Computational Modeling of the Hydraulics in a Realistic Subglacial Conduit in Arctic

Yunxiang Chen[1], Xiaofeng Liu[1], and Kenneth D. Mankoff[2]
[1]Department of Civil & Environmental Engineering, Pennsylvania State University
[2]Department of Geosciences, Pennsylvania State University

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Introduction

The global warming is accelerating the ice losses of the **Greenland Ice Sheet** (GIS), resulting speedy sea level rise and changing global ocean circulation and regional climate[1]. There have been a lot of studies on the surface ice losses in GIS, however, very few exists on the subsurface ice losses processes due the lack of real geometry data. To this end, we measured a realistic **subglacial conduit** under Svalbard, near the Arctic, as illustrated in Figure 1.

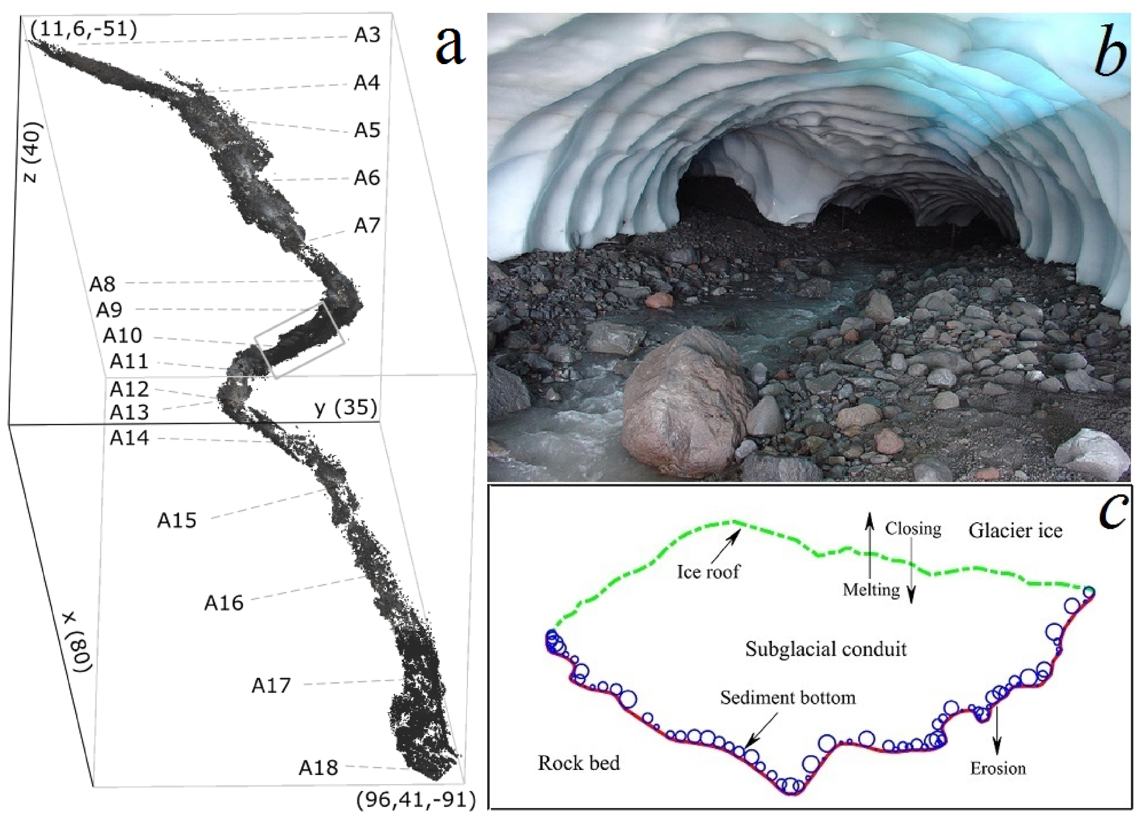

Figure 1: The measured subglacial conduit (a), the appeareance of the conduit (b), and the idealized conduit cross-section.

