User Manual For PCOMCOT 1.0

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1. Introduction

PCOMCOT is a parallelized multi-grid tsunami simulation software, which is developed based on COMCOT (Cornell Multi-grid Coupled Tsunami Model). It is capable of simulating the entire life span of tsunamis – generation, propagation and inundation by solving nonlinear shallow water equations in a system of nested grids. Some important and novel features of PCOMCOT are listed below:

- Linear and nonlinear shallow water equations are solved in both cartesian and Earth spherical coordinates.

- Run-up and run-down processes are captured naturally without explicit treatment of moving boundary.

- Nested grids are set up automatically, and different nesting algorithms can be chosen.

- Calculation of tsunami Green's functions of fault slip and initial surface elevation is supported.

- The program is completely parallelized with Open MPI, and thus is highly suitable to be implemented on clustered high-performance computers.

2. Governing Equations

Conservative form of nonlinear shallow water equations in Cartesian Coordinates are given below:

$$\begin{cases} \dfrac{\partial \eta}{\partial t} + \dfrac{\partial M}{\partial x} + \dfrac{\partial N}{\partial y} = 0 \\[2mm] \dfrac{\partial M}{\partial t} + \dfrac{\partial}{\partial x}(\dfrac{M^2}{D}) + \dfrac{\partial}{\partial y}(\dfrac{MN}{D}) + gD\dfrac{\partial \eta}{\partial x} + F_x = 0 \\[2mm] \dfrac{\partial N}{\partial t} + \dfrac{\partial}{\partial x}(\dfrac{MN}{D}) + \dfrac{\partial}{\partial y}(\dfrac{N^2}{D}) + gD\dfrac{\partial \eta}{\partial y} + F_y = 0 \end{cases} \tag{1}$$

where η is the free surface elevation, (M, N) denote the volume fluxes in x- and y-directions, D is the flow depth (i.e., sum of still water depth h and surface elevation η), g is gravitational acceleration, and (F_x, F_y) are bottom friction in x- and y-directions. F_x and F_y can be evaluated with Manning's formula:

$$\begin{cases} F_x = \dfrac{gn^2}{D^{7/3}} M (M^2 + N^2)^{1/2} \\ F_y = \dfrac{gn^2}{D^{7/3}} N (M^2 + N^2)^{1/2} \end{cases} \tag{2}$$

with Manning's roughness coefficient n set to be 0.03 in general cases.

In Earth spherical coordinates defined by (R, x, y), where R is the constant radius of Earth, x and y are longitude and latitude respectively, the governing equations are presented as:

$$\begin{cases} \dfrac{\partial \eta}{\partial t} + \dfrac{1}{R \cos y} \left[\dfrac{\partial M}{\partial x} + \dfrac{\partial (N \cos y)}{\partial y} \right] = 0 \\ \dfrac{\partial M}{\partial t} + \dfrac{1}{R \cos y} \dfrac{\partial}{\partial x} (\dfrac{M^2}{D}) + \dfrac{1}{R} \dfrac{\partial}{\partial y} (\dfrac{MN}{D}) - \dfrac{\sin y}{R \cos y} \dfrac{2MN}{D} + \dfrac{gD}{R \cos y} \dfrac{\partial \eta}{\partial x} - 2N\Omega \sin y + F_x = 0 \\ \dfrac{\partial N}{\partial t} + \dfrac{1}{R \cos y} \dfrac{\partial}{\partial x} (\dfrac{MN}{D}) + \dfrac{1}{R} \dfrac{\partial}{\partial y} (\dfrac{N^2}{D}) + \dfrac{\sin y}{R \cos y} \dfrac{M^2 - N^2}{D} + \dfrac{gD}{R} \dfrac{\partial \eta}{\partial y} + 2M\Omega \sin y + F_y = 0 \end{cases} \tag{3}$$

where Ω is the angular velocity of Earth rotation, and the corresponding terms represent Coriolis force.

3. How to use PCOMCOT

3.1 Source Files and Compilation

All the source files of PCOMCOT and their content are listed in the table below. These files are written with Fortran90 and parallelized with MPI library.

