National Aeronautics and Space Administration

FY23 Strategic University Research Partnership (SURP)

Modeling of Enceladus Landing Stability using Resistive Force Theory

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Objectives: This effort aims to model interactions between surface material and lander footpads during Enceladus landings. It informs safe landing on its unconsolidated ice surface and aids landing system design. The CRAB Lab at Georgia Tech, led by Professor Goldman, specializes in mechanical systems interacting with granular materials, utilizing Resistive Force Theory (RFT). Partnering with CRAB Lab enables JPL to model lander, sampler, and mobility system interactions with deformable terrain using RFT.

Significance/Benefits to JPL and NASA: This work introduces RFT, an emerging terramechanics modeling method, to JPL. The collaboration enhances research areas of mutual interest for CRAB Lab at Georgia Tech and JPL. It advances understanding of complex granular mechanical systems, improving terrain interaction, locomotion, and autonomy. This effort fuels strategic research in astrobiological and oceanographic exploration of Enceladus, fostering stronger ties between Georgia Tech and JPL communities.

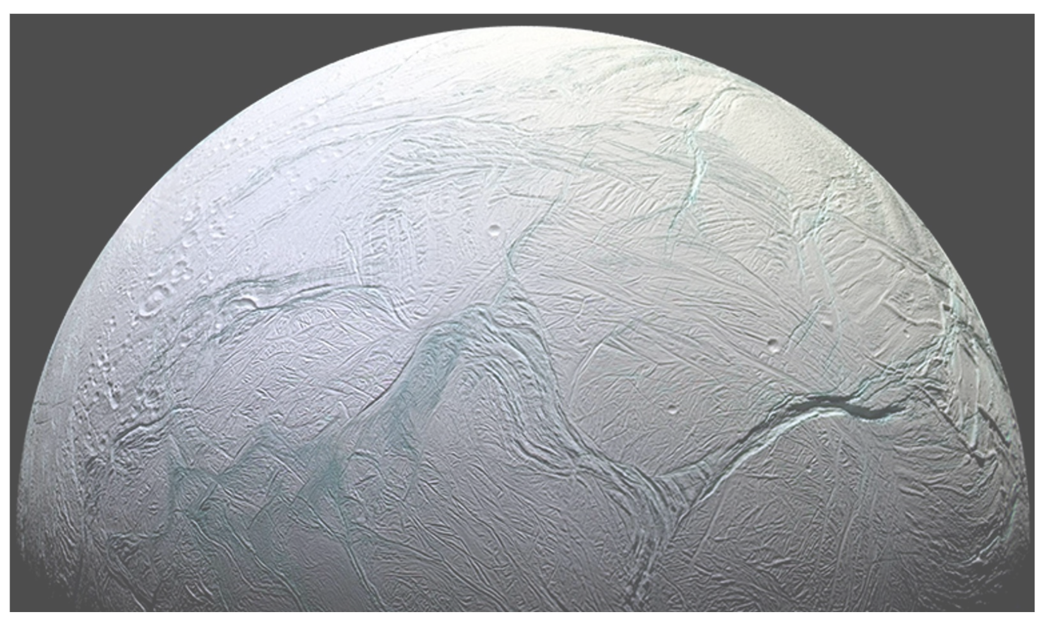


Photo credit: NASA

Background Enceladus, Saturn's small yet active icy moon, remains one of the most scientifically compelling worlds in the solar system. There is great interest in sending an in-situ mission to Enceladus because Cassini's orbital exploration revealed it to be a complex Ocean World with astrobiological relevance. It is one of the very few places where materials originating from a potentially habitable ocean are deposited on the surface, giving a unique opportunity to assess the moon's habitability and potential for life right at the surface. This effort has direct and immediate implications for ongoing and future mission concepts in development. Future exploration of Enceladus by a lander will require a detailed understanding of Enceladus surface material and of the complex interactions during lander touchdown event.

