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Suppressing the Pressure-Source Instability in Modeling Deep-Draft Vessels with Low Under-Keel Clearance in FUNWAVE-TVD

by Matt Malej and Fengyan Shi

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) documents the development through verification and validation of three instability-suppressing mechanisms in FUNWAVE-TVD, a Boussinesq-type numerical wave model, when modeling deep-draft vessels with a low under-keel clearance (UKC). Many large commercial ports and channels (e.g., Houston Ship Channel, Galveston, US Army Corps of Engineers [USACE]) are traveled and affected by tens of thousands of commercial vessel passages per year. In a series of recent projects undertaken for the Galveston District (USACE), it was discovered that when deep-draft vessels are modeled using pressure-source mechanisms, they can suffer from model instabilities when low UKC is employed (e.g., vessel draft of 12 m[1] in a channel of 15 m or less of depth), rendering a simulation unstable and obsolete. As an increasingly large number of deep-draft vessels are put into service, this problem is becoming more severe. This presents an operational challenge when modeling large container-type vessels in busy shipping channels, as these often will come as close as 1 m to the bottom of the channel, or even touch the bottom. This behavior would subsequently exhibit a numerical discontinuity in a given model and could severely limit the sample size of modeled vessels. This CHETN outlines a robust approach to suppressing such instability without compromising the integrity of the far-field vessel wave/wake solution.

The three methods developed in this study aim to suppress high-frequency spikes generated near-field of a vessel. They are a shock-capturing method, a friction method, and a viscosity method, respectively. The tests show that the combined shock-capturing and friction method is the most effective method to suppress the local high-frequency noises, while not affecting the far-field solution. A strong test, in which the target draft is larger than the channel depth, shows that there are no high-frequency noises generated in the case of ship squat as long as the shock-capturing method is used.

BACKGROUND: Applications in modeling large-size vessels with a draft close to the channel depth may cause an instability problem due to large water surface oscillations occurring at the vessel bottom. The oscillations are usually induced by sharp changes in vessel geometry and numerical instabilities associated with the dispersion terms in the Boussinesq equations. A Shallow-Water Equation (SWE) solver in a ship-wake model has a similar issue as reported by Fenical et al. (2006), who observed "high-frequency ripples" generated by the ship-wake source

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

(pressure gradient). Fenical et al. (2006) used a filtering technique to suppress the pressure spikes around the vessel.

The pressure source mechanism has been widely used for ship wake generation in Boussinesq-type wave models (e.g., Nwogu and Demirbilek 2001; David et al. 2017; Shi et al. 2018) and SWE-based models (e.g., Stockstill and Berger 1999). The pressure source is usually specified according to vessel geometry, such as length, width (beam), and draft, as a *target shape* of a vessel. However, in modeling a moving vessel, the pressure-induced water surface deformation may differ from the target shape due to the dynamic adjustment of the mass and momentum balance. Here, the pressure-induced water surface deformation is referred to as "dynamic draft" of a vessel. In FUNWAVE-TVD, the target shape of a vessel is initially prescribed as the target draft based on the hydrostatic momentum balance. When a vessel is moving, the pressure-induced surface displacement at the vessel location deviates from the target shape, resulting in a dynamic form adjusting to flow conditions.

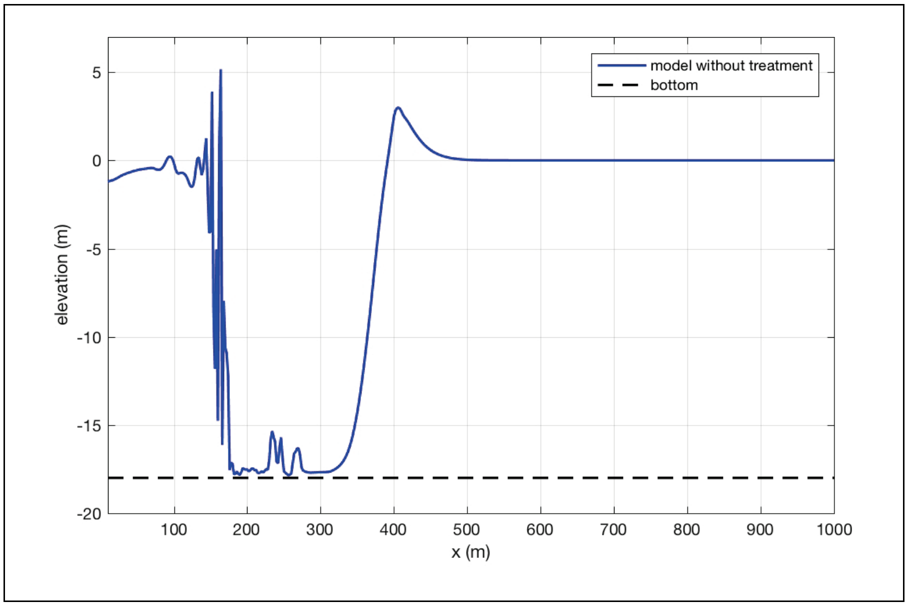

Figure 1. An example of numerical instability from the model without any treatment for high-frequency noises. Water elevation is along the middle section of the vessel.