Based on the surface data and computational fluid dynamics tools, i.e., OpenFOAM, and NGA, we are trying to answer four **questions**:

1. How does the equivalent roughness height relate to the parameterized surface features?
2. How does the conduit development relate to the fluid and thermodynamics?
3. How does the sediment change the conduit and glacier outlet environments?
4. Can we back-calculate the discharge of the subglacial conduit from the characteristics of its turbulent buoyant plumes?

Surface features

The subglacial surface is a complex geometry with **multi-scale roughness, sinuosity**, and **cross-sectional contraction and expansion**. Identification and parameterization of those surface features is the first step to quantify their influences on the hydraulics and transport. A Matlab® code, named as **STL2Conts**, was developed to achieve this goal. The code follows the following procedures:

(a). Extracting contours from original STL.

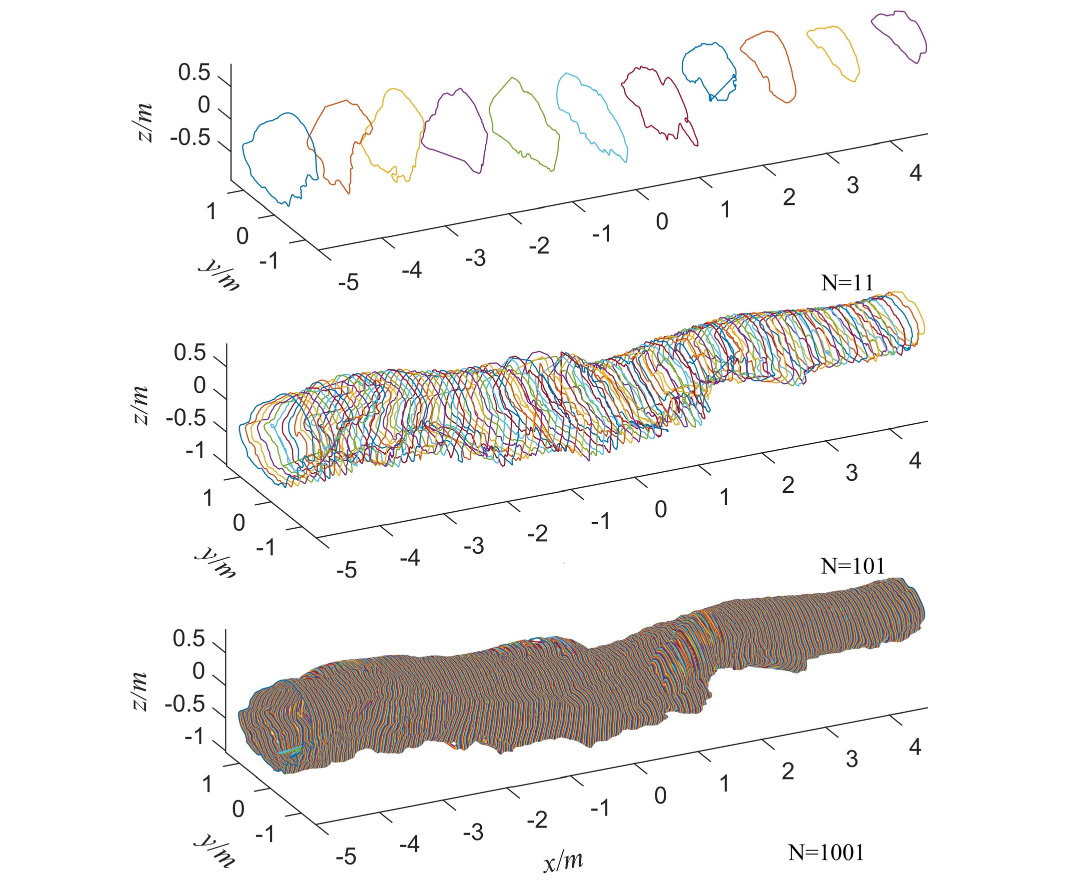

Figure 2: The contours sliced from original STL. The slicing spacing is 0.1m (N=11), 0.01m (N=101), and 0.001m (N=1001).

