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Finite Element Modeling of Biomass Hopper Flow

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Abstract. *The hopper is one of the widely used biomass handling devices that channels the bulk biomass from storage to the subsequent handling systems. Although Jenike's approach has been successfully used for hoppers handling grains and other agricultural produces for decades, designing a hopper, ensuring reliable biomass handling is found to be challenging. This study aims to address this engineering problem with alternative constitutive material models concerning the flow behavior of bulk solids. Finite element modeling is an approach that allows for implementing different material models. Underlying constitutive theories of different material models assist in investigating the mechanical behavior of a particulate system, including the flow characteristics of ground biomass. This study demonstrates hopper flow models of two types of biomass, i.e., ground corn stover and Douglas fir, with the Mohr-Coulomb model, which is based on Jenike's approach, modified Cam-Clay model, and Drucker-Prager/Cap model. The modeling results are compared with hopper flow experiments to highlights the advantages and shortfalls of each constitutive biomass flow model.*

Introduction

The term' Biomass flowability' suggests quantitative metrics indicating the ability of biomass to flow. In reality, the 'flowability' of bulk solid cannot be expressed with a single parameter or set of parameters. This is because that a' flowability' is the result of interactions between the physical properties of bulk biomass, which affect the material flow, and the equipment, which is used for handling and storing biomass. In order to analyze and predict the flow behavior of biomass, an appropriate' biomass flowability' model should account for the material properties and equipment characteristics in tandem. Therefore, the computational approach is a capable tool for modeling the' biomass flowability.'

In this study, the biomass flow model comprises a material model describing bulk biomass behavior and a structural model describing biomass handling and storing equipment. The popular material flow model of the particulate system includes the continuum model and particle-based model. Widely used elasto-plasticity models (Jenike 1964, 1967, 1961; Jin et al. 2020; Resende Luis and Martin John B. 1985; Jiang and Wu 2012; Han et al. 2008; Drucker and Prager 1952) or critical state models (Szalwinski 2017; Schofield and Wroth 1968) are continuum models. Recently, the discrete element model is actively studied in biomass flow and is the most widely used particle-based model owing to the advancement of computing capability.

The structural model of biomass handling is equally important but not as systematically studied. The critical aspects of the structural model include the geometry of a specific handling and storing equipment. Also, the interaction between biomass particles and the wall of biomass handling equipment is crucial (Jin et al. 2020). From the perspective of biomass flow modeling, the biomass particle and wall interaction are implemented as a boundary condition, and therefore can be described as a structural model.

This research aims to model and predict the onset of the flow of biomass stored in a hopper using a finite element model. This study implemented three major continuum biomass flow material models, i.e., Mohr-Coulomb, Drucker-Prager/Cap model, and modified Cam-Clay models, to compare and identify an outperforming analytical biomass flow model.

Materials and Method

Materials

This study uses crop residue and woody biomass samples are studied. Crop residue is actively studied as a potential source of alternative biorenewable material. Corn stover is a crop residue that is a potential source of alternative biorenewable material. Corn stover is estimated to be more than three-fourth of primary crop residues, which are profitable to collect (Perlack et al. 2011). However, difficulties in handling is an obstacle in establishing corn stover as profitable and reliable biomass. Therefore, it is important to study its flow behavior to engineer storage and handling.

Corn stover samples are collected and oven-dried at least for 15 days before milling. Oven-dried corn stover is nominally sized 2 mm rotary-sheared and screened using Crumbler (Forest Concepts LLC.) Douglas fir is a common softwood in Northwest US with better handling characteristics than corn stover. This study uses fuel-grade Douglas fir chips that are nominally sized 1 mm rotary-sheared and screened using Crumbler (Forest Concepts LLC.)

Finite Element Model: Material Model Parameters

To implement biomass flow material models, respective materials models need to be determined. List of specific parameters of the Mohr-Coulomb model, Drucker-Prager/Cap, and modified Cam-Clay model can be found in (Menetrey and Willam 1995; Heyman 1997; Tripodi et al. 1994; Kamath and Puri 1999; Drucker and Prager 1952; Dimaggio and Sandler 1971).

Shear cell type instrument has been widely used in determining biomass flow properties, specifically, cohesion coefficient (c) and angle of internal friction (ϕ) for the Mohr-Coulomb Model, d and β for Drucker-Prager Model, and critical state line slope and shear modulus for modified Cam-Clay model. However, other material properties, such as compression index (λ), spring-back index (κ), bulk modulus (K) for the modified Cam-Clay model, are not straightforward to determine with typical shear tests.