In modeling a vessel with a deep draft, which is close to the water depth, high-frequency spikes can be generated around the vessel. This problem is usually found in applications of large-size vessels such as container and cargo ships, which pass a shallow navigation channel. The numerical spikes usually start from the stern of a vessel and gradually propagate to the vessel bottom (surface deformation) (Figure 1). Dry cells may appear at the vessel bottom due to the spikes, similar to ship squat in reality, resulting in instabilities in the numerical model. The problem is more severe in a Boussinesq-type model because of dispersion terms in the higher-frequency waves.

Filtering techniques can be used for suppressing the high-frequency spikes in general applications of ship wakes. However, filtering can cause global damping of waves in all frequencies. In this study, there was use of an alternative approach by taking advantage of the Total-Variation-Diminishing

(TVD) scheme and existing local damping techniques in FUNWAVE-TVD. The tests show that the methods proposed here are more effective in terms of local treatment than the filtering techniques.

METHODS

Shock-Capturing Method. The complete FUNWAVE-TVD equations, describing the conservative form of the fully-nonlinear Boussinesq equations, can be found in Shi et al. (2011). Only the momentum equation related to the methods in the present study is listed here.

$$\mathbf{M}_t + \nabla \cdot \left[\frac{\mathbf{MM}}{H}\right] + \nabla \left[\frac{1}{2}g(\eta^2 + 2h\eta)\right] + g\eta\nabla h + H\mathbf{DIS} + \mathbf{Cdu}_\alpha|\mathbf{u}_\alpha| + \nabla \cdot (\mathbf{Vis}\nabla\mathbf{u}_\alpha) \tag{1}$$

where M is the horizontal volume flux; $H = h + \eta$, in which h is water depth and η is surface elevation; g is the gravitational acceleration. DIS represents the terms associated with wave dispersion. The last two terms are the friction term (Cd) and viscosity term (Vis), respectively, used in the study.

The shock-capturing (SCP, hereafter) method is used by switching the Boussinesq solver to the Nonlinear Shallow Water Equation (NLSWE) solver in the vessel region (i.e., DIS = 0 in Equation (1)). The method is consistent with the SCP-based wave breaking scheme. The integer variable map MASK9 is used to mask the area of the vessel bottom and the region with a width of two ghost cells extended from the vessel bottom. In the masked region, the NLSWE is solved.

Friction Method. The Friction (FRC, hereafter) method is one of the dissipation methods used for damping waves as in the boundary sponge layers. The bottom friction described in Equation (1) is applied locally in the masked area. A proper friction coefficient, Cd, can be specified by users.

Viscosity Method. The Viscosity (VIS, hereafter) method is another dissipation method used in the eddy-viscosity-type wave breaking and sponge layers. The viscosity term is expressed in Equation (1). Unlike the normal wave-breaking scheme in FUNWAVE-TVD, the viscosity coefficient, Vis, should be specified by users rather than be based on the calculation of empirical formula as in Kennedy et al. (2000). The damping rate is usually lower than that in the friction method, as found in the sponge layer tests (Shi et al., 2011).

MODEL CONFIGURATION: To use one of the three methods or combined methods, the code needs to be recompiled with the flag **-DDEEP DRAFT VESSEL** in the Makefile. The default option (if nothing is specified in the steering file **input.txt**) is the combined SCP method and FRC method with a friction coefficient of Cd = 0.1. This default option and associated frictional parameter were obtained based on the best practice of the tests that have been conducted. Users can specify additional options and parameters in the input.txt driver file.

Setup of SCP method. In **input.txt**, specify

MaskMethod = T (case-sensitive)

Setup of friction method.

FrictionMethod = T (case-sensitive)

CdDeepDraft = <floating-point number>

Default: 0.1

Suggested number range: 0.1 – 1.0.

Setup of viscosity method

ViscosityMethod = T (case-sensitive)

VisDeepDraft = <floating-point number>

Default: 0.1

Suggested number range: 0.1 – 5.0.

TESTS: Test examples can be found in the FUNWAVE-TVD Github repository (master branch) package *`/simple_cases/vessel_deep_draft/`*.

The following simulations used a channel with a flat bottom of 18 m. The dimensions are 700 × 100 grid points. Grid step sizes are 2.0 m (in x) and 4.0 m (in y). The vessel moving speed is 7 m/s (13.6 kn). A higher-speed vessel was also tested but not shown in the report. Tests were conducted using all methods individually, followed by combined methods. The VIS method turned out to be ineffective if used alone, and therefore it is not shown here. A sample steering file can be found in the Appendix.