(b). Calculating interested surface features, e.g., area, center, maximum radius points, principle axes, mean curves, roughness, etc.

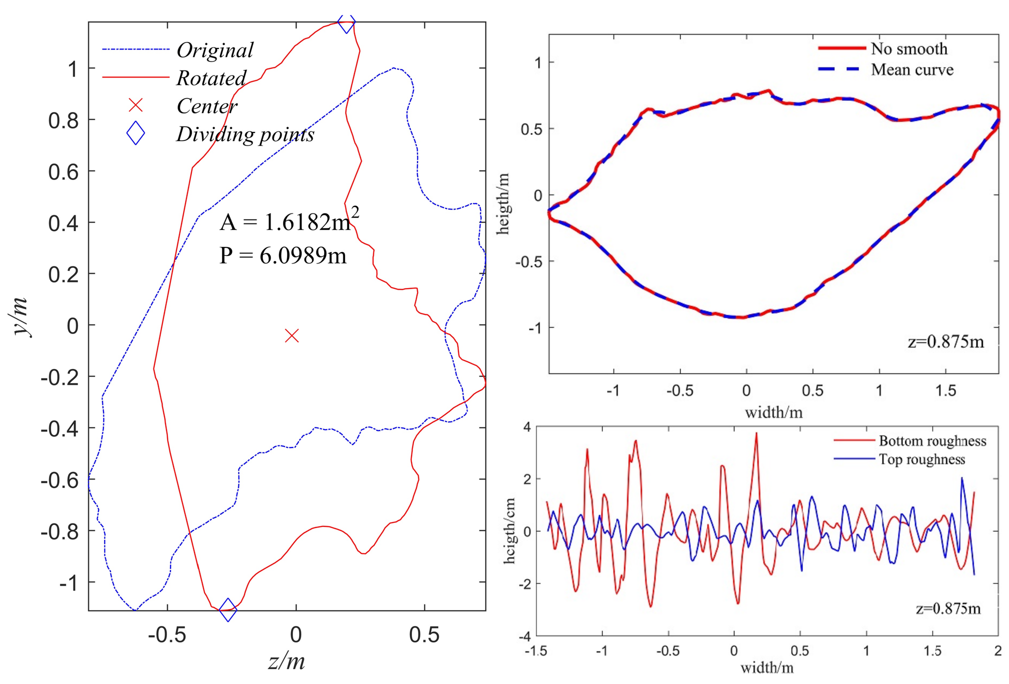

Figure 3: Surface features calculation.

CFD Simulations

Figures 2 and 3 demonstrate that we can obtain all contours that only contain interested surface features information, if we can further convert those contours into surfaces, then we can use CFD simulations to quantify the role of each surface feature. Another Matlab® code, named as **Conts2Mesh**, was developed to achieve this goal, as shown in Figure 4.

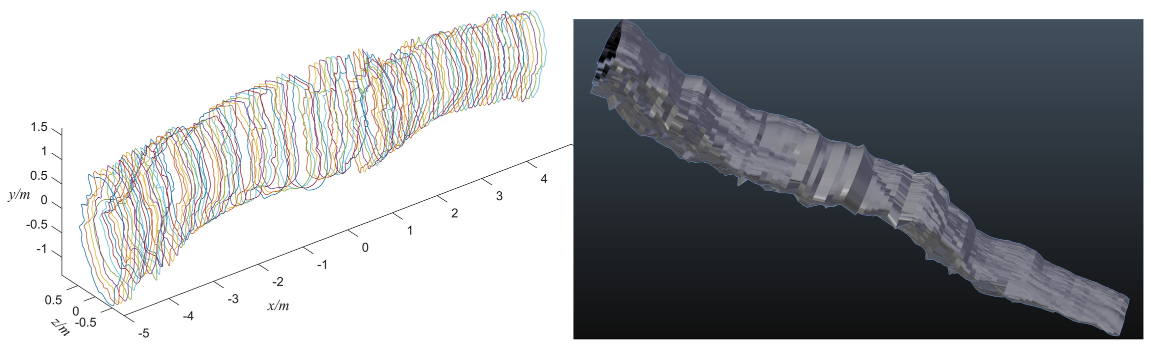

Figure 4: Reconstructing a surface from contours.