Approach: To model surface interactions during Enceladus landings, we conduct intrusion experiments in cornstarch powder, a cohesive simulant resembling Enceladus plume deposits. These experiments expand Granular Resistive Force Theory (RFT) from non-cohesive 1mm particles [1] to cohesive powder-scale substrates. We determine object stiffness by studying various angles and intrusion scenarios, using resulting forces to calibrate RFT. This enables stress predictions for any object in powder media. These predictions guide safe landing strategies and footpad design. For systematic experiments, we designed a custom chamber (Fig. 1A) capable of resetting powder to a loose state via air-fluidization.

Intrusion experiments used a Denso robotic arm with 6 degrees of freedom and a 6-axis ATI Industrial Automation force sensor. An aluminum plate, attached to the force sensor via a supporting rod, followed procedures akin to [1,2]. Plate angles (β) and (γ) were adjusted using a mount and the robotic arm (Fig. 1 A-D). Each test sequence involved: suspending the plate above the powder, lowering it to the surface, waiting 2 seconds, and then intruding into the powder (Fig. 1B). To minimize particle inertia, we conducted measurements at low speeds (1 cm/s). Force measurements were separately taken on the supporting rod, both with and without the plate, and then subtracted to isolate plate forces.

Results: In Fig. 2, vertical stresses on the plate, σz(|z|,β,γ), were calculated by dividing forces by the plate's surface area, at different depths |z| for γ = 90 deg and β=[0, 30, 60, 90] deg. We determined stress-per-depth values by fitting slopes to regions where the plate was significantly distant from the surface and boundaries, estimating substrate vertical stiffness, αz(β, γ). We repeated this procedure for β = ±90 deg and γ from 0 to +90 deg, excluding negative values to focus on intrusion stresses. Fig. 3 presents vertical and horizontal stress-per-depth heatmaps. While the vertical heatmap αz(β, γ) aligns qualitatively with non-cohesive substrate heatmaps[1], the horizontal heatmap α_x(β, γ) shows limited agreement [1].