The FRC Method (channel depth: 18.0 m; vessel draft 15 m). The FRC method was examined using a vessel with a draft of 15 m, in a channel depth of 18.0 m. Figure 2 shows surface deformations along the middle section of the vessel, modeled by the FRC method with a range of friction coefficients. A large spike can be found at the bottom of the vessel in the case of non-treatment (cyan color). As the friction coefficient increases, the magnitude of the spike is reduced. In the case of Cd = 1.0, the spike is suppressed completely. Increasing Cd results in a smaller magnitude of the dynamic draft, as shown in the case of Cd = 5.0.

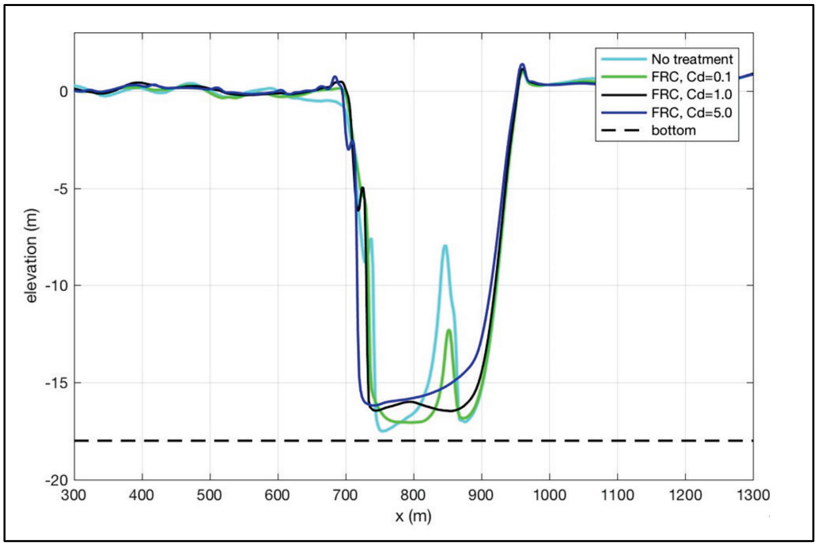

Figure 2. Water deformations at t = 100 sec along the middle section of the vessel modeled without treatment, and the FRC method with different Cd: 0.1, 1.0, and 5.0, respectively. Vessel draft: 15m; channel depth: 18 m.

Figure 3 shows snapshots of two-dimensional (2D) distribution of surface deformation from the model without treatment, versus the model with the FRC method (Cd = 1.0). The model with the FRC method predicts a smoother distribution of surface deformation induced by the pressure, while the model without the method shows the non-uniformity and asymmetry caused by instabilities.

Hence, the tests suggest that the FRC method can be effective in suppressing the numerical instabilities if a proper friction coefficient is used. A coefficient larger than 1.0 may induce a draft smaller than the target value. From the present tests, the suggested range of coefficient can be from 0.1 to 1.0.

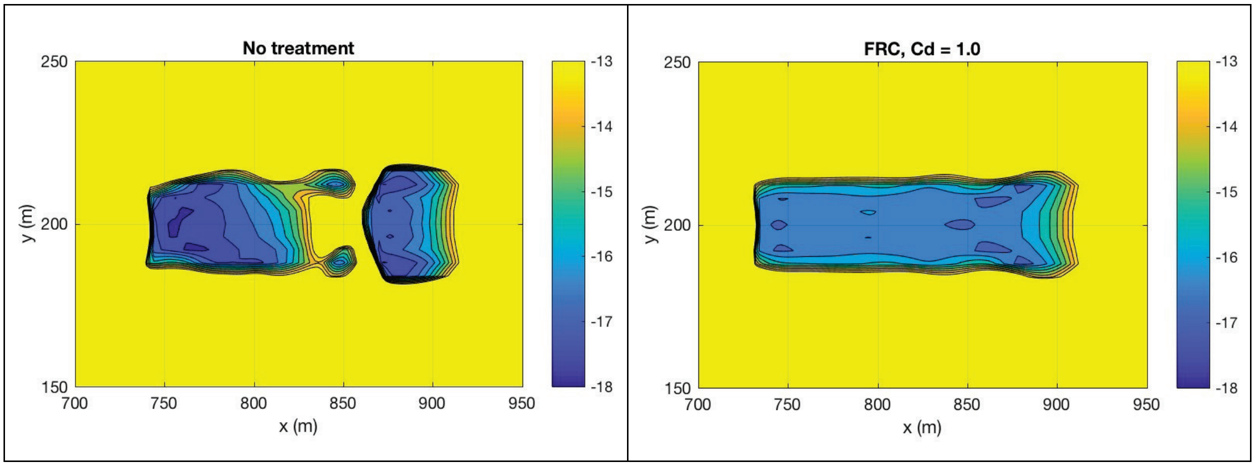

Figure 3. 2D distribution of surface deformation at t = 100 sec from the model without treatment (left) versus the FRC method with Cd = 1.0 (right). The color bar scale is in meters with zero indicating the mean water level (MWL). Vessel draft: 15m, channel depth: 18 m.

