# Depth of Burial of UXO in Estuary Environments

## MR23-3855

**Magued Iskander, PhD, PE, F.ASCE**

New York University

In-Progress Review Meeting

**May 21, 2025**

# Project Team

**Magued Iskander**
*New York University*
*(PI)*

**Stephan Bless**
*New York University*
*(Co-PI)*

**Mehdi Omidvar**
*Manhattan University*
*(Co-PI)*

**Peter Chu**
*Naval Postgraduate School*
*(Co-PI)*

**Boules Morkos**
*New York University*
*(PhD Candidate)*

**Joseph Dinotte**
*New York University*
*(PhD Candidate)*

**Umar Zada**
*New York University*
*(PhD Student)*

**Emily Specht**
*Manhattan University*
*(MSc Student)*

**Daniel Carvajal**
*New York University*
*(MSc Student)*

# Bottom Line Up Front

## Areas of substantial progress

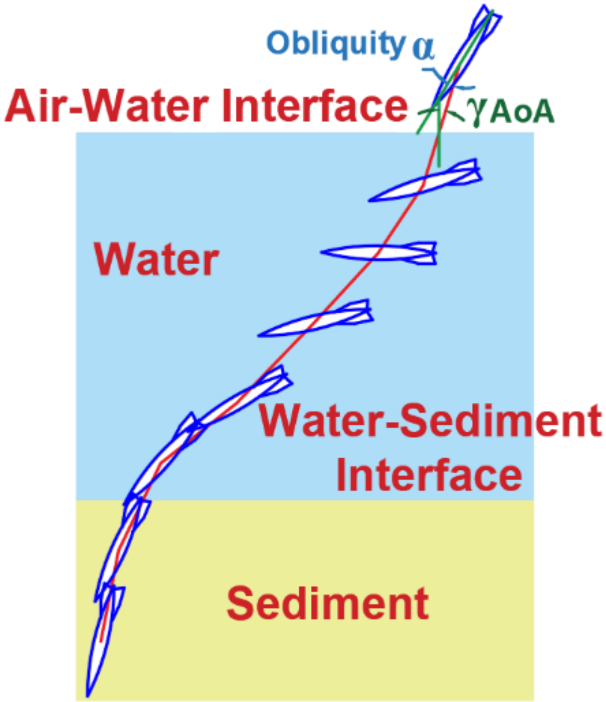
- We have developed a new stability criterion for UXO in soils.
- We have demonstrated numerical modeling of trajectory and rotation for oblique impacts.
- Lab is nearly set up for tests with obliquity in water and soils.
- We are ready for a critical milestone test to evaluate the prediction of DOB for the most common howitzer-launched UXO and vertical penetration.

## Areas where progress has been slower than expected

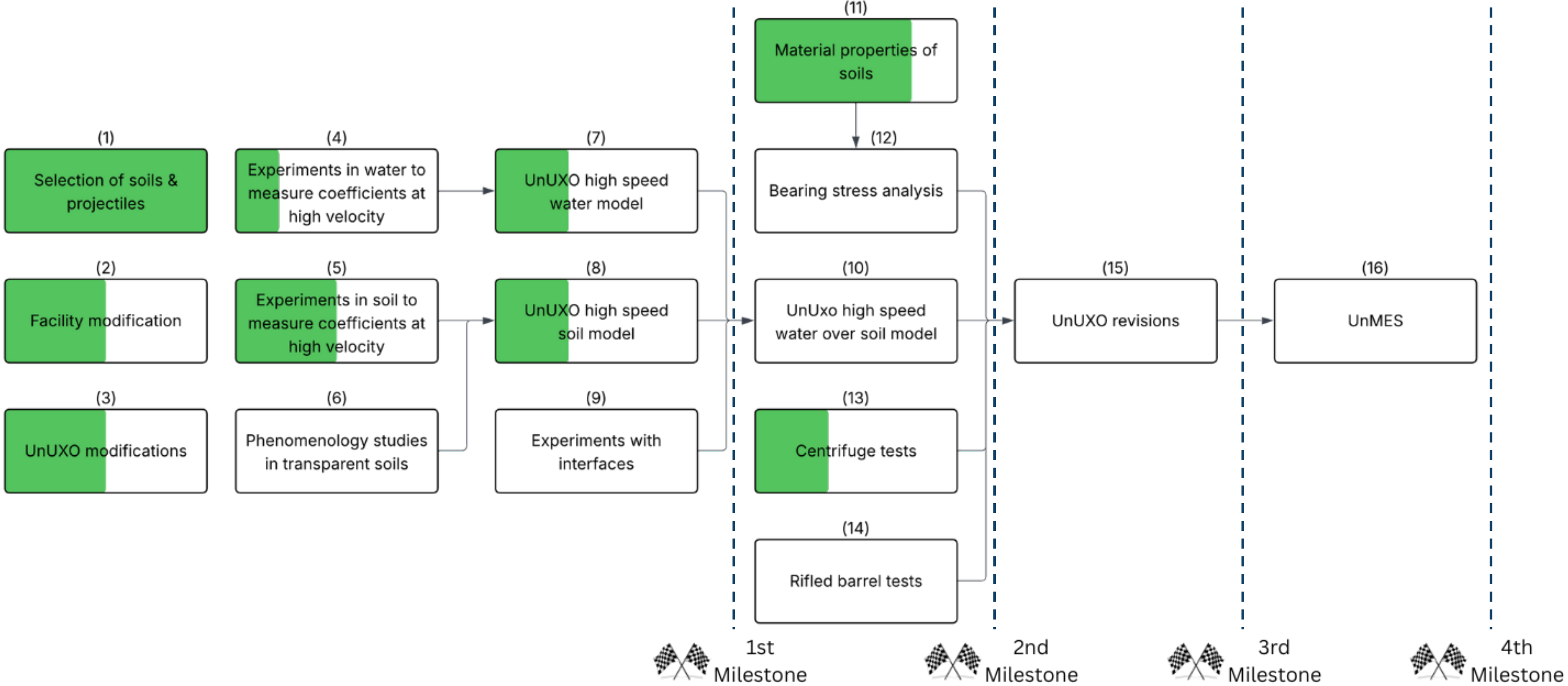
- Lab experiments have been delayed by a breech failure (now repaired).

# Technical Objective

- Expand upon past success in predicting UXO initial DOB to scenarios with obliquity and water overlay.
- Deliver new results in a format useful to facility managers.