Triaxial tests generate data that can be used in determining analytic biomass flow models in a straight forward way. This is due to the fact that the triaxial tester is a fundamental mechanical tester and independent of specific material models. Especially, Penn State's Cubical Triaxial Tester (CTT) can conduct and generate trial test results that are readily used in the calibration of these models because the CTT applies stresses in principal directions and measuring corresponding principal strains of test samples.

Finite Element Model: Hopper Flow Model

This study aimed to model and simulate a biomass flow out of the hopper. For experimental verification of the finite element biomass flow model, a hopper was designed and constructed to be able to change its wall angle, as shown in Figure 1. This hopper has an opening of 20 cm×20 cm. The hopper was filled with consistent height (15 cm) for both materials. Flow patterns emerged when the bottom gate was opened, and the throughput rates were recorded. The finite element model of biomass hopper flow was constructed with the same geometry of the hopper and fill height to be consistent with the experimental setup.

Figure 1 Lab-scale hopper with a variable wall angle and transparent sidewalls.

Results and Discussion

Hopper Flow Patterns

From the experiment, corn stover was found to have a tendency to develop a core flow pattern and resulting in a rat-hole (Figure 2A). On the contrary, Douglas fir tends to develop mass flow, and the entire mass flows out of the hopper (Figure 2 B).

Figure 2 A. Typical corn stover hopper flow exhibiting a core-flow development and often resulting in a rat-hole and B. Typical Douglas fir hopper flow indicating a mass-flow

Finite Element Predictions: Flowability

Using determined parameters of the Mohr-Coulomb model, Drucker-Prager/Cap model, and modified Cam-Clay model, hopper flow of Corn stover 2 mm and Douglas Fir 1 mm are simulated and compared with experimental results. For the details of the characterization of Corn stover 2 mm and Douglas Fir 1mm using the CTT and determination of parameters of those constitutive biomass flow models, refer to Yi et al. (2020).

As shown in Figure 3, the Mohr-Coulomb model and Drucker-Prager/Cap model accurately predict the core flow pattern of Corn stover 1 mm. However, the modified Cam-Clay model predicts a mass flow of Corn stover 1 mm out of the hopper. On the other hand, the Mohr-Coulomb model predicts a core flow for Douglas Fir 2 mm, which is not consistent with the experimental observation. Drucker-Prager/Cap and modified Cam-Clay models accurately predict the mass flow of Douglas Fir 2 mm out of the hopper. Overall, Drucker-Prager/Cap model predicts the flow pattern for both Corn stover 1 mm and Douglas Fir 2 mm more accurately than the Mohr-Coulomb and modified Cam-Clay models.

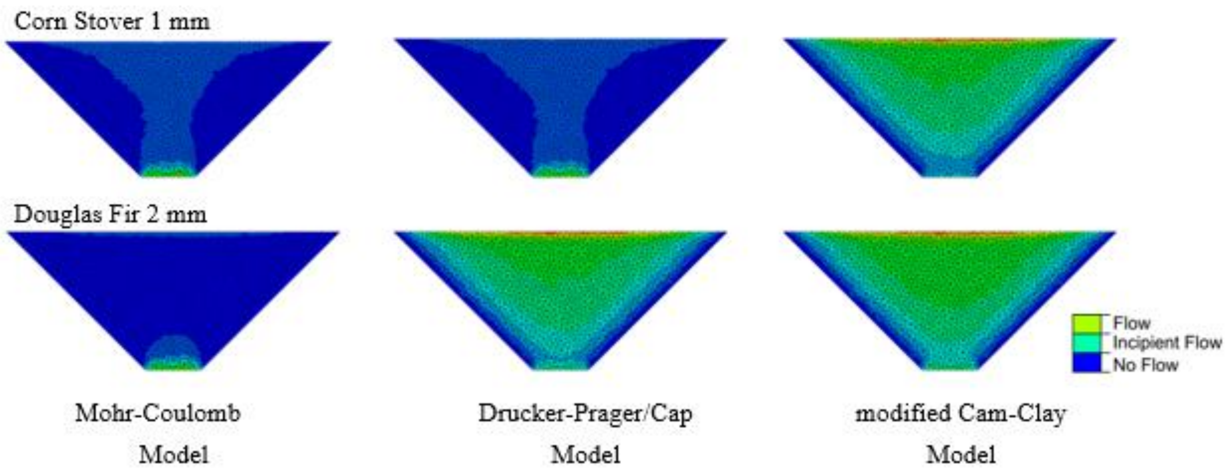

Figure 3 Biomass hopper flow predictions using Finite Element Model with Mohr-Coulomb, Drucker-Prager/Cap, and modified Cam-Clay as constitutive biomass flow models

Although the Mohr-Coulomb model predicts core flow for Douglas-Fir 2mm, it is notable that the Mohr-Coulomb model predicts a partial flow that does not result in a rat-hole that does not go through the stored biomass as shown in the cut-away view in Figure 3. Mohr-Coulomb model simulation also successfully predicts a subtle mass flow near the top of the bulk biomass. The simulation also successfully predicts rat-hole development during hopper flow.

