

SSP PhD Topic

Analysis of ocean pipeline behavior by parallel large-eddy simulation of fluid motions and sediment transport:

A Singapore–Stanford Partnership proposal

O. B. Fringer¹, Yee Meng Chiew², and R. L. Street¹

¹ Environmental Fluid Mechanics Laboratory, Stanford University, Stanford, CA 94305-4020

² Nanyang Technological University, Singapore 639798

29 February 2004

1. Overview

“With technological advancements in the field of subsea pipeline surveying and installation continuing at an astounding pace, deep waters that were only recently considered off limits to oil and gas producers are now suddenly accessible.” [1] At the same time the dangers to the longevity of the pipeline and the health of the surrounding environment grow at an equally astounding pace. Forces due to ocean current, tide, internal wave and surface wave motions can both erode sediment and protective rock barriers and subsequently exert prodigious drag forces on and break exposed and spanning pipelines.

This project begins with two solid bases. First, the experimental work of Professor Chiew establishes from laboratory data many of the key parameters and forces that need to be considered. To this is added Professor Chiew’s personal experience with subsea pipelines and their failures under rather common ocean conditions. Second, Professors Fringer and Street have established a strong base of numerical simulation techniques for wave and current processes and sediment transport. The goal of this project is then to synthesize the information from these bases and to create a numerical simulation tool for both the study of the fundamental processes occurring and for application to and analysis of real field situations. In particular, we hope to answer the following specific questions: (1) what is the effect of three-dimensional motions on the predicted outcomes as compared to laboratory results for pipeline cases which nominally are two-dimensional; (2) what is the effect of the flow field on the development of span length of the pipeline, which is crucial in determining its stability.

The study will involve merging of existing sediment transport models and numerical techniques into a parallel Navier-Stokes solver in order to obtain high-resolution computations of the velocity, sediment, and shear stress distributions around different coastal ocean beds and pipeline geometries. The forces on the pipelines will be deduced from the flow fields. The results will be compared to laboratory-scale data and field-scale data.

The project will involve one Ph.D. student from NTU who will spend half of the project time working with the simulation code at Stanford University under Professors Fringer and Street,

who specialize in parallel and sediment transport computations, and the rest of the time performing production runs and analyzing and verifying simulation data at NTU under Professor Chiew, who specializes in laboratory-scale scouring experiments and field-scale analysis and interpretation of bed behavior about real pipelines.

2. Brief background and experimental context

Sediment at the bed of a body of water does not erode as long as the shear stress imposed by the overlying flow is lower than some critical value. When an obstruction is added to the bed, such as a bridge pier, an abutment or a pipeline laid on or buried beneath the bed, the flow field adjusts to accommodate it and elevates the shear stress around the obstruction, leading to erosion. For a fixed set of flow conditions, erosion, or scouring, continues until the shear stress falls and reduces the Shields parameter below its critical value, resulting in an equilibrium condition. An understanding of this equilibrium condition is crucial to the design of water-bound structures in order to determine the depth at which the structural foundation must be built beneath the bed or, in the case of pipelines, the nature and efficacy of riprap cover layers, for example.

Professor Chiew has performed laboratory experiments to determine the scour behavior at submarine pipelines. In those studies, he has examined the mechanics of pipeline scour initiation [2] and prediction of maximum scour depth under unidirectional current [3]. Additionally, he also has explored how placement of spoilers on a pipeline would affect its self-burial behavior [4a, b]. Notwithstanding these and other studies, most research to date is confined to work done with a two-dimensional scour hole. Under such conditions it is not possible to explore how the pipeline span length evolves in response to a given flow condition. The present study aims to extend the present knowledge on pipeline scour from two-dimensional to three-dimensional conditions.

3. Numerical tools

3.1 Large-eddy simulation codes leading to sediment transport

The Environmental Fluid Mechanics Laboratory (EFML) at Stanford University has considerable experience with direct numerical and large-eddy simulations of laboratory-scale environmental flows. Our sediment transport simulations employ the method developed by Zang, et al. [5], in which the equations of motion are solved on a curvilinear coordinate nonstaggered grid. Fringer and Street [6] studied the fundamental physics of breaking interfacial waves with a version of this code. The equations are discretized in time using a fractional step approximate projection method and the pressure field is solved using the conjugate gradient method for the sediment transport case with an immersed boundary method for representation of the boundary. Zedler and Street [7 & 8] modified the code to study sediment transport over ripples. Under an ONR grant, they are currently implementing the immersed boundary method (IBM) of Tseng and Ferziger [9] in order to study erosion rates around mines. The IBM method is ideally suited to

studying erosion problems because it provides for a seamless method to implement moving boundaries into a complex LES code. Instead of moving the actual grid, the IBM method moves the boundary and effectively adds forcing terms to the Navier-Stokes equations so as to satisfy the time-varying boundary conditions.