The SCP Method and Combined SCP and FRC Method (channel depth: 18.0 m, vessel draft 15 m). Figure 4 shows the result from the model with the SCP method compared to the combined SCP/FRC method. The model with the SCP method provided a stable solution though a single spike appears at the bottom of the vessel. The spike is much smaller in magnitude than the model without treatment (Figure 2). The models with the combined SCP/FRC method with different friction coefficients smooths out the spike. The larger the coefficient, the smoother the distribution of the deformation. The model with a higher coefficient, such as Cd > 2, significantly reduced the magnitude of the deformation, as shown in the figure.

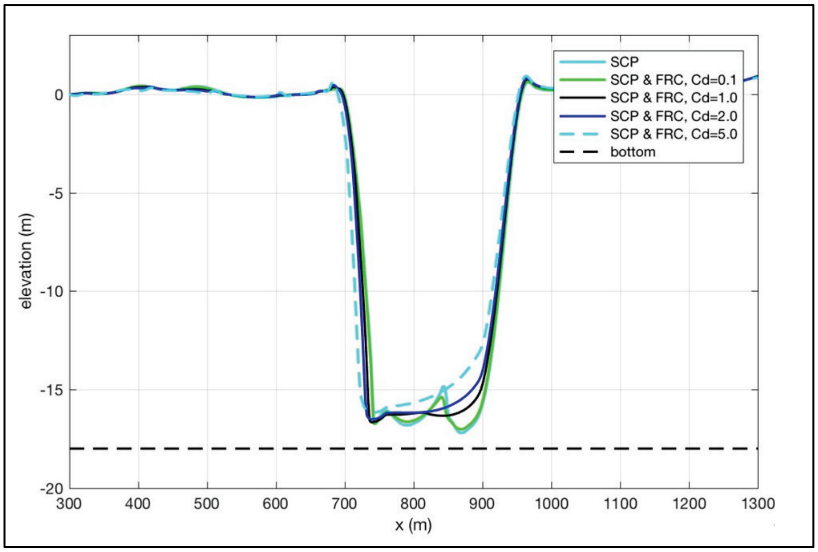

Figure 4. Water deformations at t =100 sec along the middle section of the vessel modeled by the SCP method and the combined SCP/FRC method with different Cd: 0.1, 1.0, 2.0 and 5.0, respective. Vessel draft: 15m, channel depth: 18 m.

The 2D distributions of surface deformation modeled by the SCP and the combined SCP/FRC method are illustrated in Figure 5. The surface deformation from the SCP method still shows obvious spatial variations with the peak value found at the front portion of the vessel. The combined SCP/FRC method with Cd = 1.0 smooths out the spike.

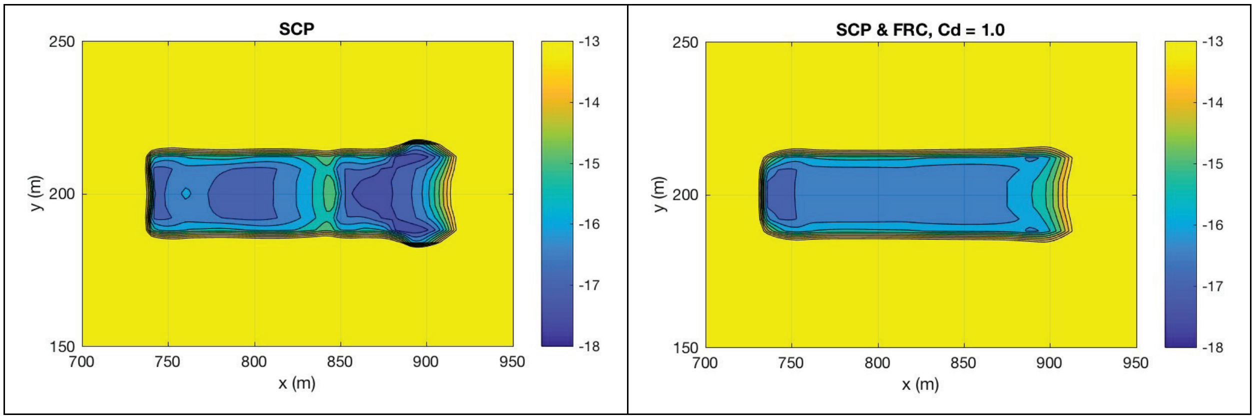

Figure 5. 2D distribution of surface deformation at t = 100 sec from the shock-capturing – SCP (left) and the combined shock-capturing and friction method – SCP and FRC with Cd = 1.0 (right). The color bar scale is in meters with zero indicating the MWL. Vessel draft: 15m; channel depth: 18 m.