With those reconstructed surfaces which denote different surface features, we use the snappyHexMesh in **OpenFOAM** to generate the mesh, as shown in Figure 5.

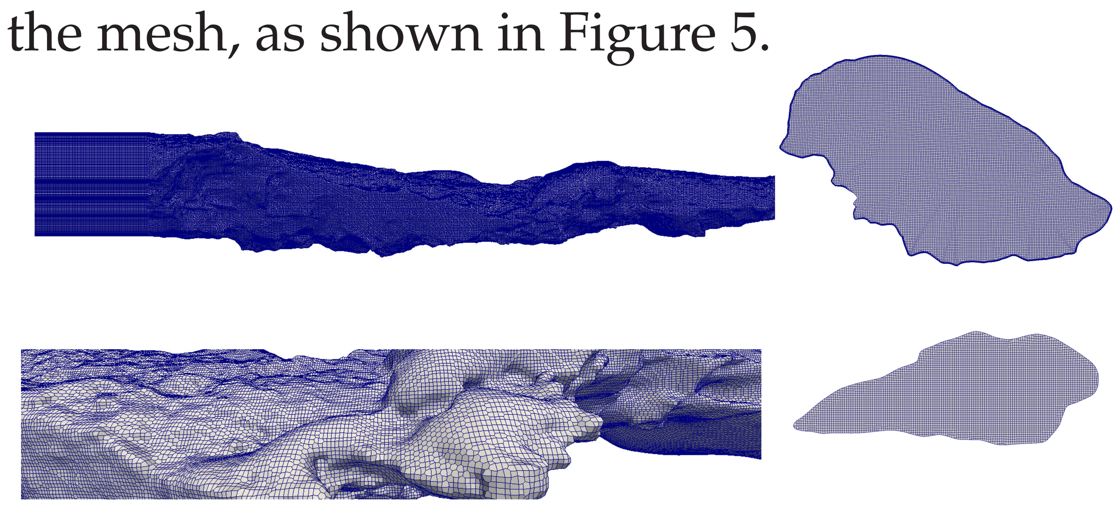

Figure 5: The generated mesh based on the original geometry. The upper and lower left figures are global and local meshes, while the upper and lower right figures denote inlet and outlet meshes.

The flow field and sediment transport process are solved by Equations 1,2, and 3, where $\overline{u}_i$ and $\overline{p}$ denote the filtered velocity and pressure, ν_{sgs} is the sub-grid scale (SGS) eddy viscosity, closed by a dynamic one-equation SGS model by[2],C is a transport scalar, while P_C are possible source terms. We will add the heat transfer and the buoyant effects into the equations later.

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + (\nu + \nu_{sgs}) \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} \tag{2}$$

$$\frac{\partial C}{\partial t} + \overline{u}_j \frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D \frac{\partial C}{\partial x_j}\right) + P_c \tag{3}$$

Results: roughness

Define **structure function**[3] by Equation 4. $z_r(x, y)$ is the de-trended roughness height, Δx and Δy denote the correlation distances, p is the order of the structure function, and Γ is domain size. Figure 6 shows the non-dimensionalized transverse and longitudinal structure functions.

$$D_{Gp} = \frac{1}{N}\sum_i \sum_j |z_r(x_i + \Delta x, y_j + \Delta y) - z_r(x, y)|^p, (x_i + \Delta x, y_j + \Delta y) \in \Gamma \tag{4}$$

