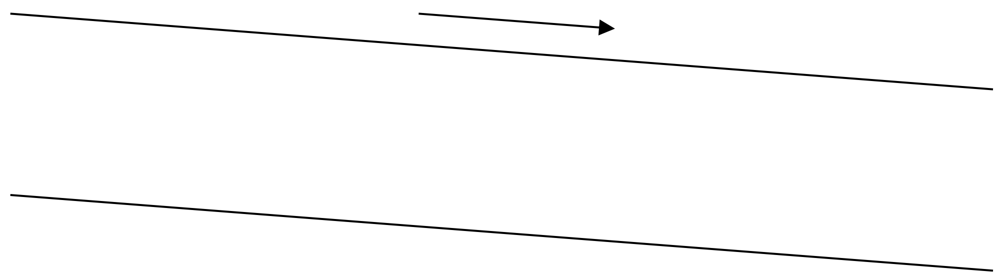
L=610 m

Dx=Dy=10 m

i=5e-5

H=5 m

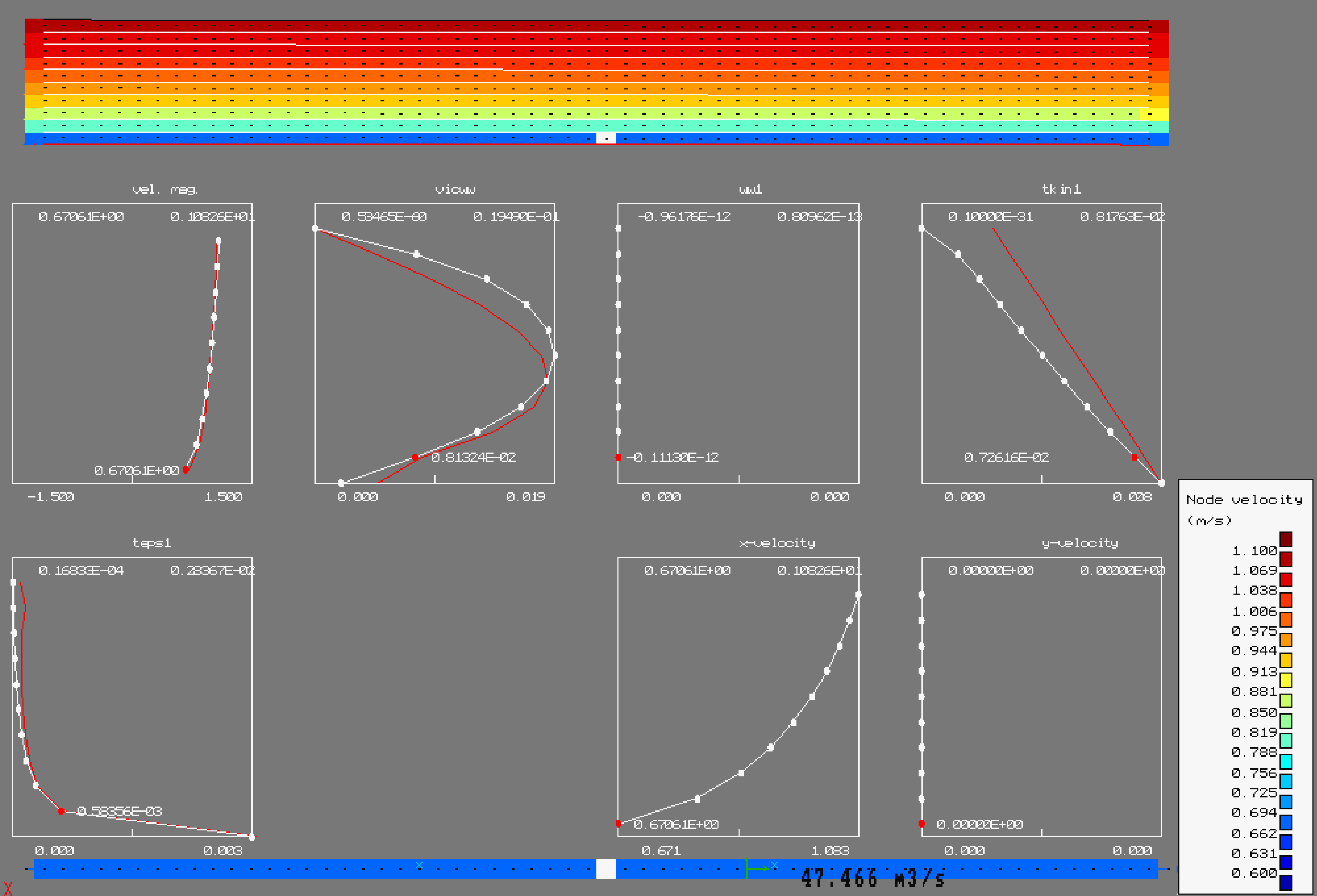
C=60 $m^{0.5}/s$



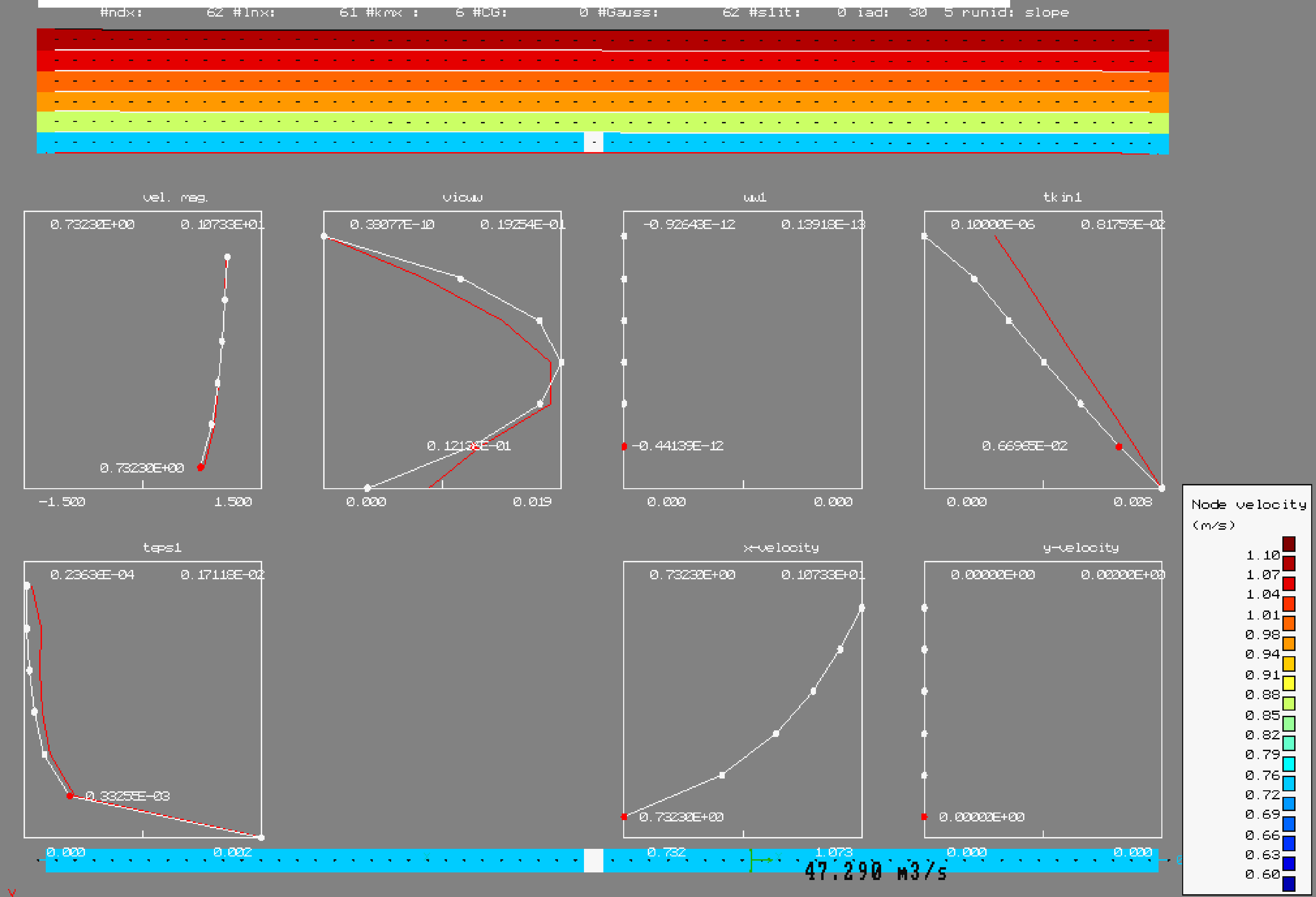