Table 1. Source Files of PCOMCOT

Source File Name	Description
pcomcot.f90	main program of PCOMCOT
pcomcotLIB.f90	all subroutines except solving governing equations
MPICommunicationLIB.f90	subroutines for MPI communication between process
pcomcotNetCDFlib.f90	subroutines for reading input files in netCDF format
pcomcotNetCDFlibEmpty.f90	empty subs for compiling without netCDF library
solvEQNs.f90	subroutines for solving continuity and linear momentum equations
nonlinearFlux.f90	subroutines for solving nonlinear momentum equations
okada.f	subroutines for seabed static displacement based on Okada model
VariableDefination.f90	Declaration of derived data type used in PCOMCOT

PCOMCOT has been compiled and tested on Linux and macOS systems. Compilation and implementation will be tested on Windows in the future. To compile the source files, **gfortran –** the GNU Fortran compiler and **Open MPI –** a widely used message passing interface library should be installed. Besides, **netcdf-fortran,** the netCDF programming interface for Fortran is optional for compilation, which enables PCOMCOT to read input files in netCDF format. In Linux system, all the software required can be downloaded and installed easily from their official websites. In macOS, it is recommended to install them via a package management tool like Homebrew or Macports.

A makefile is given together with these source files, so PCOMCOT can be compiled with netCDF library linked by a simple "make" command, or a "make nocdf" command without netCDF library. In the makefile, the -I flag is used to specify the directory containing "netcdf.mod" file, and -L flag indicates the location of netCDF Fortran library for linking, and these paths may need to be changed depending on the user's environment.

3.2 Input files

There are basically six input files of PCOMCOT, some of which are required and some are optional. All the input files and their usage are presented in Table 2. Detailed descriptions of each input file will be given in subsequent subsections.

Table 2. Input files of PCOMCOT

Input File Name	Description
pcomcot.ctl (required)	control file providing basic information
layers.ctl (optional)	file setting layer-specific parameters
layerXX.xyz/nf (required)	bathymetry data files
InitialElevation.xyz/nf (required when Initial condition=0)	initial surface elevation
FaultParameters.ctl (required when Initial condition=1)	fault parameters
Stations.ctl (required)	coordinates of output stations

3.2.1 Input parameters of pcomcot.ctl

File "pcomcot.ctl" is required to provide necessary information of PCOMCOT simulation. Following are descriptions of input parameters in pcomcot.ctl

Basic control parameters

Purpose of Calculation: 1– forward simulation of tsunami waves; 2– calculating Green functions of finite-fault; 3– calculating Green functions of initial surface elevation.

Initial condition: 0 – initial water surface elevation is given as initial condition, to simulate transient wave propagation; 1– fault parameters are given as initial condition, to simulate earthquake tsunamis.

Boundary condition: numerical boundary condition imposed to the boundary of computing domain, only 1– wall boundary is supported so far.

Coordinate system: 0– spherical coordinates on Earth surface; 1– cartesian coordinates.

Total run time: simulation time in seconds.

Time step: time step size in seconds.

Time interval to Save Snapshots: time interval in seconds to save snapshots of surface elevation and flux components during simulation.

Save flux: 1– save snapshots of both surface elevation H and volume flux (M,N); 0 – only H is saved.

Minimum grids on each computing node: minimum number of grid points assigned to each computing node in parallel implementation.

Feedback to parent layer: options of grid nesting algorithm. 1– one-way nesting from outer to inner grids; 2– two-way nesting.

Parameters for Water Waves

Governing equation: 1– linear shallow water equations; 0– nonlinear shallow water equations

Dispersion: whether wave dispersion is calculated. Dispersion solver is under development and is not supported by this version.

Artificial viscosity coefficient: coefficient of artificial viscosity to eliminate short oscillations. We have not found any artificial viscosity is needed in realistic cases.

Parameters for Inundation

Permanent dry limit: maximum elevation of inundated land in meters.

Water depth limit: depth limit in meters when wet cells turn into dry.

Water depth Limit for bottom friction: minimum depth for including bottom friction.

Manning coefficient for bottom friction: Manning roughness coefficient in Manning's formula.

Parameters for computing Green's Functions (only for initial elevation)

Source aera starting longitude: west longitude of tsunami source region of initial elevation.

Source aera ending longitude: east longitude of tsunami source region of initial elevation.

Source aera discretization of grid size x: size in meters of sub-source region in longitude direction.

Source aera starting latitude: south latitude of tsunami source region of initial elevation.

Source aera ending latitude: north latitude of tsunami source region of initial elevation.

Source aera discretization of grid size y: size in meters of sub-source region in latitude direction.

Basic function type: type of point source function. 1– Gauss function; 2– Sigmoid function

Ratio of Gaussian radius/ grid size: ratio of Gaussian function radius to sub-source region size.

Sigmoid coefficient: coefficient defining the steepness of Sigmoid function.