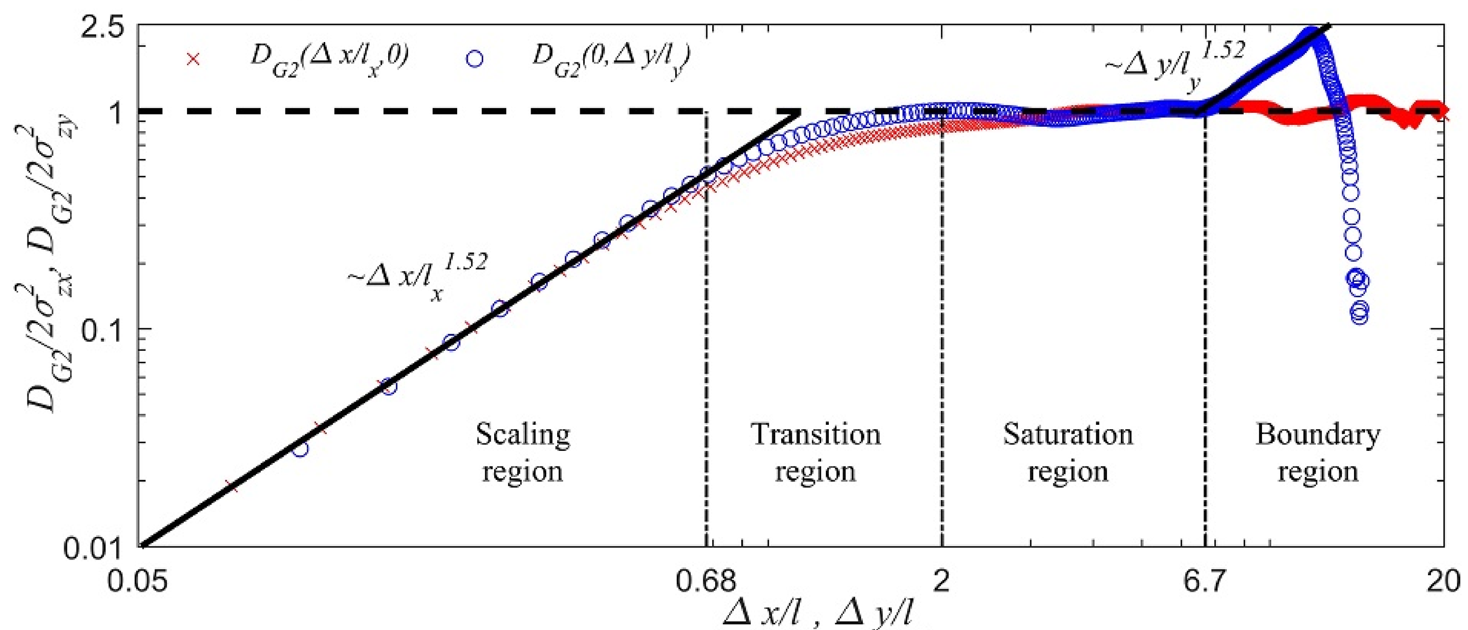

Figure 6: The non-dimensionalized transverse and longitudinal structure functions. l_x and l_y denote horizontal length scales, while σ_{zx} and σ_{zy} denote vertical roughness scales.

Results: flow structures

Figure 7 shows that the instantaneous velocity and pressure reach a quasi-steady state after a certain time, and the velocity falls into the range of a real subglacial conduit flow, proving that the meshing and boundary conditions set-up are acceptable.