# Technical Approach and Status



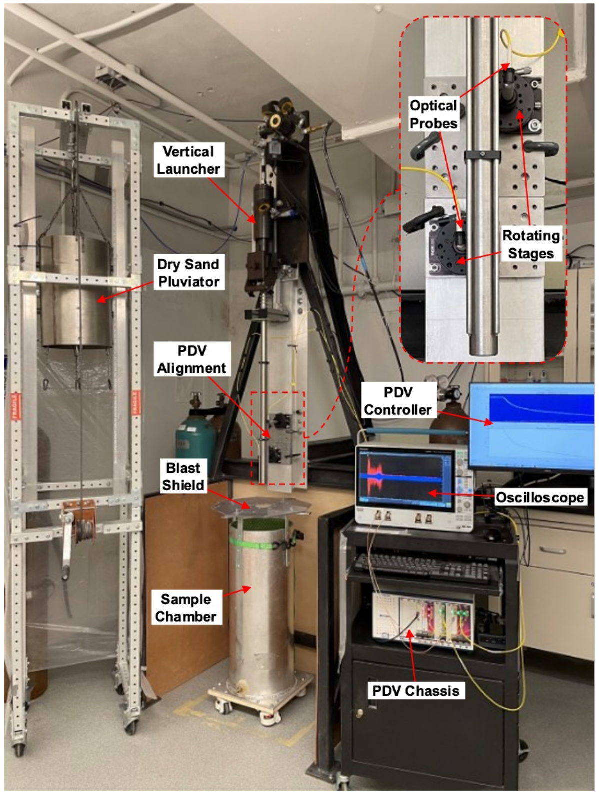
# Results to Date

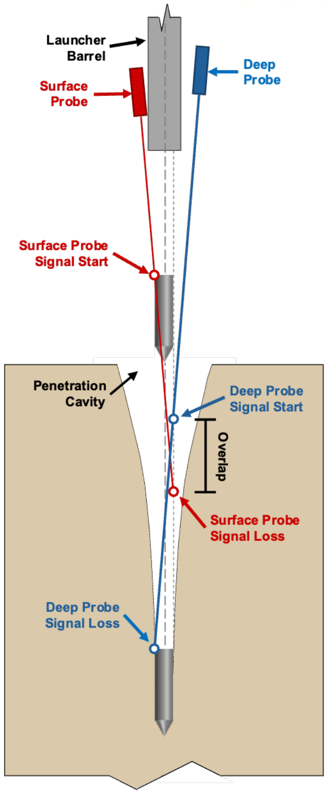
- **Range Upgrade**
- **High Strain Rate (HSR) Tests on Soils**
- **Ballistic Tests**
  - Effect of Density, W.C., saturation, etc.
  - Nose shape effects
  - Layering effects
  - Instability effects
- **Centrifuge Tests (planned)**
- **FEM Simulations**
  - Clay (verified)
  - Instability (verified)
  - Water (verification in progress)
  - Oblique impact (verification in progress)

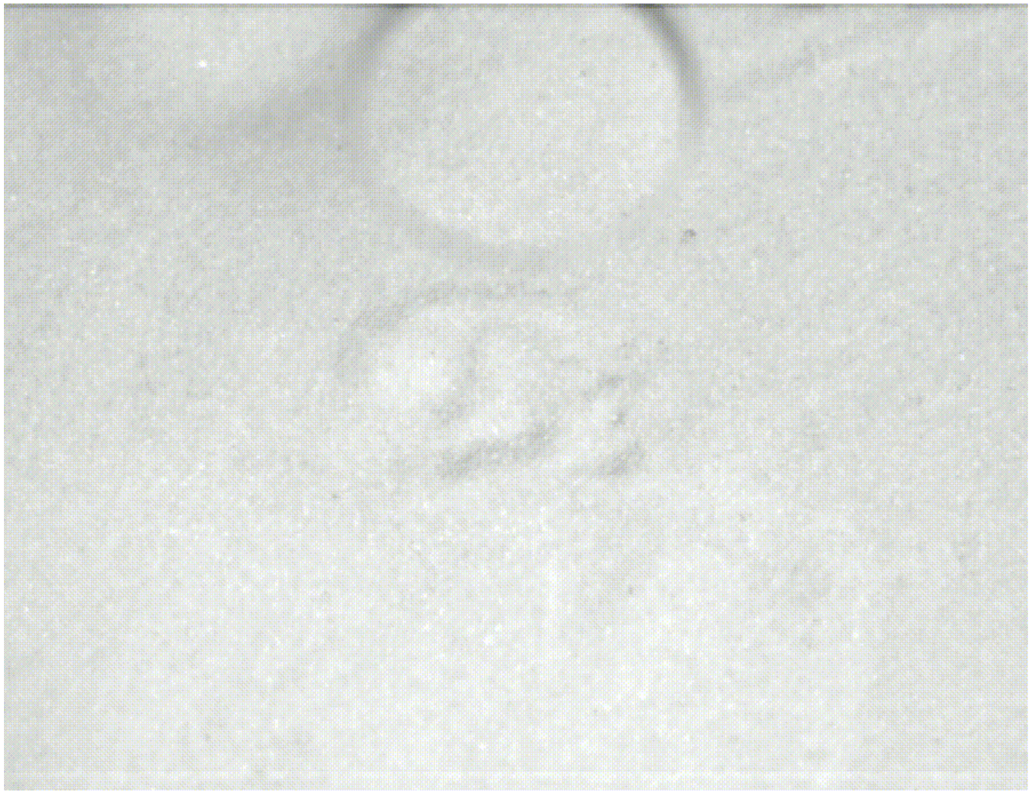
- **Developed Penetration Models**
  - Improved GeoPoncelet model
    - Instability correction factors
    - Stratification correction factors
    - Refined drag coefficients
  - Generalized GeoPoncelet model
    - Integrated with localized interaction model (LIM) using experimental data
- **Disseminated results through 11 Journal articles and 5 conference papers**