$U=C(Hi)^{0.5}=0.94868$ m/s

Q=47.434 m^3/s

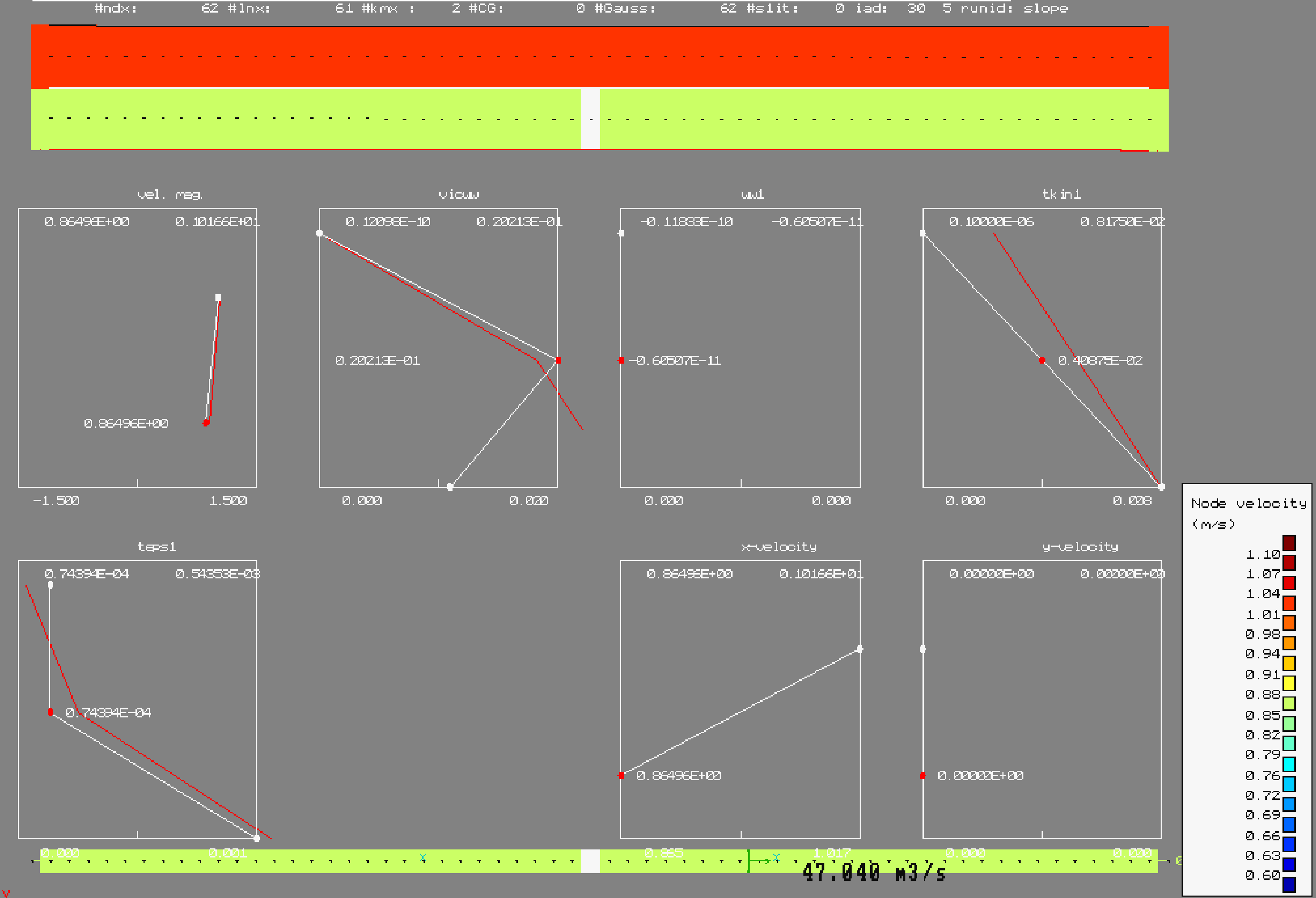
K-epsilon sigma 10 layers : 47.466 m3/s (47.434 m3/s)