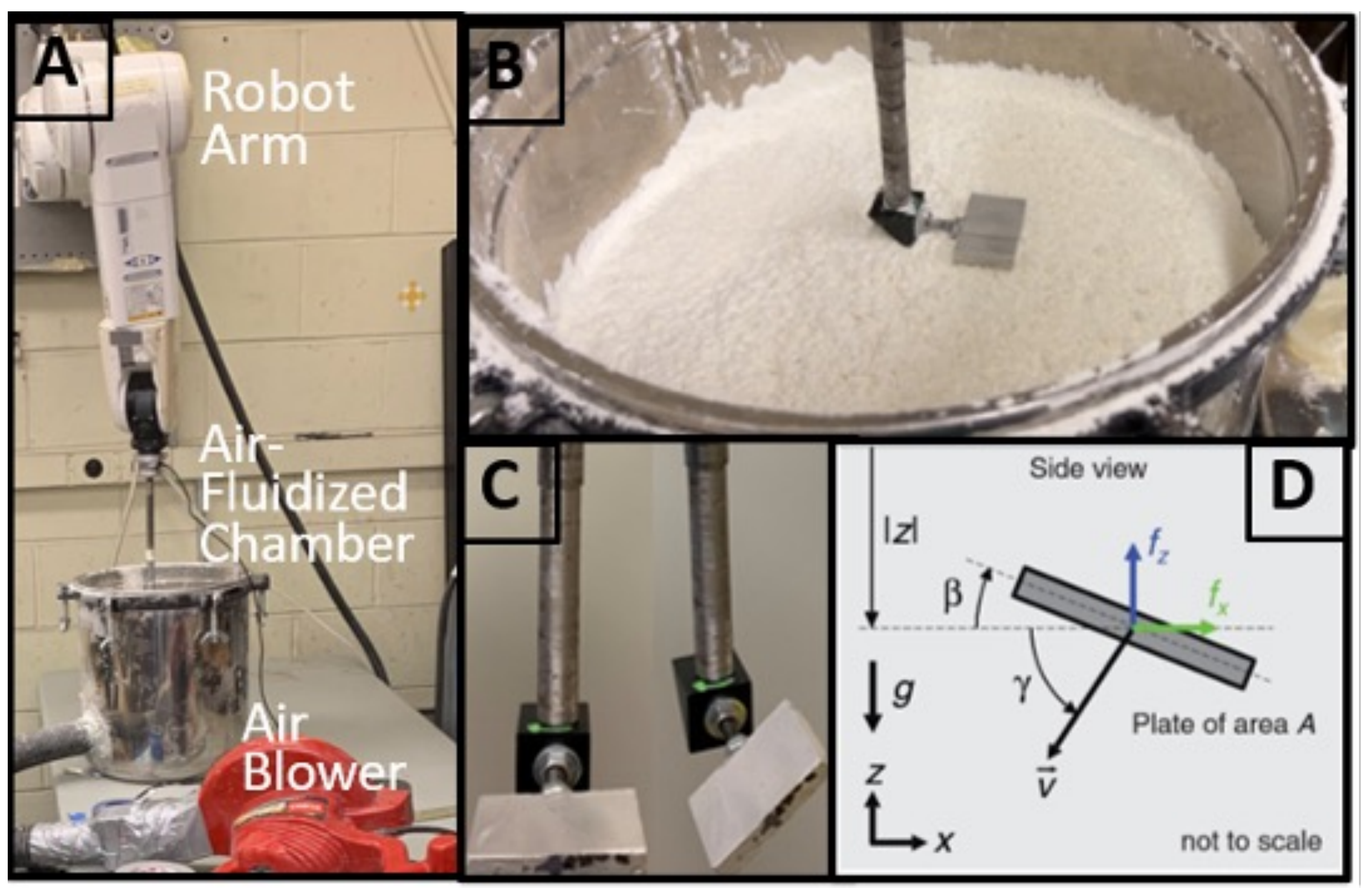


Fig 1: (A) Air fluidization chamber and robotic arm. (B) Cornstarch powder is used for plate intrusion. (C) The adjustable mount on an aluminum plate attached to an intruding rod. (D) Plate of area A at an angle of attack β, and angle of intrusion γ. The plate kinematics image taken from [1].