**Improved DOB prediction**

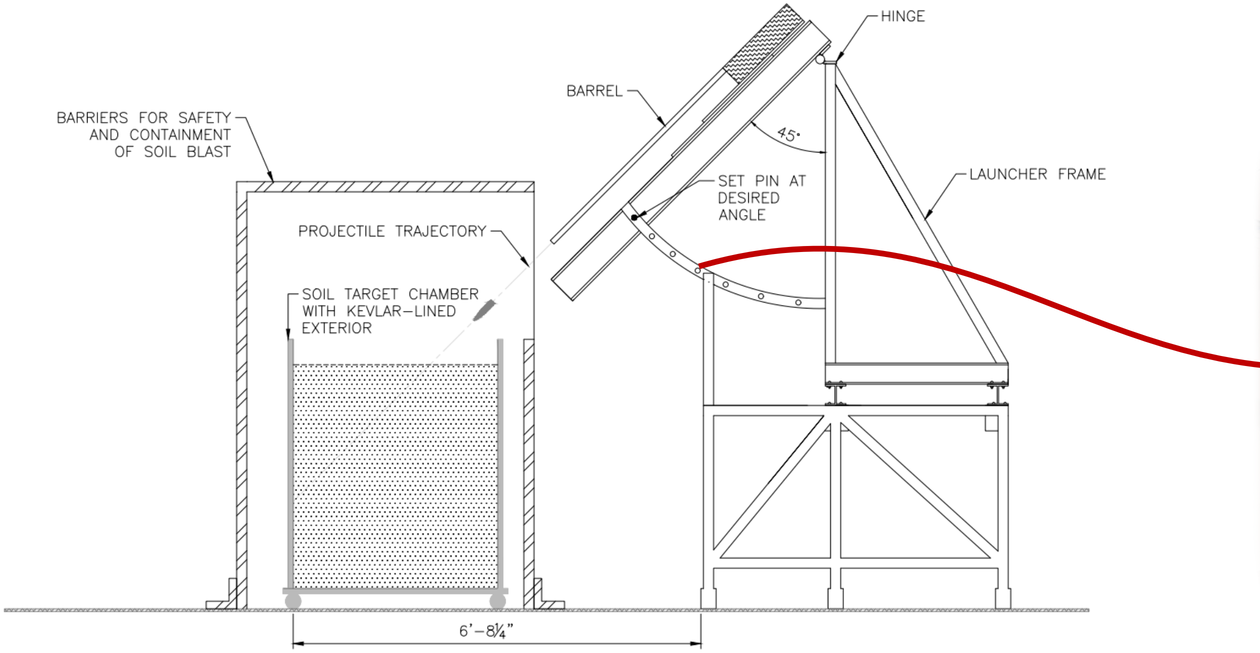
# Ballistic Range & PDV Setup

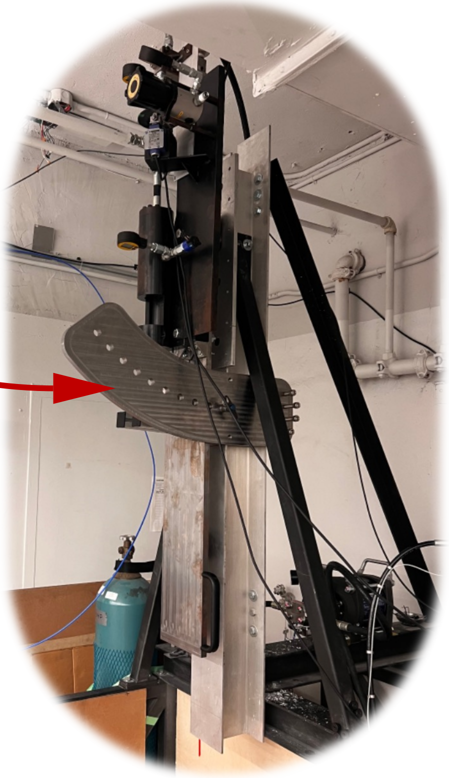






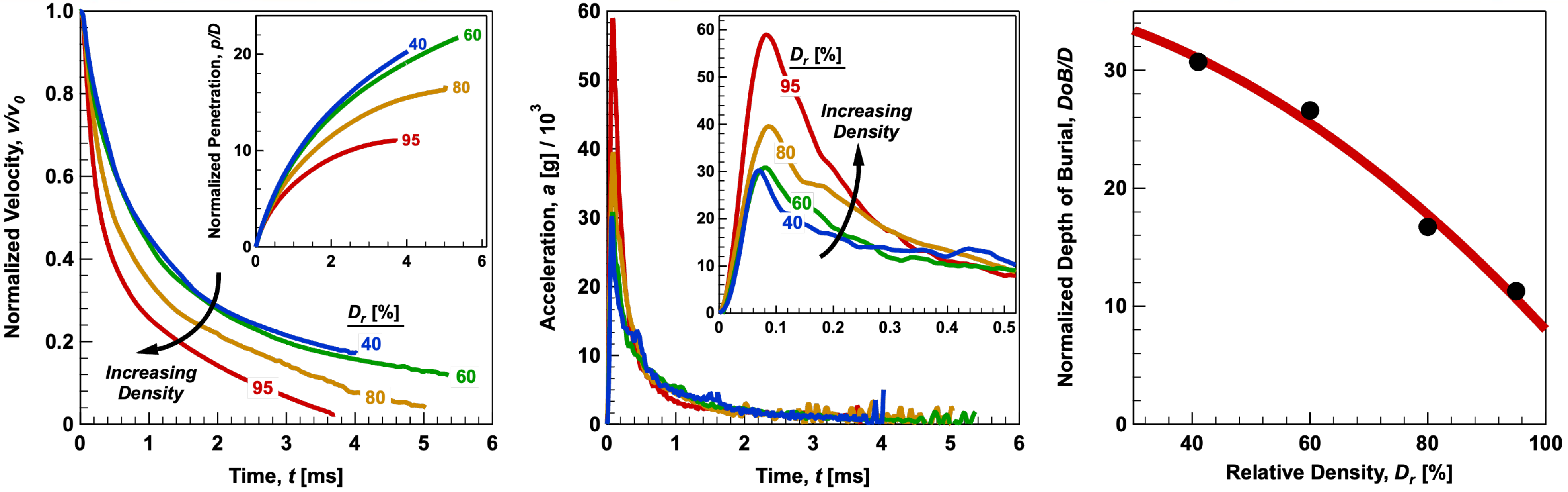
# Ballistic Range Upgrade





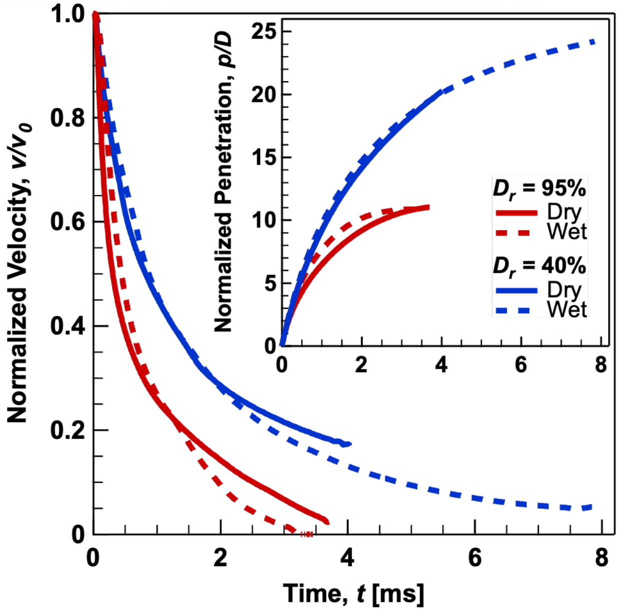
**Impact obliquities up to 45° are possible**

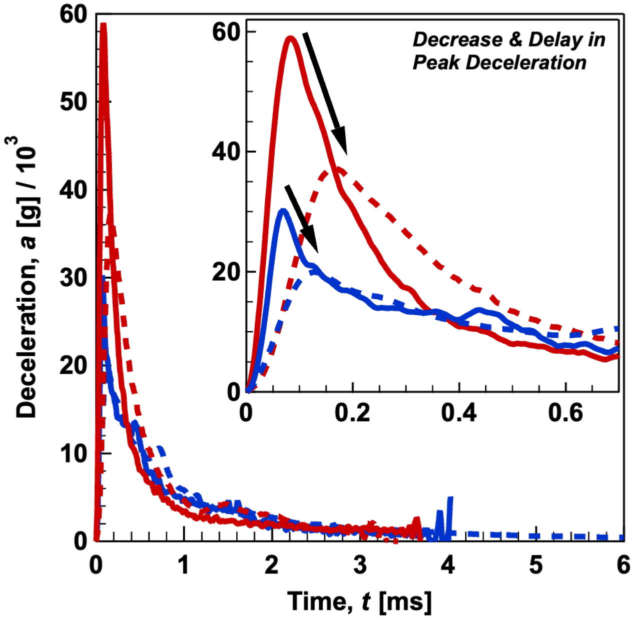
# Ballistic Tests: Density Effect in Sand