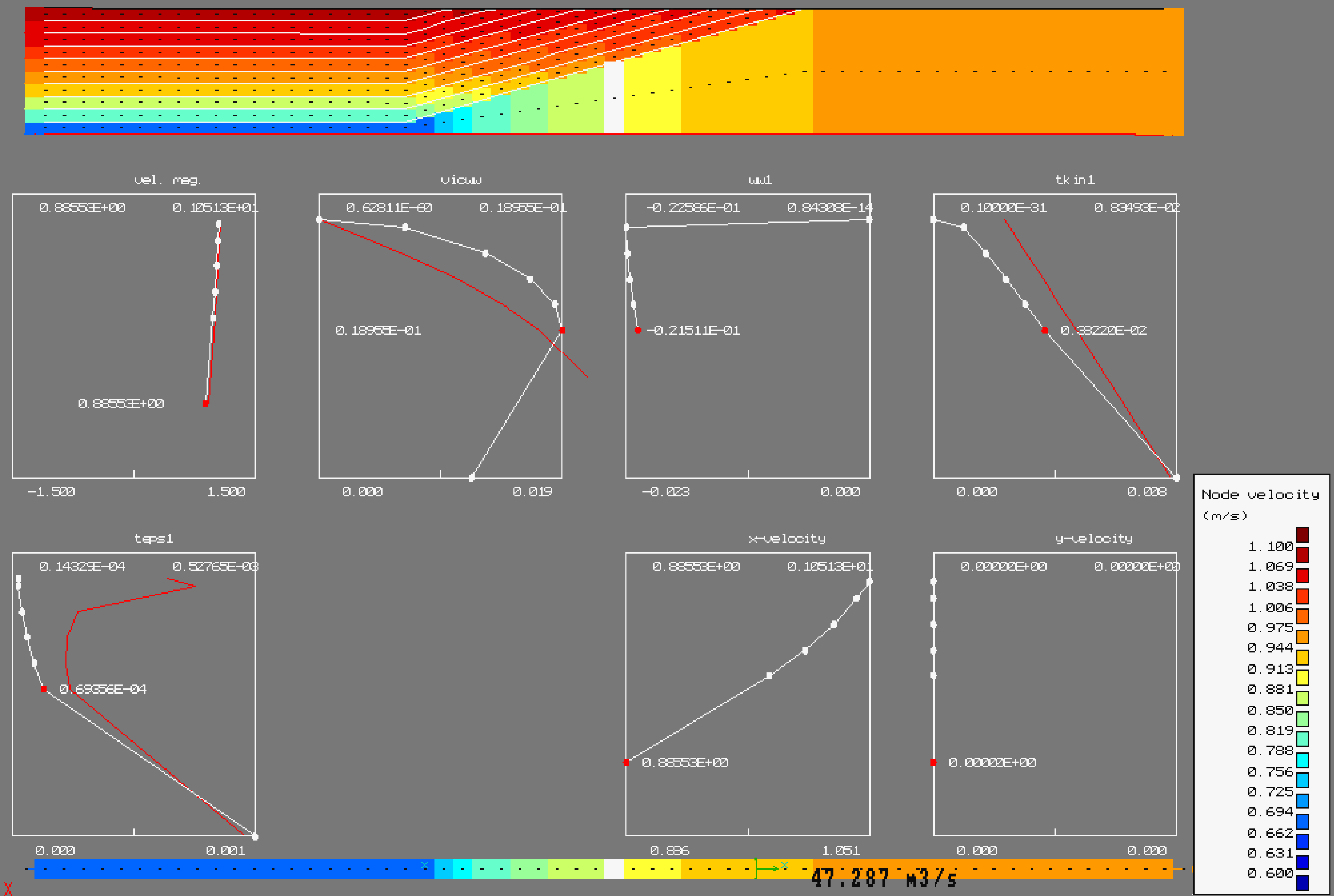
K-epsilon sigma 6 layers : 47.290 m3/s (47.434 m3/s)



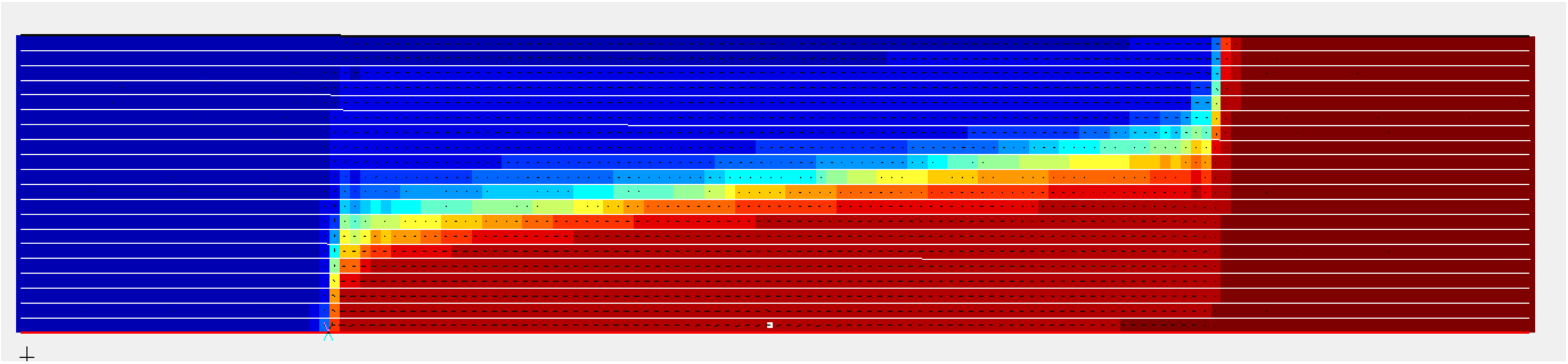
K-epsilon sigma 2 layers : 47.040 m3/s (47.434 m3/s)