3.2 Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator [SUNTANS]

The Environmental Fluid Mechanics Laboratory also has extensive experience with parallel flow solvers and parallel computing. For example, Cui and Street [10 & 11] adapted the large-eddy simulation solver of Zang to simulate laboratory-scale rotating stratified flows using MPI, the message passing interface, on parallel computers. That code was 41% faster than the next comparable code on the NASA IBM SP-2 [12]. Fringer, et al. [13 & 14] are in the process of developing a parallel coastal ocean model [SUNTANS] to simulate internal wave dynamics in Monterey Bay, California, and Mamala Bay, Hawaii. This model employs parallel unstructured adaptive grids to solve the nonhydrostatic equations with a large-eddy simulation for the resolved motions.

In SUNTANS [<http://suntans.stanford.edu>], we synthesize a number of computational and numerical tools to produce an innovative and powerful coastal ocean simulation tool. Below we summarize the main technical and computational features of the code.

a. Accurate modeling of advection

The advection is computed with a second-order-accurate, energy and momentum conserving Eulerian scheme.

b. Free surface treatment

The free surface is accurately simulated using a semi-implicit discretization. This formulation guarantees local and global mass conservation. Because of implicit treatment of vertical viscous and turbulence effects, bottom friction and wind stresses, the stability of the method is independent of these terms, as well as the surface wave celerity.

c. Efficient calculations in the vertical

Our code requires intense computations in the vertical for the vertical integration resulting from the free surface, as well as large eddy simulation. We employ structured grids in the vertical and store data in each vertical line in the water column contiguous in memory to ensure data locality and hence improve the code efficiency. Also the structured grid volume and scalar conservation are important when integrals over each water column are computed, and they improve the accuracy in computing baroclinic pressure gradients.

d. Accurate representation of bathymetric and coastal features

Accurate representation of bathymetric and coastal features requires severe changes in grid density from one part of the computational domain to another. Unstructured grids are ideal for dealing with these large grid changes. They are employed in horizontal planes, each of which may have a different thickness as one moves vertically in the water column. The unstructured grids are generated using the Triangle code developed by Shewchuk [15], which employs Delaunay triangularization. Delaunay grids generally are of high quality with triangles as close to equilateral as possible.

e. Parallelization

The most time-consuming part of the code is likely solving the elliptic pressure equations. We use the Parallel Extensive Toolkit for Scientific Computing (PETSC) for this purpose. PETSc is a parallel solver package written in C and based on the MPI message passing interface. PETSC offers state-of-the-art elliptic solvers that have been shown to perform exceptionally well on parallel computer architectures, including algebraic multigrid solvers. Load balancing is done with the graph partitioning software ParMetis.

f. Capturing internal waves breaking and other fine-scale phenomena

To accurately model internal wave breaking and turbulent mixing, very high grid densities are required locally. In areas, such as in canyons and near ridges, where we expect important fine-scale phenomena, the base computational grid is refined.

g. Boundary representation

The boundary representation will be implemented by the use of the immersed boundary method, which allows smooth representation of the boundaries without need for terrain-following grids. One of our colleagues has already implemented this IBM method in several codes [9], and we will port his implementation to SUNTANS.

h. Turbulence modeling

A simple vertical subfilter-scale turbulence model and a horizontal eddy viscosity are currently available in our unstructured codes. In the future we will employ large-eddy simulation combined with an accurate subfilter scale model to resolve the important energetic motions of the flow. The subfilter scale model we employ is a state-of-the-art velocity estimation model [16 & 17].

i. Sediment transport

Sediment transport calculations will be made using the excellent method developed by Spasojevic and Holly, and presented by Gessler et al. [18]. Sedimentation computations will be based on a two-dimensional solution of the conservation equation for sediment mass at the bed, and a three-dimensional advection-diffusion equation for suspended sediment transport. The sediment transport will be calculated at each time step and the bed will be adjusted to account of the effects of erosion and deposition. Dr. Zedler is implementing these options in her version of the Zang/Cui codes at this time so there will be important progress to build on.

3.3 Computational resources

We have the ability to use SUNTANS on-site in our laboratory with the use of our Beowulf parallel computing cluster at the Peter A. McCuen Environmental Computing Center [<http://fluid.stanford.edu/mccuencenter/>]. Currently, the cluster consists of 40 Compaq/Alpha 667 MHz CPUs with a total of 24 Gb of RAM and a 2 Gigabit Myrinet interconnect. The cluster is presently capable of performing simulations with 256^3 computation cells, and we are constantly updating and expanding it to accommodate improved architectures and programming methodologies.

4. Proposed Work

The work involves merging of existing sediment transport models and numerical techniques into a parallel Navier-Stokes solver in order to obtain high-resolution computations of the velocity, sediment, and shear stress distributions around different coastal ocean beds and pipeline geometries. The forces on the pipelines will be deduced from the flow fields. The results will be compared to laboratory-scale data and field-scale data.