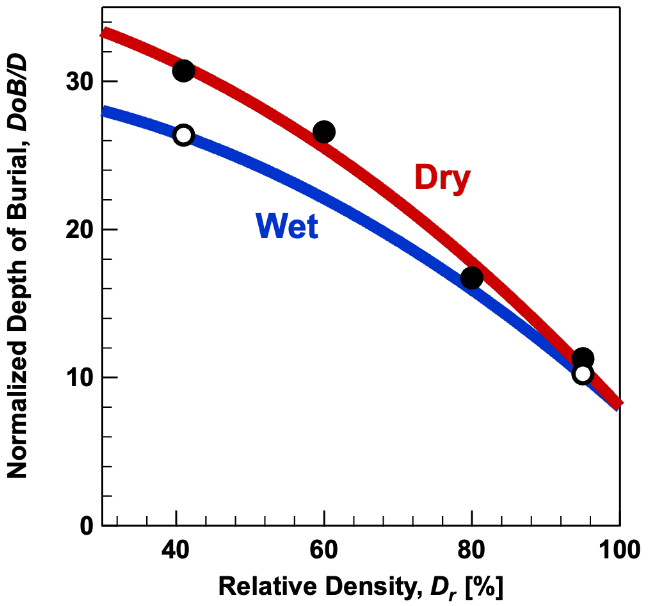


**Density is the primary factor affecting DoB**

# Ballistic Tests: Saturation Effect in Sand



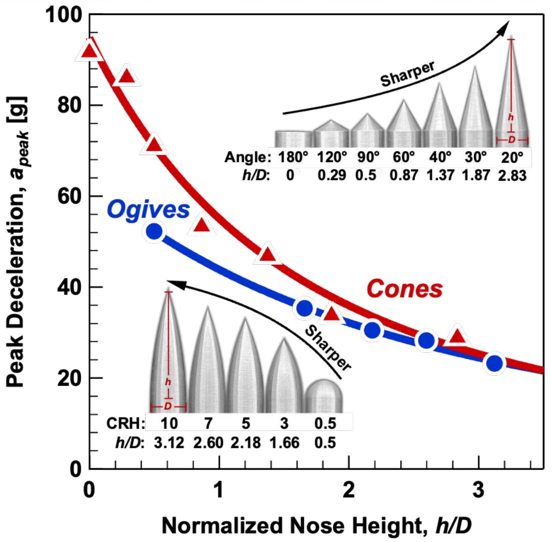


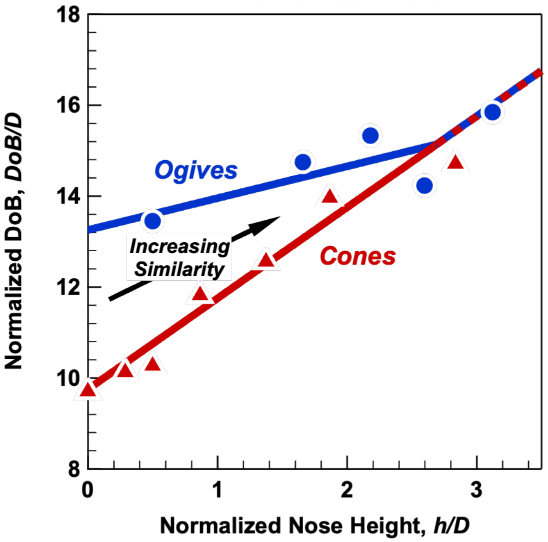


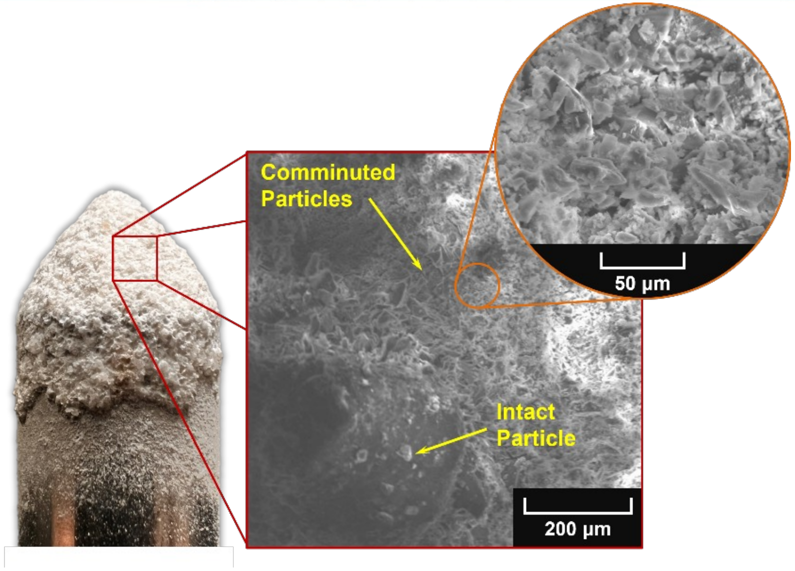
## Saturation has a secondary effect on DoB

Saturation ↓ high-velocity resistance, ↑ low velocity resistance, ↓ DoB

# Ballistic Tests: Nose Shape Effect in Sand





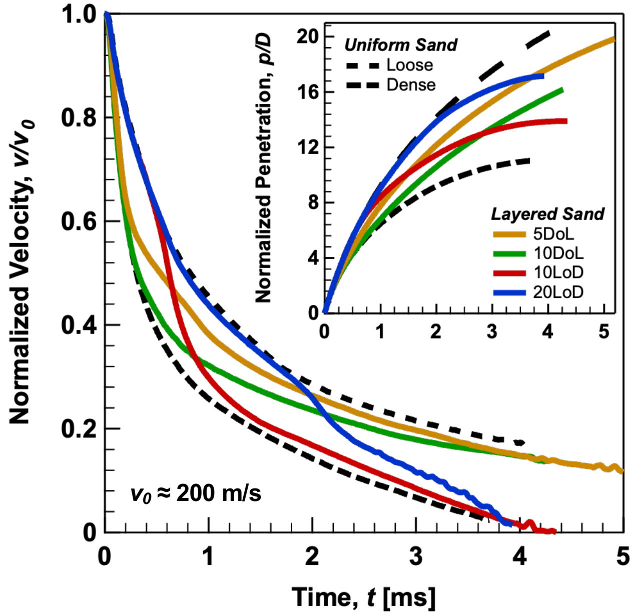


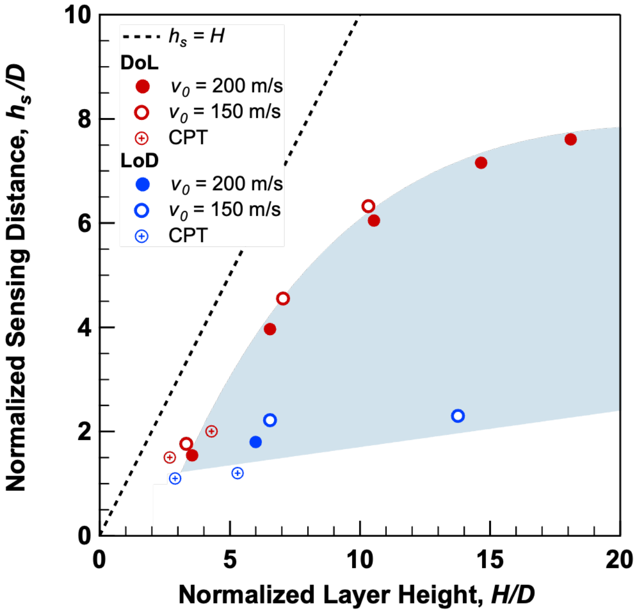
## Sharpness heavily influences impact behavior

Has a secondary effect on DoB in dense sands

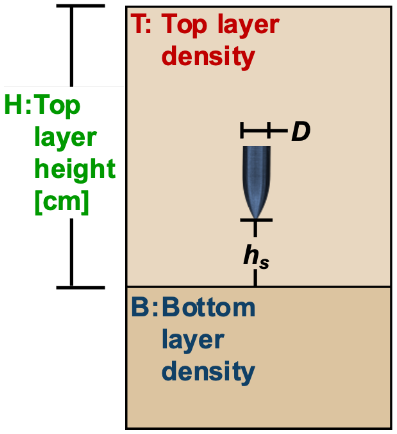
False nose generation mitigates the effect of nose shape for blunt projectiles