The test results indicate that the SCP method alone can effectively suppress high-frequency spikes. The combined SCP/FRC method provides extra damping of spikes, resulting in a smoother solution in the deformation of water surface.

The combined SCP and VIS method (channel depth: 18.0 m; vessel draft 15 m) The tests show that the VIS method alone is unable to suppress the high-frequency spikes effectively. Here, the test results from the combined SCP/VIS method are presented. As shown in Figure 6, the VIS method with moderate viscosity coefficients (0.1 – 1.0) made a negligible change from the model with just the SCP method. The model with an extremely large viscosity coefficient (Vis = 10.0) modified the result with the spike shifting towards the rear of the vessel.

The Combined SCP and FRC Method Using the Critical Draft (channel depth: 18.0 m; vessel draft 18 m). The aforementioned tests indicate that the combined SCP/FRC method is the most effective method to suppress high-frequency spikes. Here, tests using the critical draft (i.e., the draft value being the same as the channel depth) were carried out. Figure 7 shows the surface deformation along the middle section of the vessel modeled by the SCP method and the combined SCP/FRC method with a small frictional parameter value Cd: 0.001 and 0.01. It is interesting that the SCP method and the combined SCP/FRC method with different Cd provide smooth surface deformations closely identical to each other. There are no high-frequency spikes found in the results, probably because the dynamic draft is too close to the water depth, leaving no space to generate spikes. Figure 8 shows a nearly uniform distribution of the surface deformation. Tests with larger coefficients such as Cd = 1.0 and 2.0 did not alter the result much, except for an extremely large coefficient, Cd > 5.0, which reduced the magnitude of the draft. Note that the model without treatment does not survive much beyond the initial stage in the case of a critical draft.

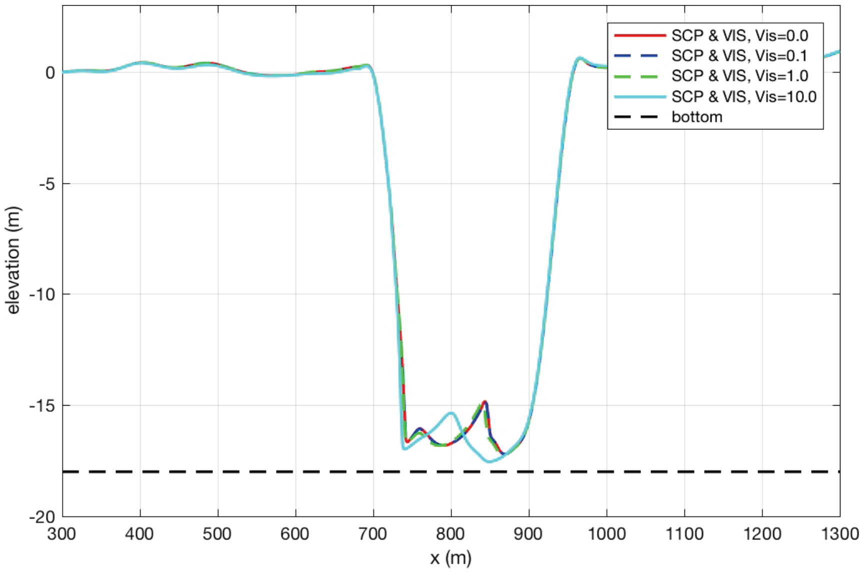

Figure 6. Water elevations along the middle section of the vessel modeled by the combined SCP and VIS method with different viscosity: 0.1, 1.0, and 10.0, respectively. Vessel draft: 15 m; channel depth: 18 m.