3.2.2 Input parameters of layers.ctl

Input file "layers.ctl" is not required but optional. By giving "layers.ctl", PCOMCOT is more flexible for both accuracy and time-efficiency in realistic cases. When nested grids are used, every single grid file is called a layer. In "layers.ctl", the name of each layer is a two-digital integer consistent with the corresponding bathymetry file. There are three input parameters specific to each layer which are shown in the figure below. We can solve linear equations in the outer layer, and switch to nonlinear equations in fine inner layers near the coast where nonlinearity becomes significant. Besides, we can prescribe that a particular layer does not start computing until the tsunami waves approach its boundary from outside by setting the value of Computing starting time. If a layer is absent from "layers.ctl", all its parameters take the same values as those in "pcomcot.ctl".

```
#######################################################################
#                                                                     #
#          Layer Control file for PCOMCOT program (v1.0)              #
#                                                                     #
#######################################################################
#=====================================:===============================
#               Layer Name            :      01                      |
#=====================================:===============================
GoverningEquation      (0:nonlinear; 1:linear):     0
Dispersion                    (0:no; 1:yes):     0
Computing Starting Time            (second):     0.0

#=====================================:===============================
#               Layer Name            :      02                      |
#=====================================:===============================
GoverningEquation      (0:nonlinear; 1:linear):     0
Dispersion                    (0:no; 1:yes):     0
Computing Starting Time            (second):     500.0
```

Figure1. Content of layers.ctl

3.2.3 Format of bathymetry files

The input bathymetry data files must be named as "layerXX.nf" or "layerXX.xyz", where "XX" is a two digital number from 01 to 99 and does not have to be continuous if there are multiple bathymetry files. All files must have the format of NetCDF (binary, ending with ".nf") or "xyz" (ASCII, ending with ".xyz"). "nf" files can be obtained from commonly used bathymetry data sets provided by different organizations (e.g., GEBCO2020) with GMT commands (e.g., "grdcut" and "grdsample"); "xyz" files contains three columns, with the first column indicating x coordinates, the second y coordinates and the last one the local depth in meters. x and y coordinates should be given in meters for cartesian coordinates and in degrees for Earth coordinates. Data in "xyz" files must be sorted by x ascending and then y ascending order, e.g.:

(Line 1:)	138.000000000	33.000000000	4033.7974
(Line 2:)	138.016666667	33.000000000	4016.6523
(Line 3:)	138.033333333	33.000000000	4005.2083
(Lines...)	…		
(Line 842:)	138.000000000	33.016666667	4054.6309
(Lines...)	…		

Note that "nf" files have negative water depth compared with "xyz" files. For the settings of nested grids, there are two general rules. First, only one top layer is allowed; Second, one layer can contain others but cannot overlap another one without containing. There are no constraints on the location and grid size of any layer, but child layers with larger grid sizes than parent layers have not been tested.

3.2.4 Format of initial condition files

If initial elevation is selected as the initial condition in "pcomcot.ctl", an initial elevation file named "InitialElevation.nf" or "InitialElevation.xyz" must be prepared. "InitialElevation.nf/xyz" must have the same format as described above, with the exact same x and y coordinates as the bathymetry file of the top layer.

If initial condition is set to be "fault", fault slip of an earthquake is used as the tsunami source, and fault parameters of Okada's model must be given in the file "FaultParameters.ctl". An example of

"FaultParameters.ctl" is presented in Figure 2, where focal depth, latitude and longitude are all defined on the center of a rectangular fault.

```
################################################
#                                              #
# Control file for PCOMCOT program (v1.0)      #
#         MULTI-FAULT CONFIGURATION            #
################################################
#=============================================:=============================
#Parameters for Fault Segment 001             :Values                      |
#=============================================:=============================
 Fault Rupture Starting Time      (second):       0.0
 Focal Depth                      (meter):    4100.0
 Length of source area            (meter):   50000.0
 Width of source area             (meter):   25757.3
 Dislocation of fault plate       (meter):       0.000
 Rake                             (degree):     90.0
 Strike                           (degree):    193.0
 Dip                              (degree):     13.9
 Epicenter: Latitude              (degree):     39.506
 Epicenter: Longitude             (degree):    144.092

#=============================================:=============================
#Parameters for Fault Segment 002             :Values                      |
#=============================================:=============================
 Fault Rupture Starting Time      (second):       0.0
 Focal Depth                      (meter):    4100.0
 Length of source area            (meter):   50000.0
 Width of source area             (meter):   25757.3
 Dislocation of fault plate       (meter):       0.691
 Rake                             (degree):     90.0
 Strike                           (degree):    193.0
 Dip                              (degree):     13.9
 Epicenter: Latitude              (degree):     39.069
 Epicenter: Longitude             (degree):    143.961
```

Figure 2. Parameters in FaultParameters.ctl

3.2.5 Input Parameters of Station file

"Stations.ctl" is a three-column ASCII file indicating the x and y coordinates, and the name of each probe respectively. After simulation is done, the time series of surface elevation at each station are output. An example of "Stations.ctl" is given below.

```
141.424      40.925      202
144.397      42.911      613
141.684      38.233      801
141.894      38.858      803
142.187      39.627      804
148.6940     38.7110     21418
```

Figure 3. Example of Stations.ctl

3.3 Output Files

All the output files of PCOMCOT are presented in Table 3.