# Ballistic Tests: Layering Effect in Sand





**Nomenclature**
**(HToB)**



**H:Top layer height [cm]**

**T: Top layer density**

**B:Bottom layer density**

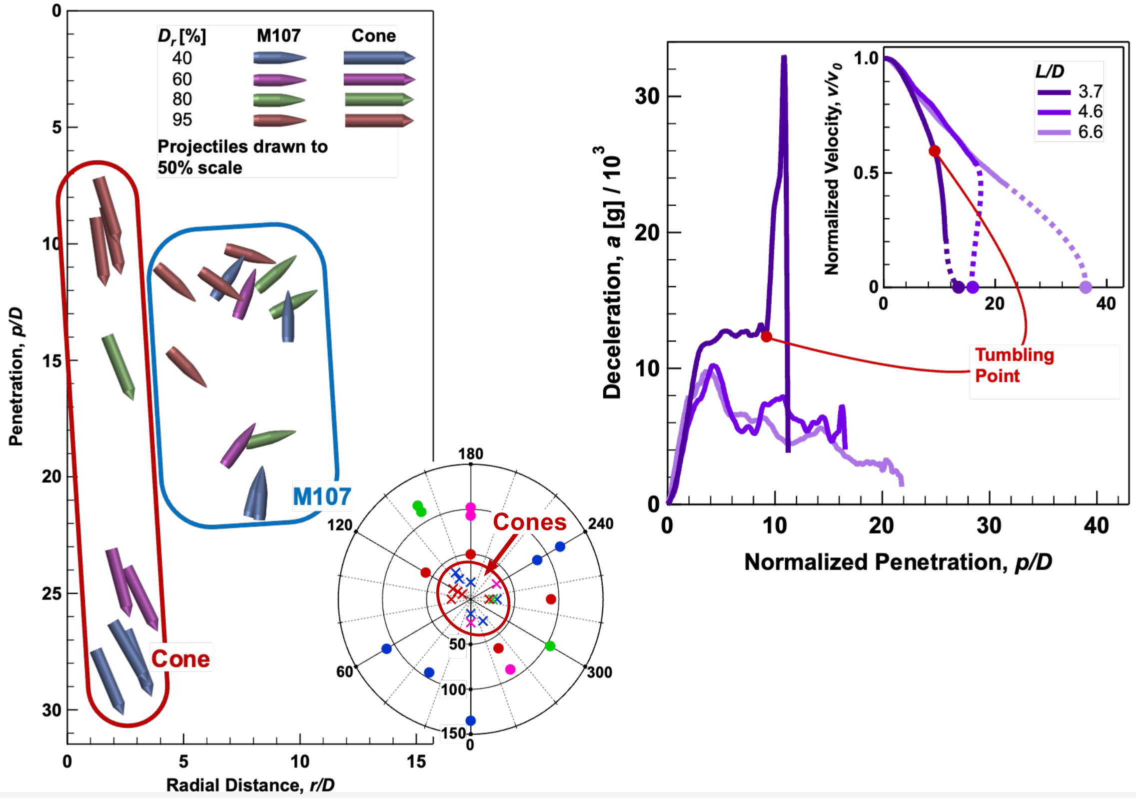
## The influence of an underlying layer begins before the interface is reached

The extent depends on the thickness of the top layer and the density margin between both layers

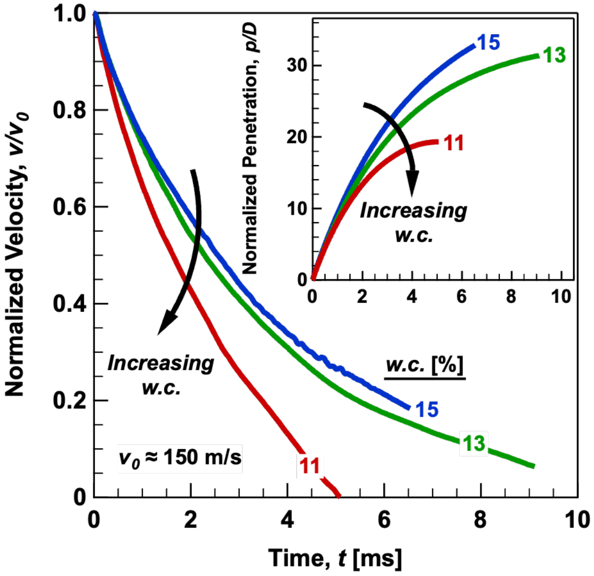
# Ballistic Tests: Instability Effect in Sand

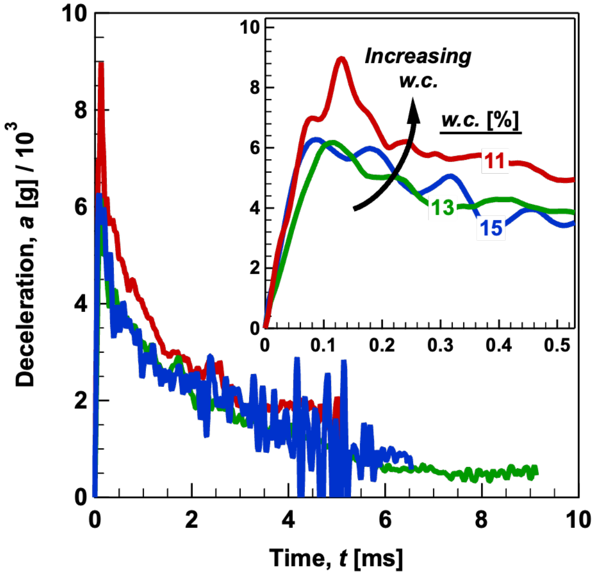
## Instability greatly affects DoB

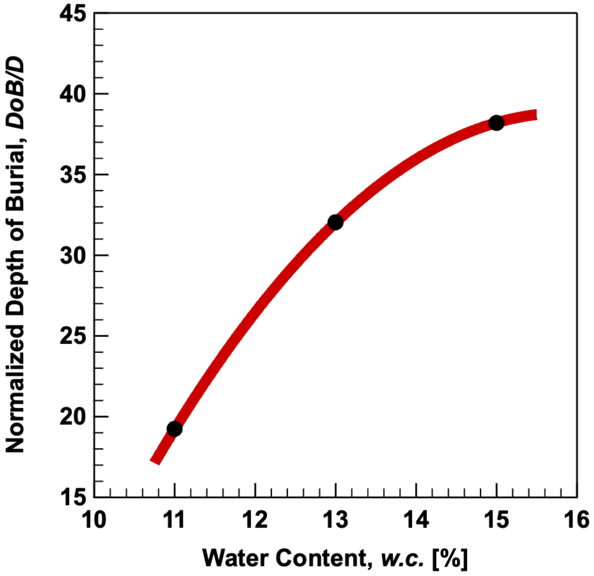
- Long, nose-heavy projectiles are more stable while short, tail-heavy projectiles  are less stable
    - Cones penetrated straighter and deeper than M107
    - DoB is influenced by density
    - Tumbling is marked by sharp rise in deceleration