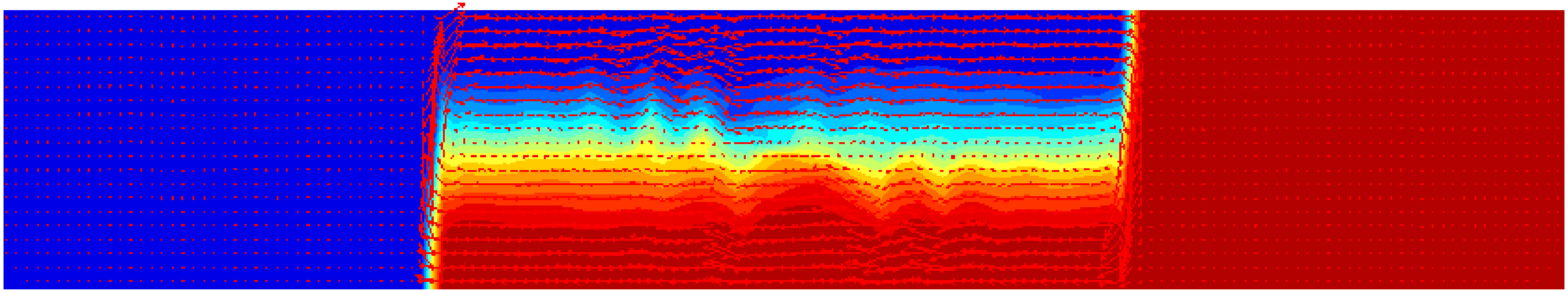
K-epsilon ustar layer integral mixed layers, noadv : Q = 47.287 m3/s (47.434 m3/s)