Table 3. Output files of PCOMCOT

File Name	Format	Description
_xcoordintesXX.dat	ASCII	x coordinates for layer XX; row vector
_ycoordintesXX.dat	ASCII	y coordinates for layer XX; row vector
bathymetryXX.dat	Binary	bathymetry for layer XX
zmax_XX.dat	Binary	maximum water elevation for layer XX
z_XX_xxxxxx.dat	Binary	snapshots of water elevation for layer XX, at time step xxxxxx
M_XX_xxxxxx.dat	Binary	snapshots of flux component M for layer XX, at time step xxxxxx
N_XX_xxxxxx.dat	Binary	snapshots of flux component N for layer XX, at time step xxxxxx
Stationyyyy.dat	Binary	time series of water elevation at station yyyy
Stationyyyy_M.dat	Binary	time series of water elevation at station yyyy
Stationyyyy_N.dat	Binary	time series of water elevation at station yyyy

*xxxxxx is a six-digital integer indicating the number of time step rather than the actual time.

*yyyy is a four-digital integer corresponding to the order in which stations are listed in "Stations.ctl".

Format of "bathymetryXX.dat", "z_XX_xxxxxx.dat", "zmax_XX.dat" "M_XX_xxxxxx.dat" and

"N_XX_xxxxxx.dat" is:

nColumn nRow (interger*4)

The first row of data (large y) (real*8) ...

The last row of data (small y) (real*8).

Format of "Stationyyyy.dat", "Stationyyyy_M.dat", "Stationyyyy_N.dat" is:

NDataLength NFaults (integer*4)

time (NDataLength, real*8)

water elevation in time (NDataLength, real*8).

The Matlab script "COMCOT_readBinaryDataSnapShot" provided together with the source files

can be used to read files "bathymetryXX.dat", "z_XX_xxxxxx.dat", "zmax_XX.dat"

"M_XX_xxxxxx.dat" and "N_XX_xxxxxx.dat", and "COMCOT_readBinaryDataStations" is for

reading files "Stationyyyy.dat", "Stationyyyy_M.dat", "Stationyyyy_N.dat".

4. Example – 2011 Tohoku Tsunami

Tsunami waves triggered by 2011 Tohoku earthquake is simulated with PCOMCOT as a test. We use two layers for deep ocean and coastal area of Japan, which is shown in Figure 4. The resolution of laye01 is 1 arcmin and layer02 is a 15-arcsec grid, both of which are cut from GEBCO2020. We add 6 stations in the case, to compare the simulation results with observation data.
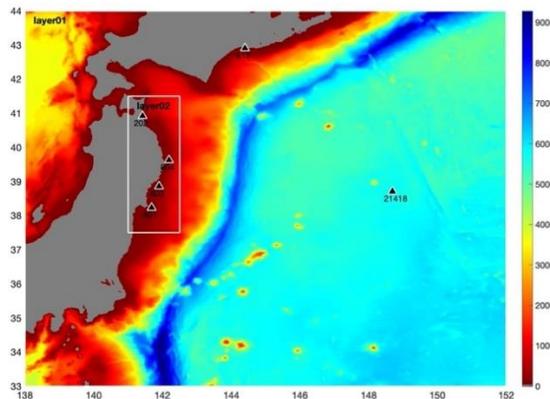
Figure 4. Bathymetry around Japan