# Ballistic Tests: Water Content Effect in Clay

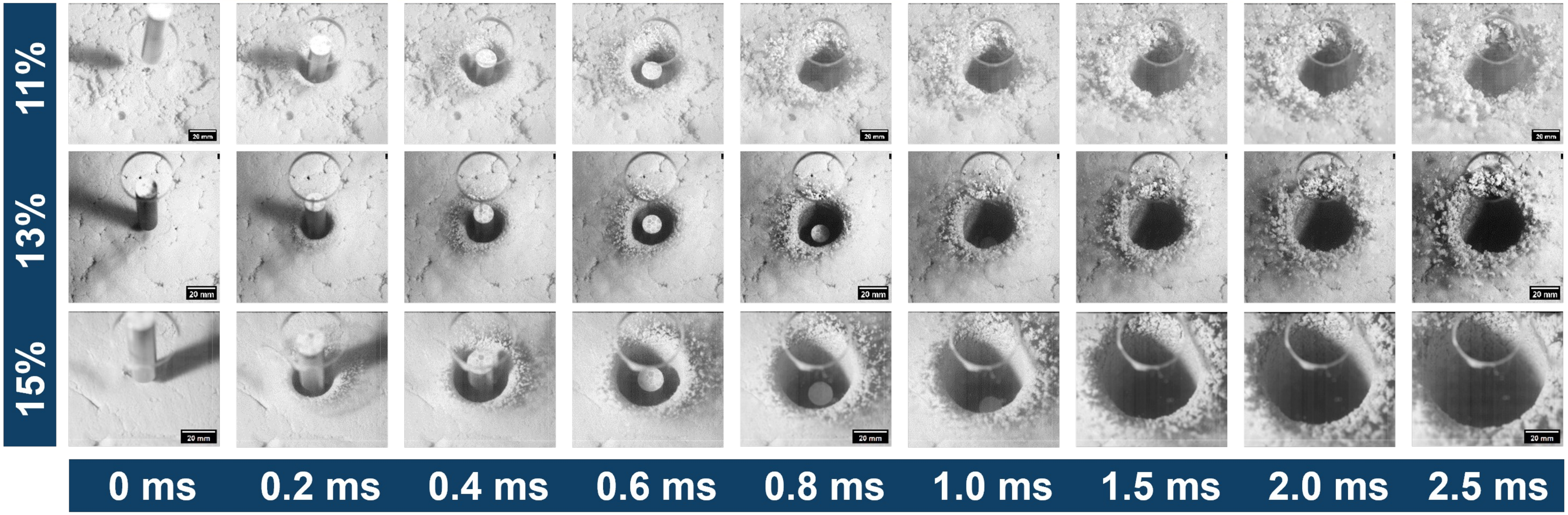






**DoB is very sensitive to moisture content (∝ shear strength)**

# Ballistic Tests: Instability Effect in Clay

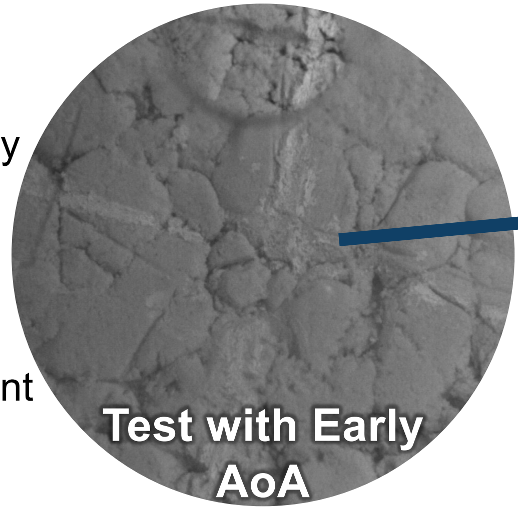


**Softer soils = more rapid expansion**

This affects the overturning coefficient

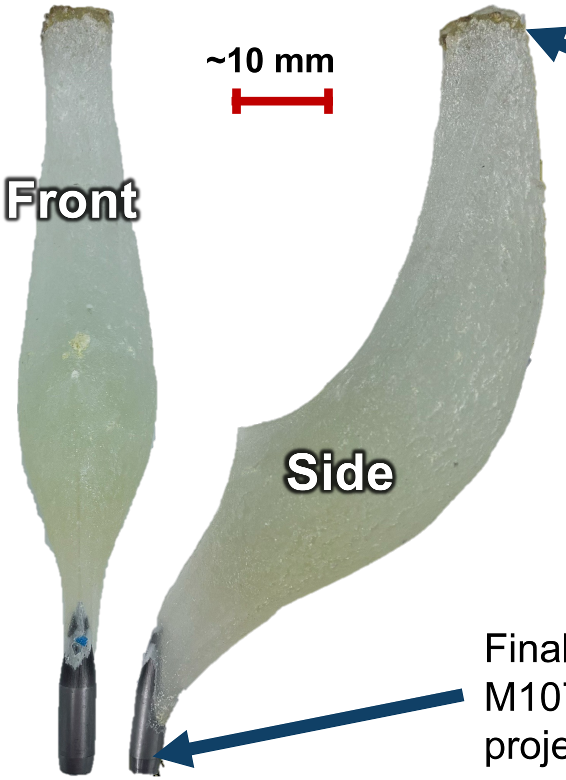
# Ballistic Tests: Instability Effect in Clay

Note cavity rebounds inwards after projectile embedment



## M107 in clayey sands are unstable

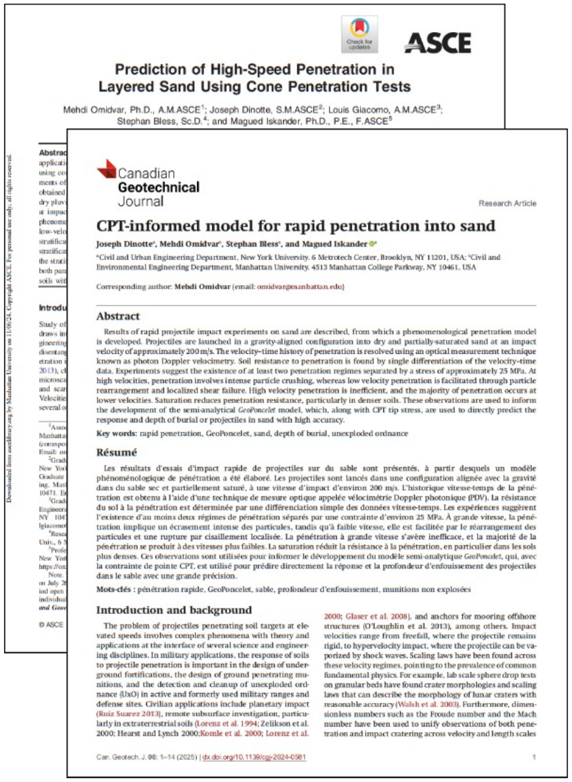
Increasing w.c. (lower strength) = Instability



Early onset AoA causes tail swipe, followed by projectile inversion

Final position of M107 replica projectile is inverted

# Ballistic Tests: Publications



ASCE

## Prediction of High-Speed Penetration in Layered Sand Using Cone Penetration Tests

Mehdi Omidvar, Ph.D., A.M.ASCE[1]; Joseph Dinotte, S.M.ASCE[2]; Louis Giacomo, A.M.ASCE[3]; Stephan Bless, Sc.D.[4]; and Magued Iskander, Ph.D., P.E., F.ASCE[5]

---

Canadian Geotechnical Journal

Research Article

## CPT-informed model for rapid penetration into sand

Joseph Dinotte[a], Mehdi Omidvar[b], Stephan Bless[a], and Magued Iskander[a]

[a]Civil and Urban Engineering Department, New York University. 6 Metrotech Center, Brooklyn, NY 11201, USA; [b]Civil and Environmental Engineering Department, Manhattan University. 4513 Manhattan College Parkway, NY 10461, USA

Corresponding author: **Mehdi Omidvar** (email: omidvar@manhattan.edu)

### Abstract

Results of rapid projectile impact experiments on sand are described, from which a phenomenological penetration model is developed. Projectiles are launched in a gravity-aligned configuration into dry and partially-saturated sand at an impact velocity of approximately 200 m/s. The velocity–time history of penetration is resolved using an optical measurement technique known as photon Doppler velocimetry. Soil resistance to penetration is found by single differentiation of the velocity–time data. Experiments suggest the existence of at least two penetration regimes separated by a stress of approximately 25 MPa. At high velocities, penetration involves intense particle crushing, whereas low velocity penetration is facilitated through particle rearrangement and localized shear failure. High velocity penetration is inefficient, and the majority of penetration occurs at lower velocities. Saturation reduces penetration resistance, particularly in denser soils. These observations are used to inform the development of the semi-analytical *GeoPoncelet* model, which, along with CPT tip stress, are used to directly predict the response and depth of burial or projectiles in sand with high accuracy.

**Key words:** rapid penetration, GeoPoncelet, sand, depth of burial, unexploded ordnance

### Résumé

Les résultats d'essais d'impact rapide de projectiles sur du sable sont présentés, à partir desquels un modèle phénoménologique de pénétration a été élaboré. Les projectiles sont lancés dans une configuration alignée avec la gravité dans du sable sec et partiellement saturé, à une vitesse d'impact d'environ 200 m/s. L'historique vitesse-temps de la pénétration est obtenu à l'aide d'une technique de mesure optique appelée vélocimétrie Doppler photonique (PDV). La résistance du sol à la pénétration est déterminée par une différenciation simple des données vitesse-temps. Les expériences suggèrent l'existence d'au moins deux régimes de pénétration séparés par une contrainte d'environ 25 MPa. À grande vitesse, la pénétration implique un écrasement intense des particules, tandis qu'à faible vitesse, elle est facilitée par le réarrangement des particules et une rupture par cisaillement localisée. La pénétration à grande vitesse s'avère inefficace, et la majorité de la pénétration se produit à des vitesses plus faibles. La saturation réduit la résistance à la pénétration, en particulier dans les sols plus denses. Ces observations sont utilisées pour informer le développement du modèle semi-analytique *GeoPoncelet*, qui, avec la contrainte de pointe CPT, est utilisé pour prédire directement la réponse et la profondeur d'enfouissement des projectiles dans le sable avec une grande précision.