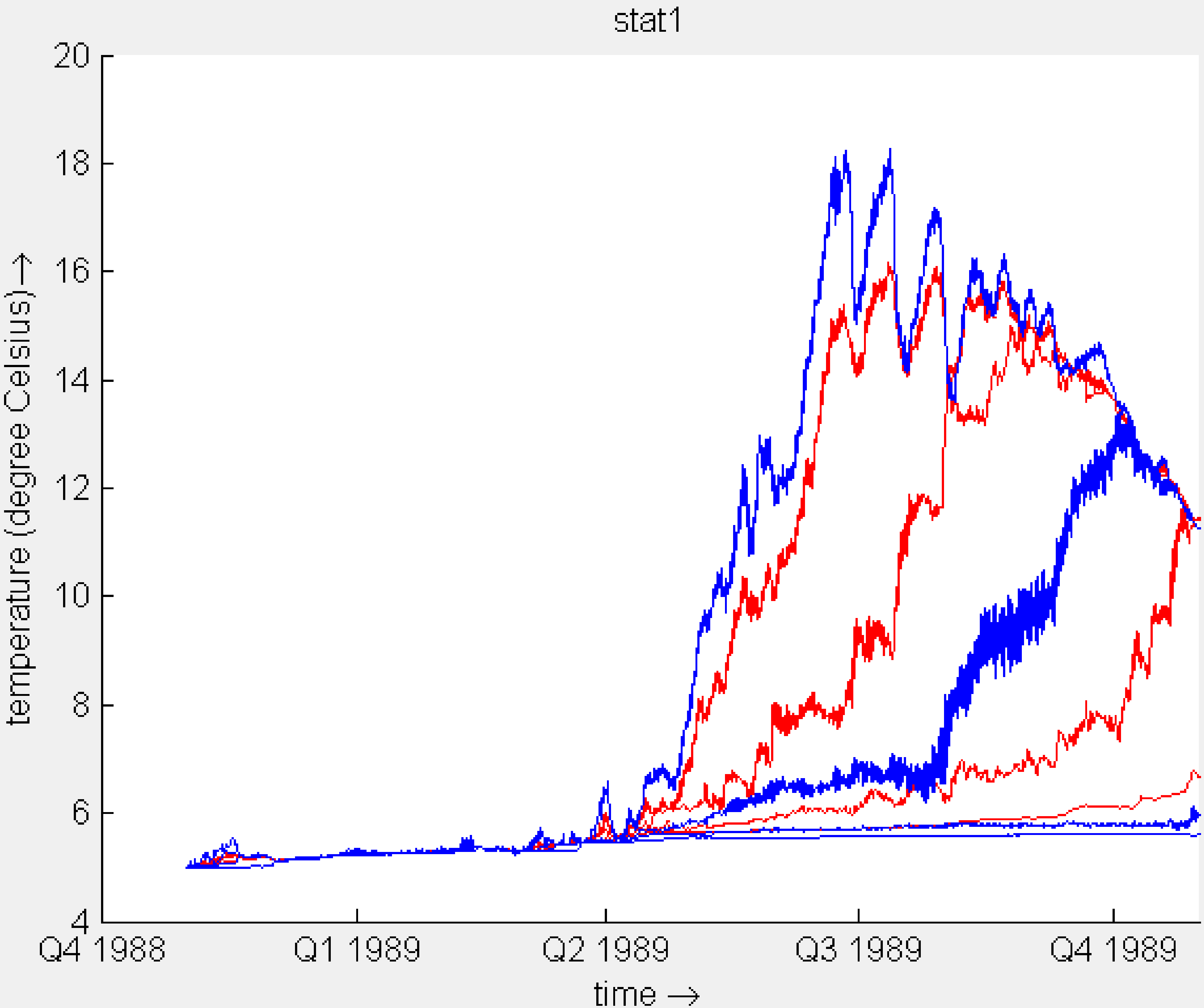
Lock exchange



DFM



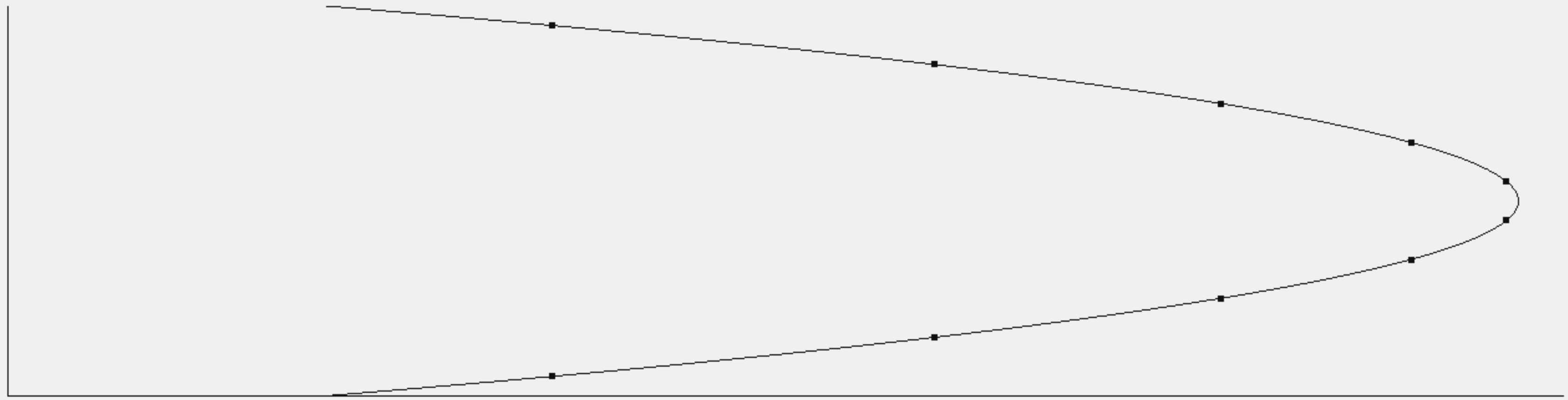
D3D

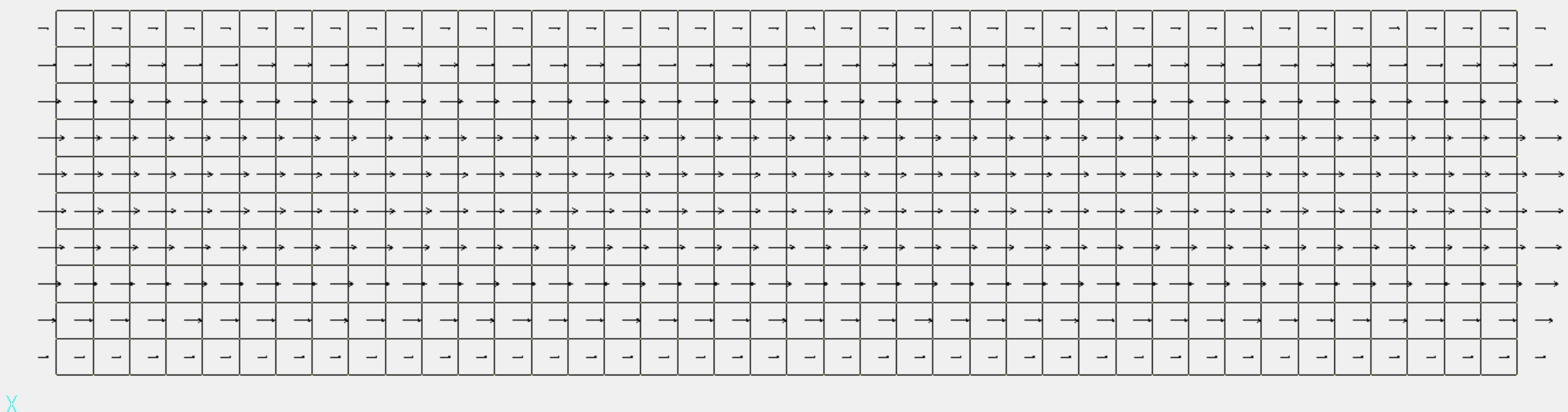

stat1
temperature (degree Celsius) →
20
18
16
14
12
10
8
6
4
Q4 1988
Q1 1989
Q2 1989
Q3 1989
Q4 1989
time →

Issues to tackle:

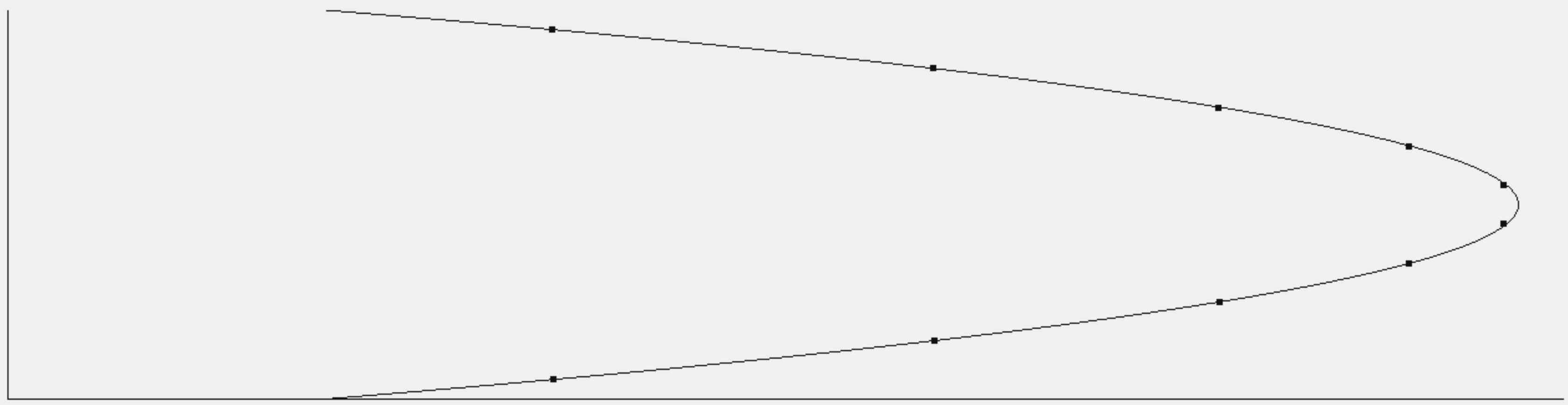
Strongly horizontally sheared flows on irregular grids