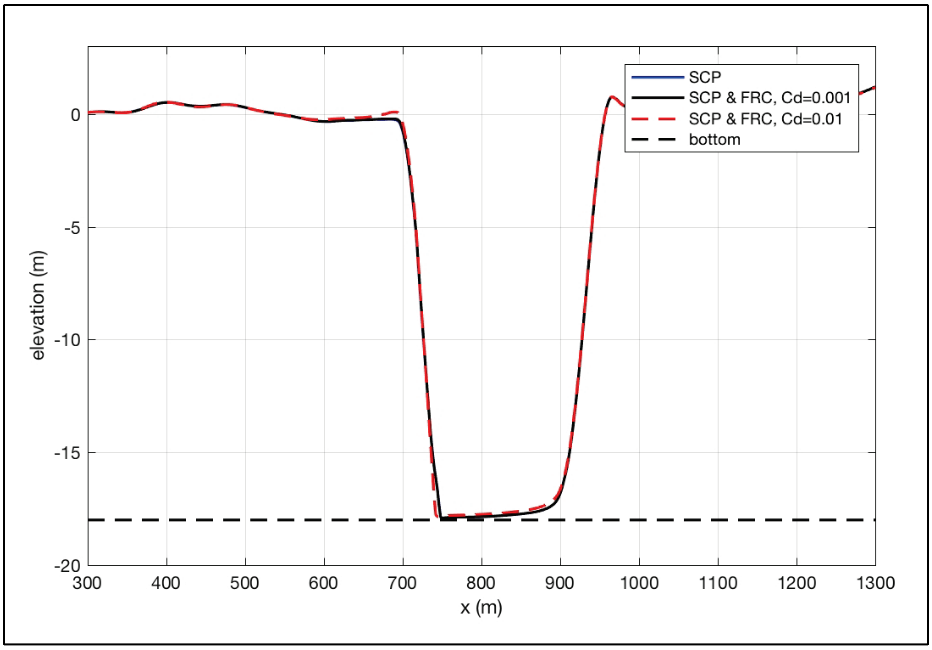

Figure 7. Surface deformation along the middle section of the vessel modeled by the SCP method and the combined SCP/FRC method with Cds: 0.001 and 0.01, respectively. Vessel draft: 18m; channel depth: 18 m.

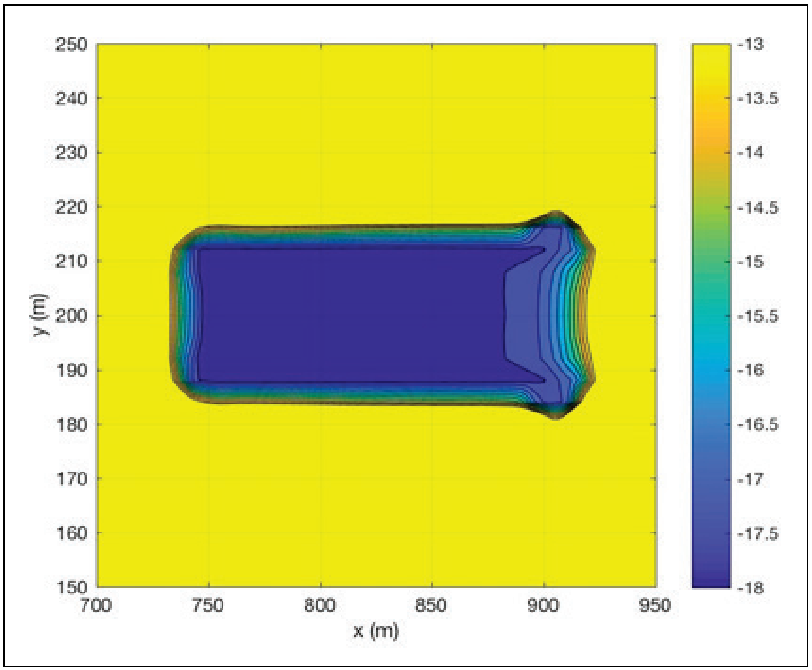

Figure 8. 2D distribution of surface deformation at t = 100 sec from the SCP method. Vessel draft: 18m; channel depth: 18 m.

Strong Test (channel depth: 18.0 m; target draft 20 m). A strong test case was conducted using a target draft larger than the channel depth. Although the model configuration is not realistic, it can serve as a strong test for numerical instability. Here, a target draft of 20 m with a channel depth of 18 m was applied. The large pressure source should generate a number of dry grid points under the vessel bottom due to the momentum balance. The SCP method in the test was used.

Figure 9 shows the one-dimensional (1D) (top) and 2D distributions of surface deformation modeled using the SCP method. As expected, the surface deformation reaches the channel bottom (18 m) as shown in the 1D plot of surface deformation. The 2D plot shows that a large portion of grid cells are dry (white area). The dry points did not cause any high-frequency noises due to the application of the SCP method.