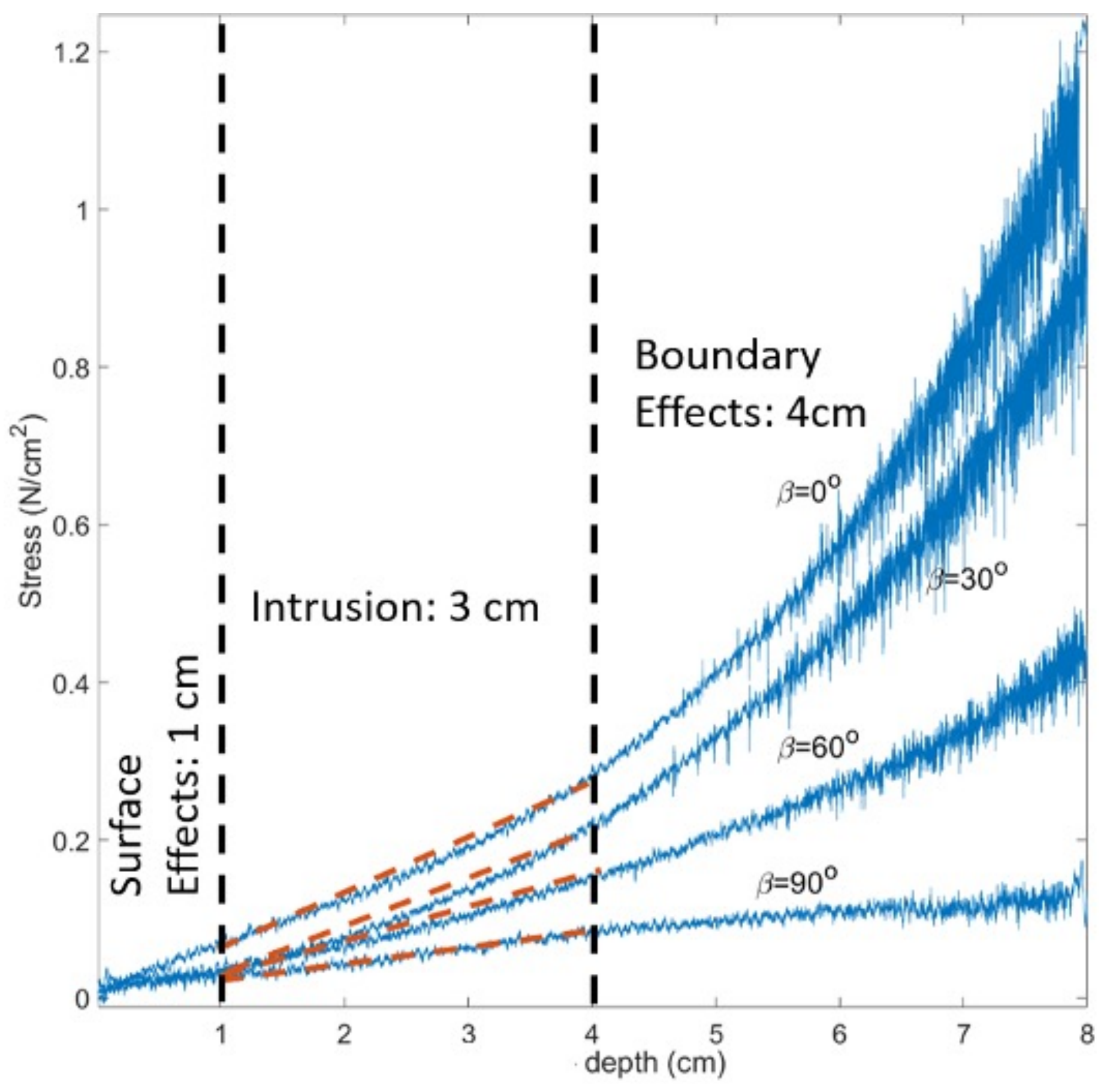
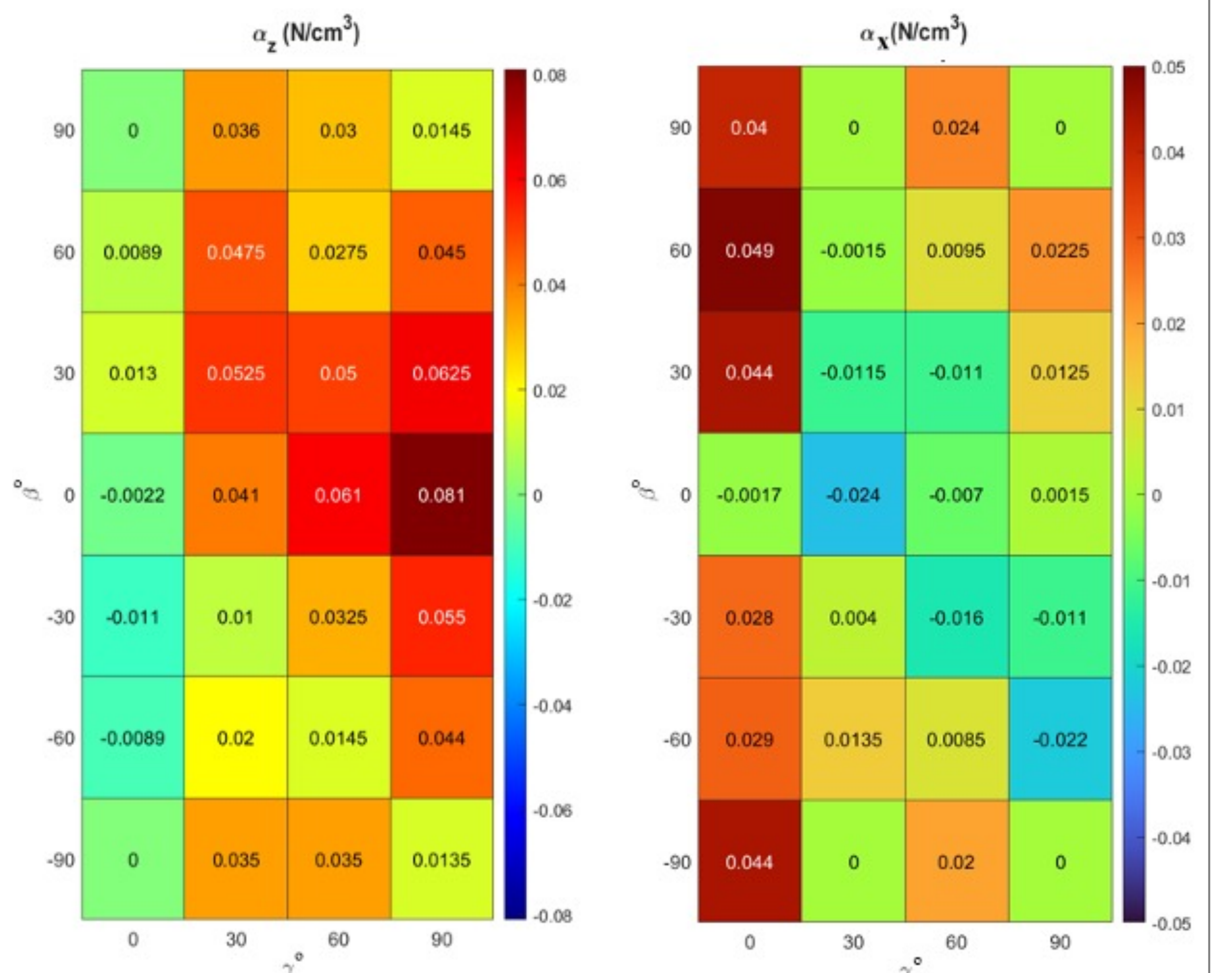