**Mots-clés :** pénétration rapide, GeoPoncelet, sable, profondeur d'enfouissement, munitions non explosées

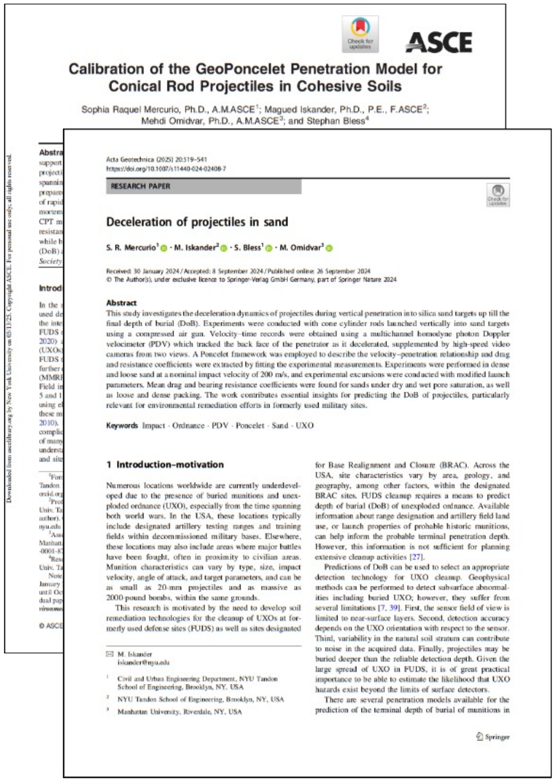
### Introduction and background

The problem of projectiles penetrating soil targets at elevated speeds involves complex phenomena with theory and applications at the interface of several science and engineering disciplines. In military applications, the response of soils to projectile penetration is important in the design of underground fortifications, the design of ground penetrating munitions, and the detection and cleanup of unexploded ordnance (UxO) in active and formerly used military ranges and defense sites. Civilian applications include planetary impact (Ruiz Suarez 2013), remote subsurface investigation, particularly in extraterrestrial soils (Lorenz et al. 1994; Zelikson et al. 2000; Hearst and Lynch 2000;Komle et al. 2000; Lorenz et al. 2000; Glaser et al. 2008), and anchors for mooring offshore structures (O'Loughlin et al. 2013), among others. Impact velocities range from freefall, where the projectile remains rigid, to hypervelocity impact, where the projectile can be vaporized by shock waves. Scaling laws have been found across these velocity regimes, pointing to the prevalence of common fundamental physics. For example, lab scale sphere drop tests on granular beds have found crater morphologies and scaling laws that can describe the morphology of lunar craters with reasonable accuracy (Walsh et al. 2003). Furthermore, dimensionless numbers such as the Froude number and the Mach number have been used to unify observations of both penetration and impact cratering across velocity and length scales

Can. Geotech. J. 00: 1–14 (2025) | dx.doi.org/10.1139/cgj-2024-0581

1

---



ASCE

## Calibration of the GeoPoncelet Penetration Model for Conical Rod Projectiles in Cohesive Soils

Sophia Raquel Mercurio, Ph.D., A.M.ASCE[1]; Magued Iskander, Ph.D., P.E., F.ASCE[2]; Mehdi Omidvar, Ph.D., A.M.ASCE[3]; and Stephan Bless[4]

---

Acta Geotechnica (2025) 20:519–541
https://doi.org/10.1007/s11440-024-02408-7

RESEARCH PAPER

## Deceleration of projectiles in sand

S. R. Mercurio[1] · M. Iskander[2] · S. Bless[1] · M. Omidvar[3]

Received: 30 January 2024 / Accepted: 8 September 2024 / Published online: 26 September 2024

### Abstract

This study investigates the deceleration dynamics of projectiles during vertical penetration into silica sand targets up till the final depth of burial (DoB). Experiments were conducted with cone cylinder rods launched vertically into sand targets using a compressed air gun. Velocity–time records were obtained using a multichannel homodyne photon Doppler velocimeter (PDV) which tracked the back face of the penetrator as it decelerated, supplemented by high-speed video cameras from two views. A Poncelet framework was employed to describe the velocity–penetration relationship and drag and resistance coefficients were extracted by fitting the experimental measurements. Experiments were performed in dense and loose sand at a nominal impact velocity of 200 m/s, and experimental excursions were conducted with modified launch parameters. Mean drag and bearing resistance coefficients were found for sands under dry and wet pore saturation, as well as loose and dense packing. The work contributes essential insights for predicting the DoB of projectiles, particularly relevant for environmental remediation efforts in formerly used military sites.

**Keywords** Impact · Ordnance · PDV · Poncelet · Sand · UXO

### 1 Introduction–motivation

Numerous locations worldwide are currently underdeveloped due to the presence of buried munitions and unexploded ordnance (UXO), especially from the time spanning both world wars. In the USA, these locations typically include designated artillery testing ranges and training fields within decommissioned military bases. Elsewhere, these locations may also include areas where major battles have been fought, often in proximity to civilian areas. Munition characteristics can vary by type, size, impact velocity, angle of attack, and target parameters, and can be as small as 20-mm projectiles and as massive as 2000-pound bombs, within the same grounds.

This research is motivated by the need to develop soil remediation technologies for the cleanup of UXOs at formerly used defense sites (FUDS) as well as sites designated for Base Realignment and Closure (BRAC). Across the USA, site characteristics vary by area, geology, and geography, among other factors, within the designated BRAC sites. FUDS cleanup requires a means to predict depth of burial (DoB) of unexploded ordnance. Available information about range designation and artillery field land use, or launch properties of probable historic munitions, can help inform the probable terminal penetration depth. However, this information is not sufficient for planning extensive cleanup activities [27].

Predictions of DoB can be used to select an appropriate detection technology for UXO cleanup. Geophysical methods can be performed to detect subsurface abnormalities including buried UXO; however, they suffer from several limitations [7, 39]. First, the sensor field of view is limited to near-surface layers. Second, detection accuracy depends on the UXO orientation with respect to the sensor. Third, variability in the natural soil stratum can contribute to noise in the acquired data. Finally, projectiles may be buried deeper than the reliable detection depth. Given the large spread of UXO in FUDS, it is of great practical importance to be able to estimate the likelihood that UXO hazards exist beyond the limits of surface detectors.

There are several penetration models available for the prediction of the terminal depth of burial of munitions in

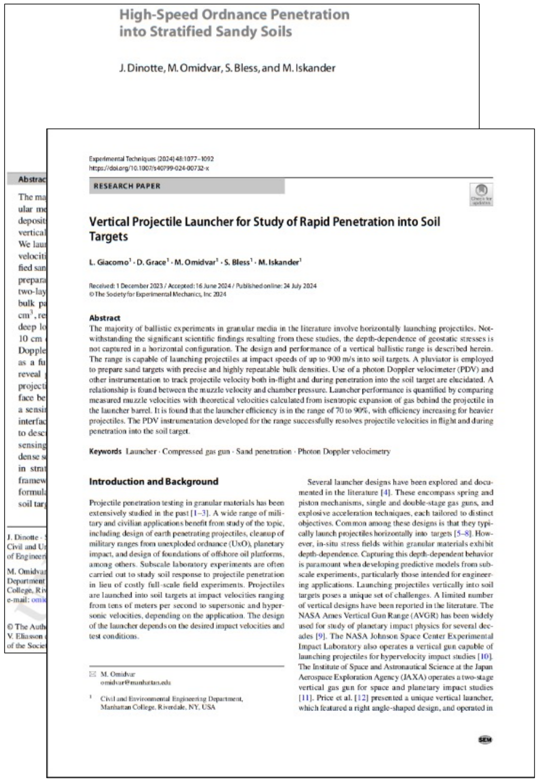
---

✉ M. Iskander
iskander@nyu.edu

1 Civil and Urban Engineering Department, NYU Tandon School of Engineering, Brooklyn, NY, USA
2 NYU Tandon School of Engineering, Brooklyn, NY, USA
3 Manhattan University, Riverdale, NY, USA