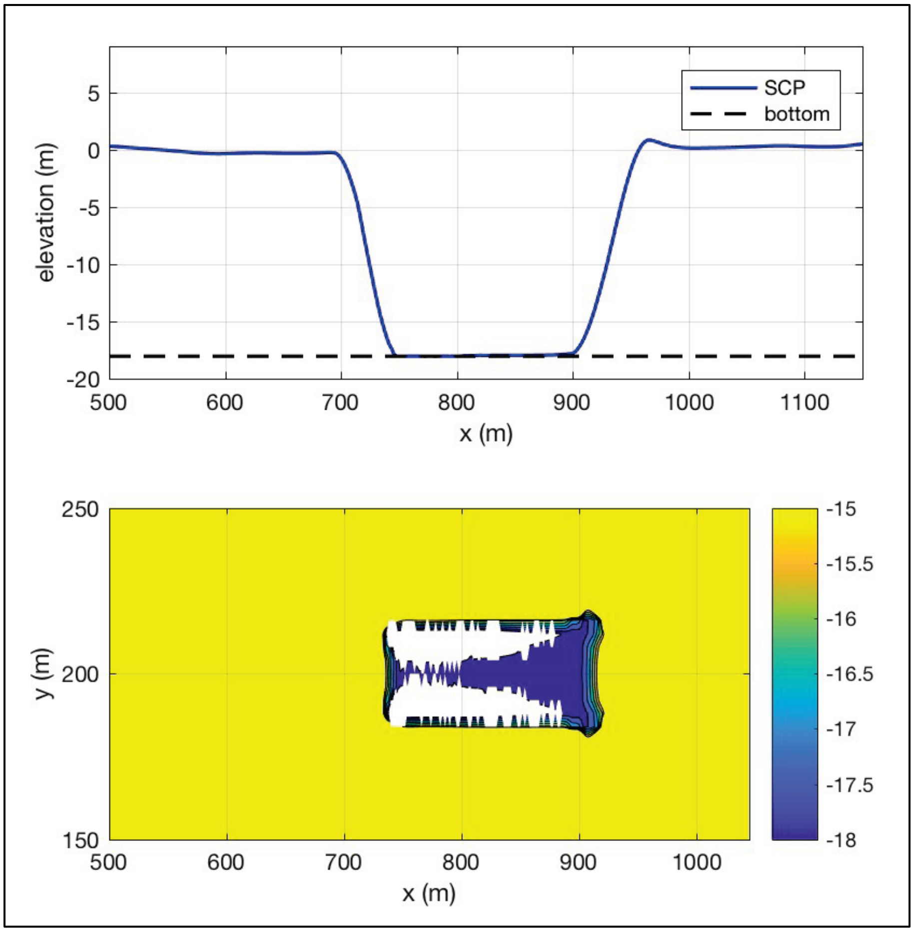

Figure 9. Strong test. 1D (top) and 2D (bottom) distributions of surface deformation modeled using the SCP method. Target draft: 20m; channel depth: 18 m. The white area represents dry points.

Far-Field Effects. To estimate the effects of the SCP and FRC methods on ship wakes in the far-field, comparisons were performed of surface elevations at a far-field location among cases: without treatment, with the SCP, and FRC methods. The recording gauge was specified at (x,y) = (600, 40) m, 160 m from the center line of the channel. Figure 10 shows the time series of surface elevation from the case without any treatment, the SCP method, and the FRC method with different frictional coefficients, respectively. The four models predict large bow wave crests with the magnitudes identical to each other. The magnitudes of depression waves predicted by the four different models are also similar. The FRC method with a large friction coefficient Cd = 1.0 slightly underpredict the wave trough. The model without treatment shows high-frequency oscillations, which may be induced by the spike under the vessel bottom as shown in Figure 2. The models with the SCP method and FRC method effectively reduces the high-frequency oscillations, and maintains the same longer wavelength trend as in the model without treatment. This comparison indicates that the SCP method and FRC method have a minimal effect on wave propagation in the far-field.

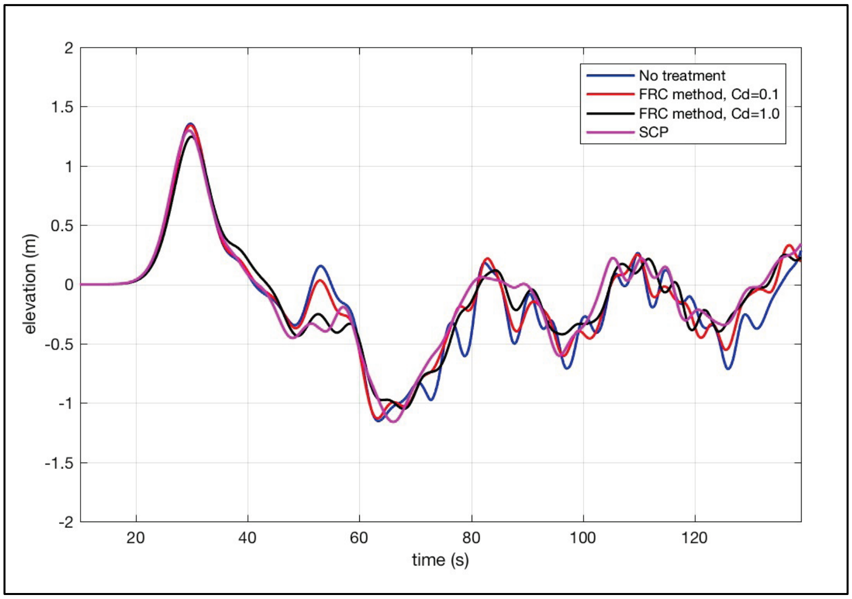

Figure 10. Time series of surface elevation at the location of (600 m, 40 m) from models without treatment, the SCP method, and FRC method with Cd = 0.1 and 1.0, respectively. Vessel draft: 15m, channel depth: 18 m.