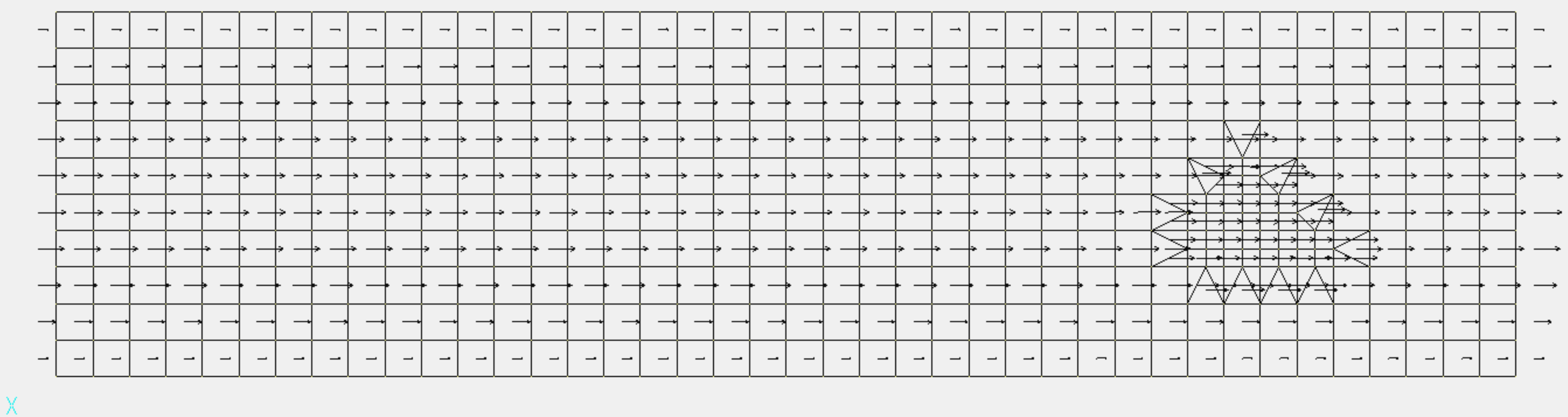
```
19920831 025036  dt:    0.902 Avg.dt:  0.902 CPU/step:  0.000 Tot:     2.4 Sol/Rest:.27E+00 Samer: 0.00000000E+00 Samtot:0.00000000
k/nplot:   1   200 znod(nn): -.99999802E-02 Vol1: 0.20000000E+06 Vler: 0.31560828E+00 #setb:       0 #dt:       11344 #itsol:     0
#ndx:       420 #lnx:       770 #kmx :     0 #CG:       180 #Gauss:       240 #slit:     0 iad:  30  5 runid: horvic_partialslip
```