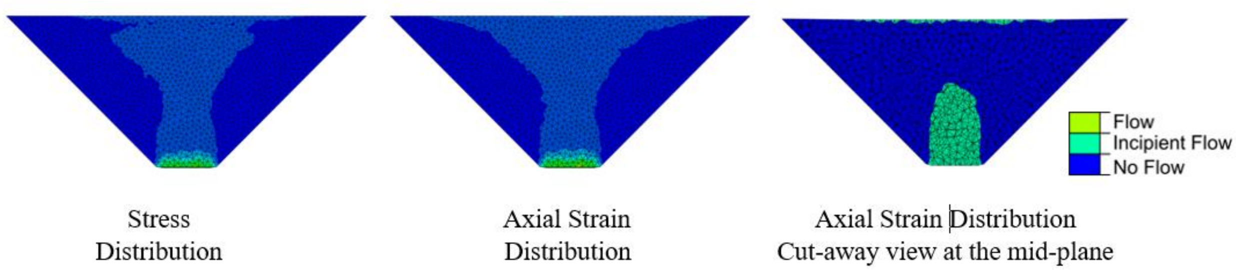

Figure 4 Finite element hopper flow simulation results of Corn stover 1 mm.

Finite Element Predictions: Varying Hopper Angle

To verify the performance finite element biomass flow models, Mohr-Coulomb model parameters were determined for air-dried (10 % w.b. for Corn stover 1 mm and 6 % w.b. for Douglas Fir 2mm), rehydrated at 25 % and 50 % moisture content (w.b.) of Corn stover 1 mm and Douglas Fir 2 mm, respectively. Because this work is an

Figure 5 Typical experimental biomass flow set-up. Shown here are 45° and 60° hoppers filled with Corn stover 1 mm

on-going effort, Drucker-Prager/Cap and modified Cam-Clay model will also be implemented, and their simulation results will be compared with experimental results. Corn stover 1 mm and Douglas Fir 2 mm biomass at these moisture contents levels were also used in hopper flow test at two wall angles, including 45° and 60° as shown in Figure 5. From the finite element simulation, the region whose axial strain is equal to or larger than the failure criteria used in the mechanical parameter determination (Yi et al., 2020) was used in calculating the fully developed biomass flow. As listed in Table 1, the Mohr-Coulomb model predicted experimental results reasonably well except Douglas Fir 2 mm flow out of the 45° hopper, in which case. In this case, the Mohr-Coulomb model tends to underestimate the biomass flow. Overall, finite element biomass flow simulation with the Mohr-Coulomb model predicted the experimental result less than or around 15 differences.

Table 1 Results of experimental and predicted biomass hopper flow

Hopper Wall Angle		Corn Stover 1 mm			Douglas Fir 2 mm		
	Moisture Contents (%, w.b.)	10	25	50	6	25	50
45°	Experiment	0.8±0.1	0.3±0.1	0.3±0.1	2.7±0.5	2.5±0.3	2.7±0.2
	Simulation	0.9	0.3	0.3	2.3	2.1	3.1
	Difference	13 %	0 %	0 %	-15 %	-16 %	15 %
60°	Experiment	0.9±0.2	0.5±0.1	0.6±0.1	3.5±0.1	3.0±0.1	4.4±0.3
	Simulation	0.9	0.5	0.6	3.4	3.1	4.4
	Difference	0 %	0 %	0 %	-3 %	3 %	0 %

Unit is in kg/min unless noted otherwise

Conclusion

Biomass flowability is the result of interactions between the physical properties of bulk biomass and the handling equipment. Finite element analysis is a desirable modeling tool that can utilize a wide range of continuum bulk biomass flow models and incorporate diverse biomass handling equipment geometries. Penn State's Cubical Triaxial Tester (CTT) was used in conducting fundamental triaxial tests and in determining continuum biomass flow models, i.e., Mohr-Coulomb, Drucker-Prager/Cap, and modified Cam-Clay models. Mohr-Coulomb model simulation was compared with experimental hopper flow out of 45° and 60° wall angles with 20 cm square opening using Corn stover 1 mm and Douglas Fir 2 mm at air-dried, 25 %, and 50 % moisture contents. Finite element models predicted the flow rate out of the laboratory hopper reasonably accurately with less than or around 15 differences from the experimental results.

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