SUMMARY: Three methods were developed to suppress numerical instabilities in modeling deep-draft vessels. The three methods are based on the SCP technique used in the TVD scheme and the local damping techniques originally used for modeling wave breaking and sponge layers in FUNWAVE-TVD. The three methods can be used as a stand-alone or a combination of two or three methods.

A series of tests was carried out using each method and their combinations. The test results are summarized below.

1. The SCP method and the FRC method are effective in suppressing high-frequency spikes generated by a deep-draft vessel. Without combining the methods, the SCP method alone is more effective compared to the FRC method.
2. The combined SCP/FRC method is the most effective method and was thus selected as the default option in the model. Both the SCP method and FRC method have limited effect on wave propagation in the far-field.
3. The VIS method had only a limited effect on suppressing high-frequency noises in the present tests. Further tests may be conducted with a large range of the viscosity coefficient and various model configurations.
4. A strong test shows that the high-frequency noises are not developed in the case of ship squat whenever the SCP method is used.

Model test examples can be downloaded from the **Github repository**. Additional documentation can be found on the **Project Wiki**.

ADDITIONAL INFORMATION: This CHETN is a product of the Navigation Systems (NavSys) Research Program being executed by the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this CHETN can be addressed to Dr. Matt Malej (voice: 603-646-4455; email: Matt.Malej@usace.army.mil). For information about the NavSys Program, please contact the NavSys Program Manager, Ms. Morgan M. Johnston (voice: 601-634-2365; email: Morgan.M.Johnston@usace.army.mil). This CHETN should be cited as follows:

> Malej, M., and F. Shi. 2021. *Suppressing the Pressure-Source Instability in Modeling Deep-Draft Vessels with Low Under-Keel Clearance in FUNWAVE-TVD*. ERDC/CHL CHETN-IX-55. Vicksburg, MS: US Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/40639

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APPENDIX: Sample **input.txt** steering file for FUNWAVE parallel simulation.

```
!INPUT FILE FOR FUNWAVE_TVD
  ! NOTE: all input parameter are capital sensitive
  ! --------------------TITLE-------------------------------------
  ! title only for log file
TITLE = DEEP DRAFT TEST
  ! -------------------PARALLEL INFO-----------------------------
  !    PX,PY - processor numbers in X and Y
  !    NOTE: make sure consistency with mpirun -np n (px*py)
PX = 2
PY = 2
  ! --------------------DEPTH-------------------------------------
  ! Depth types, DEPTH_TYPE=DATA: from depth file
  !              DEPTH TYPE=FLAT: idealized flat, need depth flat
  !              DEPTH_TYPE=SLOPE: idealized slope,
  !                                 need slope,SLP starting point, Xslp
  !                                 and depth_flat
DEPTH_TYPE = FLAT
DEPTH FILE = depth.txt
DEPTH_FLAT = 18.0
  ! -------------------PRINT---------------------------------
  ! PRINT*,
  ! result folder
RESULT FOLDER = output/
  ! ------------------DIMENSION-----------------------------
  ! global grid dimension
Mglob = 700
Nglob = 100
!---SPONGE LAYER----
FRICTION SPONGE = F
CDsponge = 10.0
Sponge west width=100.0
Sponge_east_width=100.0
!---NUMERICS----
CFL = 0.15
FroudeCap = 3.0
HIGH_ORDER = THIRD
  ! ----------------- TIME----------------------------------
  ! time: total computational time/ plot time / screen interval
  ! all in seconds
TOTAL TIME = 140.0
PLOT_INTV = 10.0
PLOT INTV STATION = 50000.0
SCREEN_INTV = 1.0
HOTSTART_INTV = 360000000000.0
PLOT START TIME = 0.0
  ! -----------------GRID----------------------------------
  ! if use spherical grid, in decimal degrees
  ! cartesian grid sizes
DX = 2.0
DY = 4.0
  ! ----------------SHIP WAKES ----------------------------
VESSEL_FOLDER = ./
NumVessel = 1
MASK9 = T
MaskMethod = T
FrictionMethod = T
ViscosityMethod = F
CdDeepDraft = 0.1
VisDeepDraft = 0.1
  ! -----------------OUTPUT-----------------------------
ETA = T
U = F
V = F
```