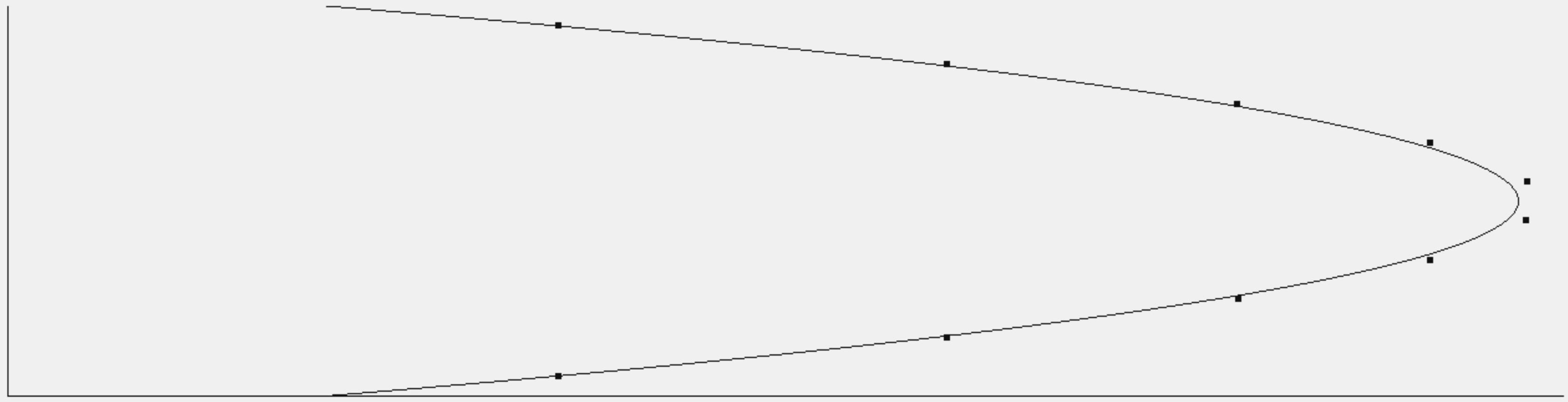


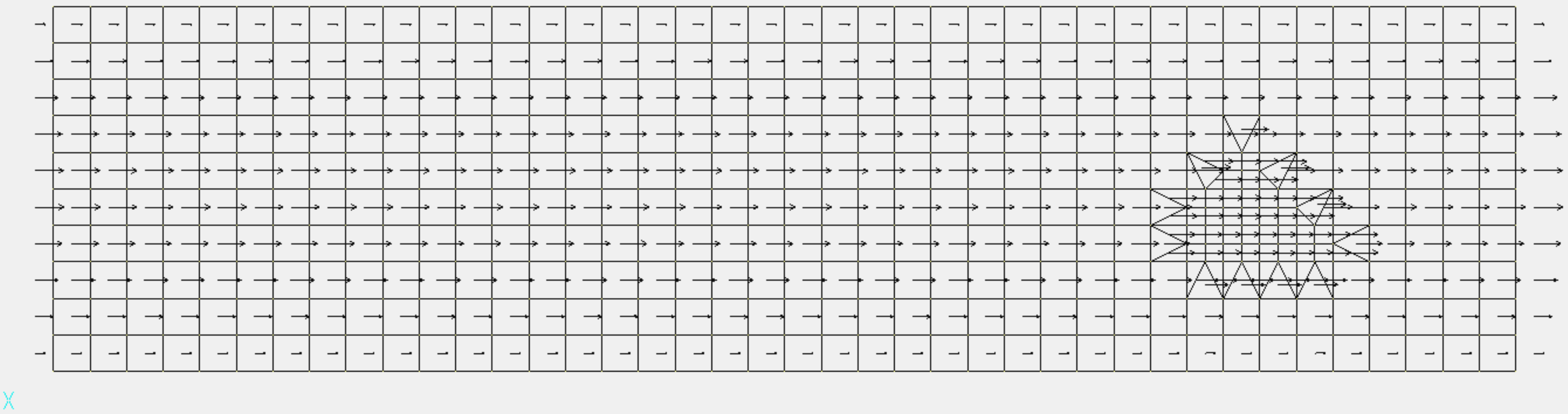
```
19920831 040000  dt:    0.227 Avg.dt:  0.227 CPU/step:  0.000 Tot:    14.3 Sol/Rest:.32E+00 Samer: 0.00000000E+00 Samtot:0.00000000
k/nplot:   1   224 znod(nn): -.94805597E-02 Vol1: 0.20000043E+06 Vler: 0.31544551E+00 #setb:      0 #dt:      63513 #itsol:     1
#ndx:      469 #lnx:      850 #kmx :    0 #CG:      197 #Gauss:      272 #s1it:     0 iad:    0  5 runid: horvic_partialslip
```



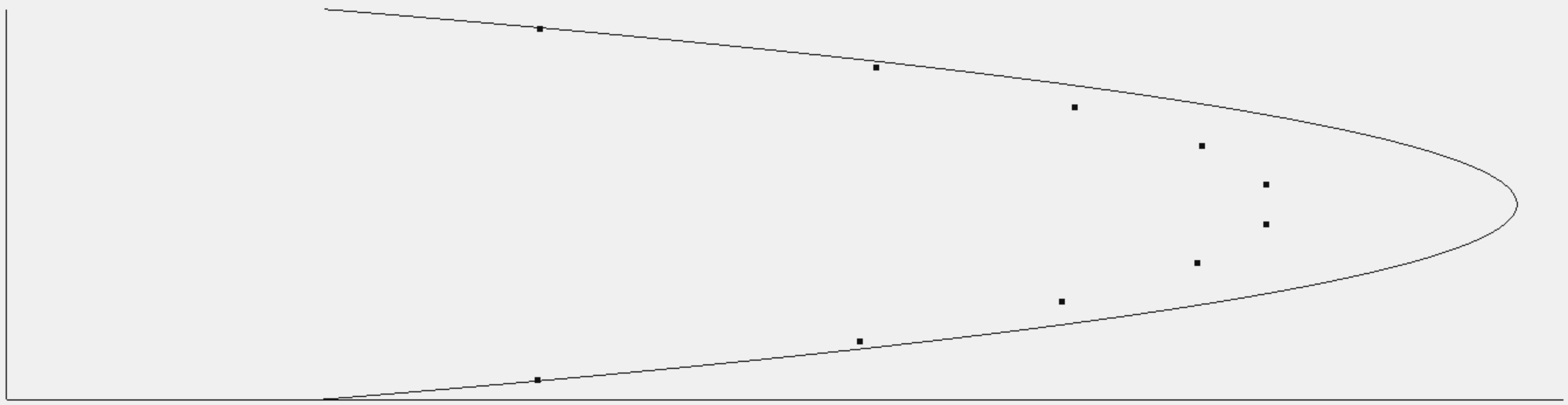


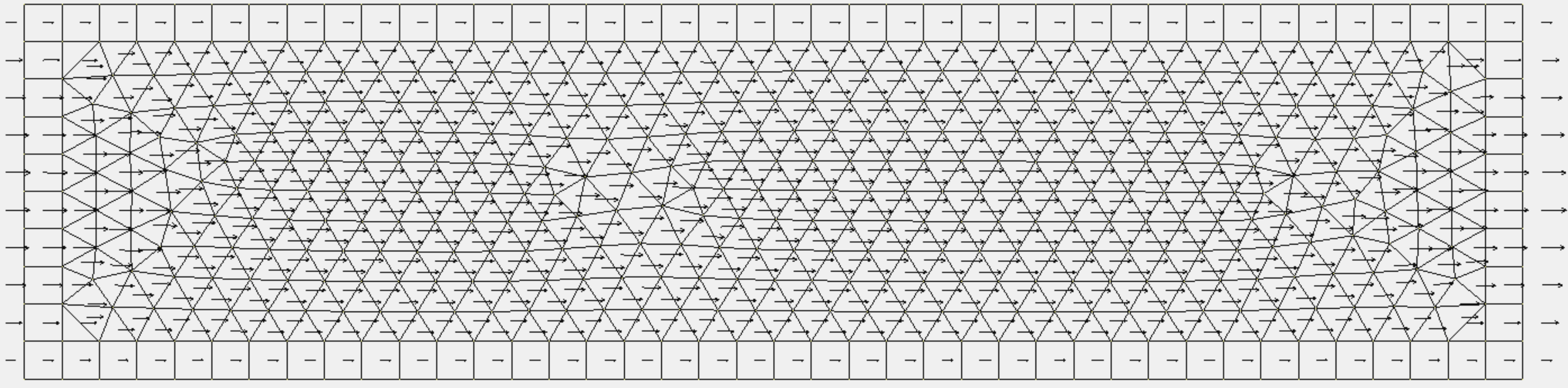
```
19920831 040000  dt:    0.224 Avg.dt:  0.225 CPU/step:  0.000 Tot:    15.7 Sol/Rest:.30E+00 Samer: 0.00000000E+00 Samtot:0.00000000
k/nplot:   1   224 znod(nn): -.99837185E-02 Vol1: 0.19998605E+06 Vler: 0.31556999E+00 #setb:      0 #dt:      64011 #itsol:     2
#ndx:       469 #lnx:       850 #kmx :    0 #CG:       197 #Gauss:      272 #s1it:     0 iad: 330  5 runid: horvic_partialslip
```