Fig 2: Stress curves of plate intrusion experiments as a function of intruder depth for various angles of attack. The orange dashed line represents the slope of the data in which the plate is far away from the surface and the boundary.



α_z (N/cm³)

β° \ γ°	0	30	60	90
90	0	0.036	0.03	0.0145
60	0.0089	0.0475	0.0275	0.045
30	0.013	0.0525	0.05	0.0625
0	-0.0022	0.041	0.061	0.081
-30	-0.011	0.01	0.0325	0.055
-60	-0.0089	0.02	0.0145	0.044
-90	0	0.035	0.035	0.0135

α_x(N/cm³)

β° \ γ°	0	30	60	90
90	0.04	0	0.024	0
60	0.049	-0.0015	0.0095	0.0225
30	0.044	-0.0115	-0.011	0.0125
0	-0.0017	-0.024	-0.007	0.0015
-30	0.028	0.004	-0.016	-0.011
-60	0.029	0.0135	0.0085	-0.022
-90	0.044	0	0.02	0

Fig 3: Stress-per-depth heatmap of the plate for positive γ and β between $\pm 90^o$. The horizontal heatmap mostly matches that of [1], while the vertical heatmap has more disagreements. The variance between heatmaps is most likely due to the cohesive nature of the cornstarch powder.

References [1] Li et al, *Science* **339**(6126):1408-12, 2013; [2] Skonieczny et al., *J. Terramechanics* **83**:35-44, 2019

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