To simulate wave nonlinearity in shallow area, we adopt linear equations in layer01, and nonlinear equations in layer02. The parameters in "pcomcot.ctl" and "layers.ctl" are given below.

```
########################################################################
#                                                                      #
#             Control file for PCOMCOT program (v1.0)                  #
#                                                                      #
########################################################################
#=====================================:================================
# Basic Control Parameters            :      Values                   |
#=====================================:================================
  Purpose of Calculation       (Choose 1,2,3)  :    1
  Initial Condition          (0:file, 1:fault):    1
  Boundary Condition    (0:Open; 1:Wall; 2:Sponge):  1
  Coordinate System     (0:spherical, 1:cartesian):  0
  Total run time                   (second):    4000.0
  Time step                        (second):    2.0
  Time interval to Save Snapshots  (second):    2000.0
  Save Flux                  (0:no, 1:yes) :    0
  Minimum grids on each computing node     :    2000
  Feedback to parent layer     (0:no, 1:yes):   0


#=====================================:================================
# Parameters for Water Waves          :      Values                   |
#=====================================:================================
  GoverningEquation     (0:nonlinear; 1:linear):   0
  Dispersion                 (0:no; 1:yes):    0
  Artificial Viscosity coefficient         :    0.0


#=====================================:================================
# Parameters for Inundation           :      Values                   |
#=====================================:================================
  Permanent Dry Limit for Inundation   (meter):    50.0
  Water depth Limit for wet -> dry     (meter):    0.01
  Water depth limit for Bottom Friction (meter):   0.05
  Manning coefficient for bottom friction  :    0.03


#=====================================:================================
# Parameters for Computing Green's Functions  :  Values               |
#=====================================:================================
  Source Area Starting Longitude           :    00.00
  Source Area Ending    Longitude          :    00.00
  Source Area Discretizatoin Grid Size X  (meter):  00.00
  Source Area Starting Latitude            :    00.00
  Source Area Ending    Latitude           :    00.00
  Source Area Discretizatoin Grid Size Y  (meter):  00.00
  Basis Function Type      (1/Guass; 2/Sigmoid):   1
  Ratio of Gaussian Raidus / Grid Size     :    1.0
  Sigmoid Coefficient 1/(1+exp(-x/(DX*coef)))  :   1.0
```

Figure 5. Parametes in pcomcot.ctl for the case of 2011 Tohoku

```
####################################################################
#                                                                  #
#             Layer Control file for PCOMCOT program (v1.0)        #
#                                                                  #
####################################################################
#===============================:===================================
#                Layer Name     :     01                           |
#===============================:===================================
GoverningEquation   (0:nonlinear; 1:linear):     1
Dispersion                  (0:no; 1:yes):       0
Computing Starting Time        (second):         0.0

#===============================:===================================
#                Layer Name     :     02                           |
#===============================:===================================
GoverningEquation   (0:nonlinear; 1:linear):     0
Dispersion                  (0:no; 1:yes):       0
Computing Starting Time        (second):         0.0
```

Figure 6. Parameters in layers.ctl for the case of 2011 Tohoku

The fault geometry is obtained from moment tensor solution provided by USGS, and the fault plane is divided into 48 sub-faults, the slip of which is estimated through tsunami inversion. The time series of water elevation at the stations are in good agreement with observations, as is shown in Figure 7.
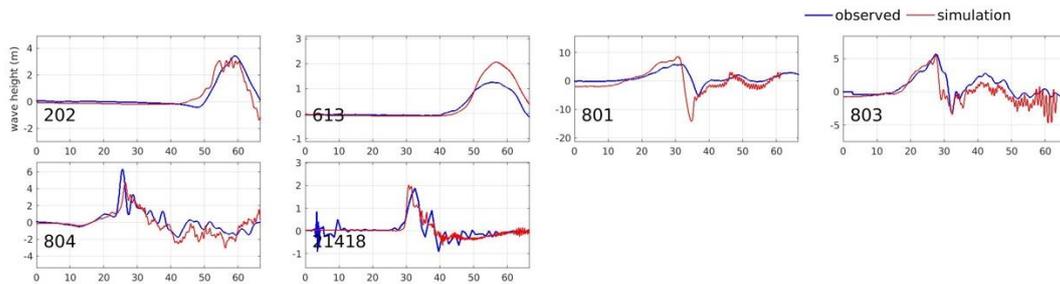
Figure 7. Comparison of PCOMCOT simulation and observed tsunami waves

5. Citation of PCOMCOT

To publish work involving the use of PCOMCOT, please cite the papers below.

1. Wang, X. & Liu, P.L.-F., 2006. An analysis of 2004 Sumatra earthquake fault plane mechanisms and Indian ocean tsunami, *J. Hydraul. Res.,* **44**(2), 147–154.

2. An, C., Sepúlveda, I. & Liu, P.L.-F., 2014. Tsunami source and its validation of the 2014 Iquique, Chile, earthquake, *Geophys. Res. Lett.,* **41**(11), 3988– 3994.

3. Zhu, Y. F., An, C., Wang, T., & Liu, H. (2021). Time-Dependent Tsunami Source Following the 2018 Anak Krakatau Volcano Eruption Inferred from Nearby Tsunami Recordings. *China Ocean Engineering*, **35**(1), 145-152.