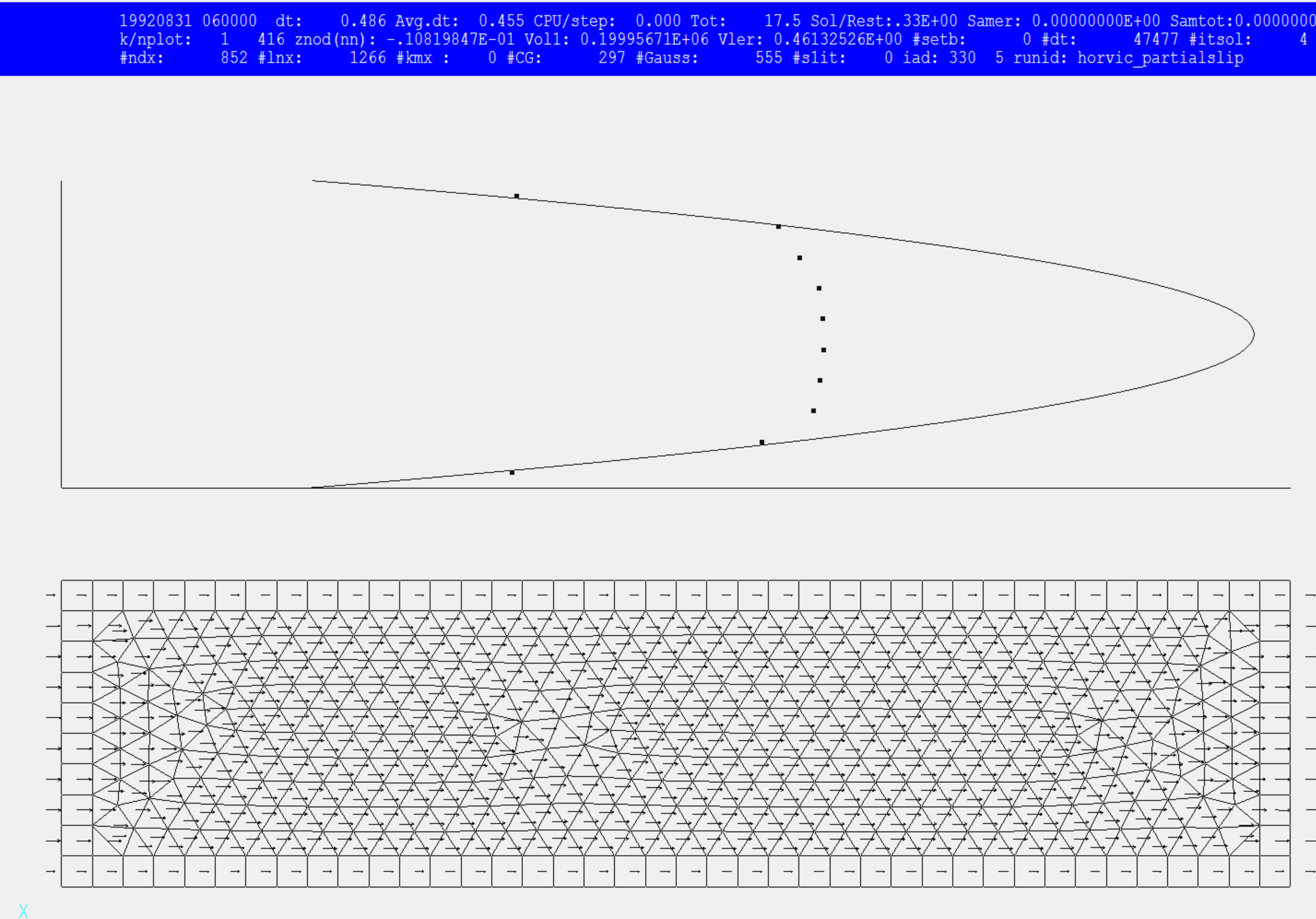




```
19920831 060000  dt:    0.375 Avg.dt:  0.355 CPU/step:  0.000 Tot:    20.3 Sol/Rest:.32E+00 Samer: 0.00000000E+00 Samtot:0.00000000
k/nplot:   1   416 znod(nn): -.94721184E-02 Vol1: 0.19999918E+06 Vler: 0.37624512E+00 #setb:      0 #dt:      60761 #itsol:     2
#ndx:       852 #lnx:      1266 #kmx :     0 #CG:       297 #Gauss:       555 #slit:     0 iad:    0  5 runid: horvic_partialslip
```






19920831 060000 dt: 0.486 Avg.dt: 0.455 CPU/step: 0.000 Tot: 17.5 Sol/Rest:.33E+00 Samer: 0.00000000E+00 Samtot:0.00000000
k/nplot: 1 416 znod(nn): -.10819847E-01 Vol1: 0.19995671E+06 Vler: 0.46132526E+00 #setb: 0 #dt: 47477 #itsol: 4
#ndx: 852 #lnx: 1266 #kmx : 0 #CG: 297 #Gauss: 555 #s1it: 0 iad: 330 5 runid: horvic_partialslip
X

Some issues to tackle:

Strongly horizontally sheared flows on irregular grids
(both advection and viscous terms)

Advection in fixed layers

Parallel performance of linear solver (PETSC)

2D vortex merge