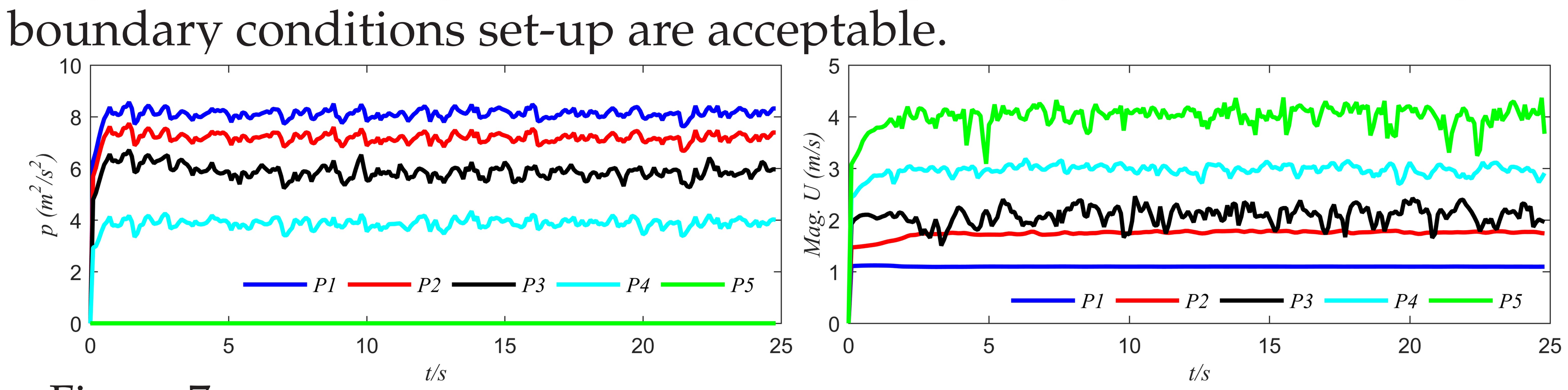

Figure 7: The time history of the instantaneous pressure and velocity magnitude at 5 locations.

Figure 8 illustrates the near wall **flow structures**, expressed by λ_2.

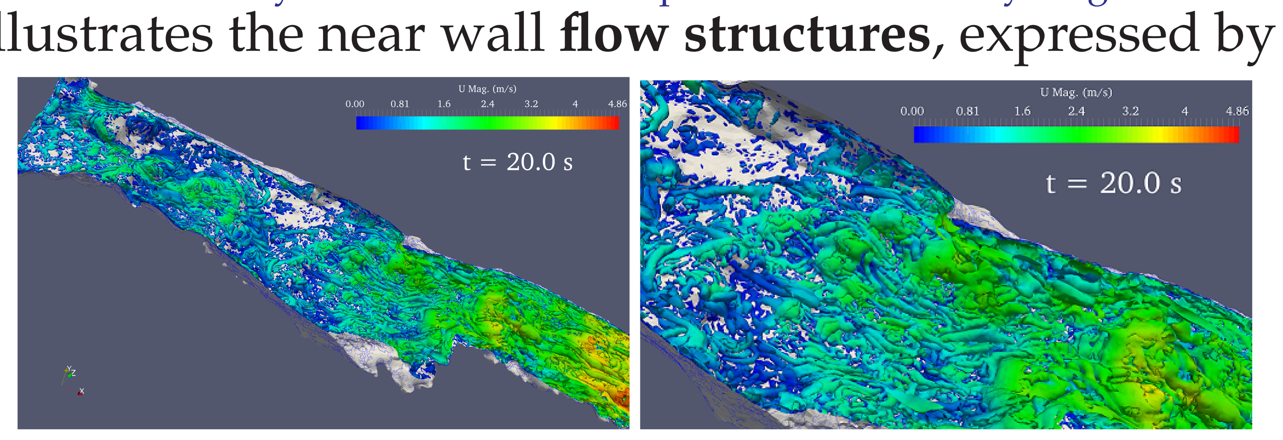

Figure 8: The near wall flow structures. The left and right figures denote global and local views.

References

[1] Intergovernmental Panel on Climate Change Assessment Report 5, Ch. 4 and Ch. 13., 2013
[2] Davidson, L., Large eddy simulation: a dynamic one-equation subgrid model for three-dimensional recirculating flow. *Proc. 11th Int. Symp. Turbul. Shear Flow*, 3(26):1-6,1997.
[3] Kolmogorov, A.N., The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. *Dokl. Akad. Nauk SSSR*, 30(1890):299-303,1941.

Future Research

(1). Optimizing the STL2Conts and Conts2Mesh codes, and combining those two codes into one STL2Mesh.
(2). Calculating and parameterizing the roughness, sinuosity, and cross-sectional areas for all contours.
(3). Reconstructing the simplified contours into geometries, and conducting simulations based on the geometries.
(4). Adding an energy equation to Eqs. (1)-(3) to consider the ice-melting and conduit enlargement processes.