4.1 Timeline of proposed work

The work would involve one Ph.D. student who would work towards the completion of his or her doctoral dissertation at Nanyang Technological University in Singapore, under the direction of Professor Chiew as the student's principal advisor, and Professors Oliver Fringer and Robert Street, as the student's co-advisors. With regard to sediment modeling and its implementation in SUNTANS, it is expected that this student will collaborate with another NTU student who is working on scour at abutments. The SUNTANS users group in the EFML will also provide a useful resource.

Year one: Stanford University

- Learn how to use the parallel solver, SUNTANS.
- Participate in implementation of sediment transport and immersed boundary method modules.

Year two: Nanyang Technological University

- Test immersed boundary and sediment transport modules.
- Set up and carry out simulation of three-dimensional flow cases related to laboratory experiments.
- Set up bathymetry and data for field-scale case.
- Prepare laboratory work and conduct experiments
- Run simulations of field-scale scour problems to study the effects of a predetermined parameter space. Compare to laboratory-scale simulations.

Year three: Nanyang Technological University

- Continue experimental study with different parameters
- Continue simulation

Year four: Nanyang Technological University

- Complete experimental study
- Complete simulations of field-scale problems to verify new implementations.
- Write up dissertation.

References

- [1] S. Troscinski. Subsea pipelines: Inspection and maintenance [at] increasing depths offer new challenge to repair contractors. UnderWater Magazine, Winter, 2 pages, 1998.

- [2] Y. M. Chiew. Mechanics of local scour around submarine pipelines. *J. Hydraulic Engineering*, 116: 515-529, 1990.
- [3] Y. M. Chiew. Prediction of maximum scour depth at submarine pipeline. *J. Hydraulic Engineering*, 117: 452-466, 1991.
- [4a] Y. M. Chiew. Effect of spoilers on scour at submarine pipelines. *J. Hydraulic Engineering*, 118: 1311-1317, 1992.
- [4b] Y. M. Chiew. Effect of spoilers on wave-induced scour at submarine pipelines, *J. Waterway, Port, Coastal and Ocean Engineering*, 119: 417-428, 1993.
- [5] Y. Zang, R. L. Street, and J. R. Koseff. A non-staggered grid, fractional step method for time-dependent incompressible Navier-Stokes equations in curvilinear coordinates. *J. Comput. Phys.*, 114:18–33, 1994.
- [6] O. B. Fringer and R. L. Street. The dynamics of breaking progressive interfacial waves. *J. Fluid Mech.*, 494:319–353, 2003.
- [7] E. A. Zedler and R. L. Street. Large-eddy simulation of sediment transport: currents over ripples. *J. Hydraulic. Eng.*, 127:442–452, 2001.
- [8] E. A. Zedler and R. L. Street. Nearshore sediment transport processes: unearthed by large eddy simulation. 28th International Conference on Coastal Engineering, ASCE, 2504-2516, 2002.
- [9] Y. H. Tseng and J. H. Ferziger. A ghost-cell immersed boundary method for flow in complex geometry. *J. Comput. Phys.*, 192: 593-623, 2003.
- [10] A. Cui and R. L. Street. Parallel computing of laboratory-scale realizations of rotating and stratified fluid flows. The 2000 International Conference on Parallel and Distributed Processing Techniques and Applications:1423–1429, 2000.
- [11] A. Cui and R. L. Street. Large eddy simulation of rotating convective flow development, *J. Fluid Mech.*, 447: 53-84, 2001, and A. Cui and R. L. Street. Large-eddy simulation of coastal upwelling flow. *Environmental Fluid Mechanics*, 4: 197-223, 2004.
- [12] R. Bergeron. Measurement of a scientific workload using the IBM hardware performance monitor. Proceedings of the Supercomputing'98 Conference, Orlando, 1998.
- [13] O. B. Fringer, M. Gerritsen, S. Jachec, and R. L. Street. A new nonhydrostatic parallel coastal ocean model. *Eos Transactions, AGU*, 83(47): Abstract OS11C-0238, 2002.
- [14] O. B. Fringer and A. B. Boehm. Cross shelf transport induced by internal tides, ASLO/TOS Ocean Research Conference, Honolulu, 2004.
- [15] J. R. Shewchuk. Triangle: Engineering a 2D Quality Mesh Generator and Delaunay Triangulator, in *Applied Computational Geometry: Towards Geometric Engineering*, vol. 1148, edited by M. C. Lin and D. Manocha, pp. 203-222, Springer-Verlag, 1996.
- [16] F. K. Chow, F. and R. Street. Modeling unresolved motions in LES of field-scale flows. 15th Conference on Boundary Layers and Turbulence, AMS, 432-435, 2002.
- [17] F. K. Chow and R. L. Street. Explicit filtering and reconstruction turbulence modeling for large-eddy simulations of field-scale flows. 6th International Conference on Hydrosience and Engineering, Brisbane, Aus, 12 pages [Invited], 2004.
- [18] Gessler, D., Hall, B., M. Spasojveic, M., Holly, F., Pourtaheri, H., and Raphelt, N. Application of 3D mobile bed, hydrodynamic model. *Journal of Hydraulic Engineering*, 125: 737-749, 2001.