Springer

---



## High-Speed Ordnance Penetration into Stratified Sandy Soils

J. Dinotte, M. Omidvar, S. Bless, and M. Iskander

---

Experimental Techniques (2024) 48:1077–1092
https://doi.org/10.1007/s40799-024-00732-x

RESEARCH PAPER

## Vertical Projectile Launcher for Study of Rapid Penetration into Soil Targets

L. Giacomo[1] · D. Grace[1] · M. Omidvar[1] · S. Bless[1] · M. Iskander[1]

Received: 1 December 2023 / Accepted: 16 June 2024 / Published online: 24 July 2024

### Abstract

The majority of ballistic experiments in granular media in the literature involve horizontally launching projectiles. Notwithstanding the significant scientific findings resulting from these studies, the depth-dependence of geostatic stresses is not captured in a horizontal configuration. The design and performance of a vertical ballistic range is described herein. The range is capable of launching projectiles at impact speeds of up to 900 m/s into soil targets. A pluviator is employed to prepare sand targets with precise and highly repeatable bulk densities. Use of a photon Doppler velocimeter (PDV) and other instrumentation to track projectile velocity both in-flight and during penetration into the soil target are elucidated. A relationship is found between the muzzle velocity and chamber pressure. Launcher performance is quantified by comparing measured muzzle velocities with theoretical velocities calculated from isentropic expansion of gas behind the projectile in the launcher barrel. It is found that the launcher efficiency is in the range of 70 to 90%, with efficiency increasing for heavier projectiles. The PDV instrumentation developed for the range successfully resolves projectile velocities in flight and during penetration into the soil target.

**Keywords** Launcher · Compressed gas gun · Sand penetration · Photon Doppler velocimetry

### Introduction and Background

Projectile penetration testing in granular materials has been extensively studied in the past [1–3]. A wide range of military and civilian applications benefit from study of the topic, including design of earth penetrating projectiles, cleanup of military ranges from unexploded ordnance (UxO), planetary impact, and design of foundations of offshore oil platforms, among others. Subscale laboratory experiments are often carried out to study soil response to projectile penetration in lieu of costly full-scale field experiments. Projectiles are launched into soil targets at impact velocities ranging from tens of meters per second to supersonic and hypersonic velocities, depending on the application. The design of the launcher depends on the desired impact velocities and test conditions.

Several launcher designs have been explored and documented in the literature [4]. These encompass spring and piston mechanisms, single and double-stage gas guns, and explosive acceleration techniques, each tailored to distinct objectives. Common among these designs is that they typically launch projectiles horizontally into targets [5–8]. However, in-situ stress fields within granular materials exhibit depth-dependence. Capturing this depth-dependent behavior is paramount when developing predictive models from subscale experiments, particularly those intended for engineering applications. Launching projectiles vertically into soil targets poses a unique set of challenges. A limited number of vertical designs have been reported in the literature. The NASA Ames Vertical Gun Range (AVGR) has been widely used for study of planetary impact physics for several decades [9]. The NASA Johnson Space Center Experimental Impact Laboratory also operates a vertical gun capable of launching projectiles for hypervelocity impact studies [10]. The Institute of Space and Astronautical Science at the Japan Aerospace Exploration Agency (JAXA) operates a two-stage vertical gas gun for space and planetary impact studies [11]. Price et al. [12] presented a unique vertical launcher, which featured a right angle-shaped design, and operated in

---

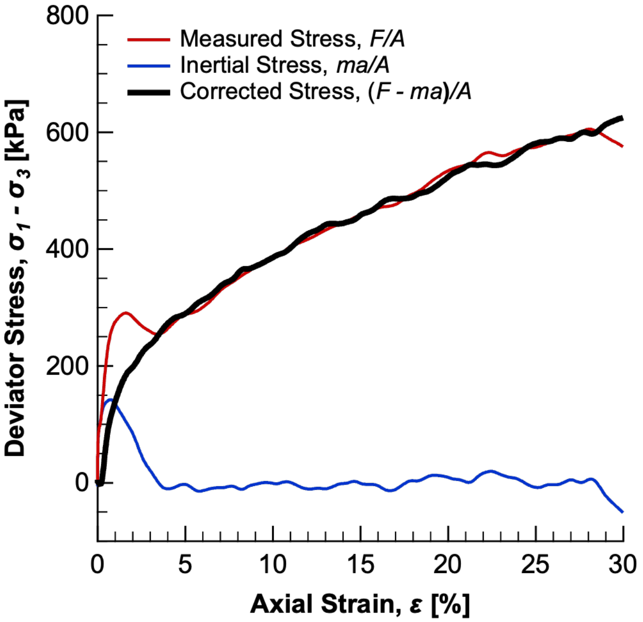
✉ M. Omidvar
omidvar@manhattan.edu

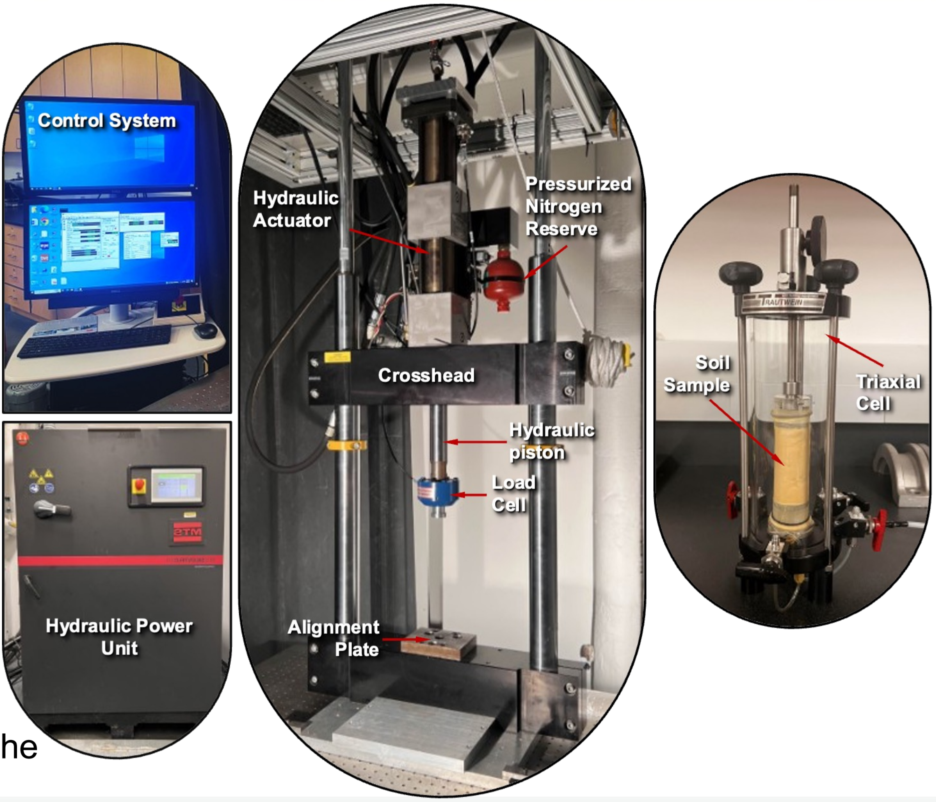
1 Civil and Environmental Engineering Department, Manhattan College, Riverdale, NY, USA

SEM

SERDP

# HSR Tests on Soils

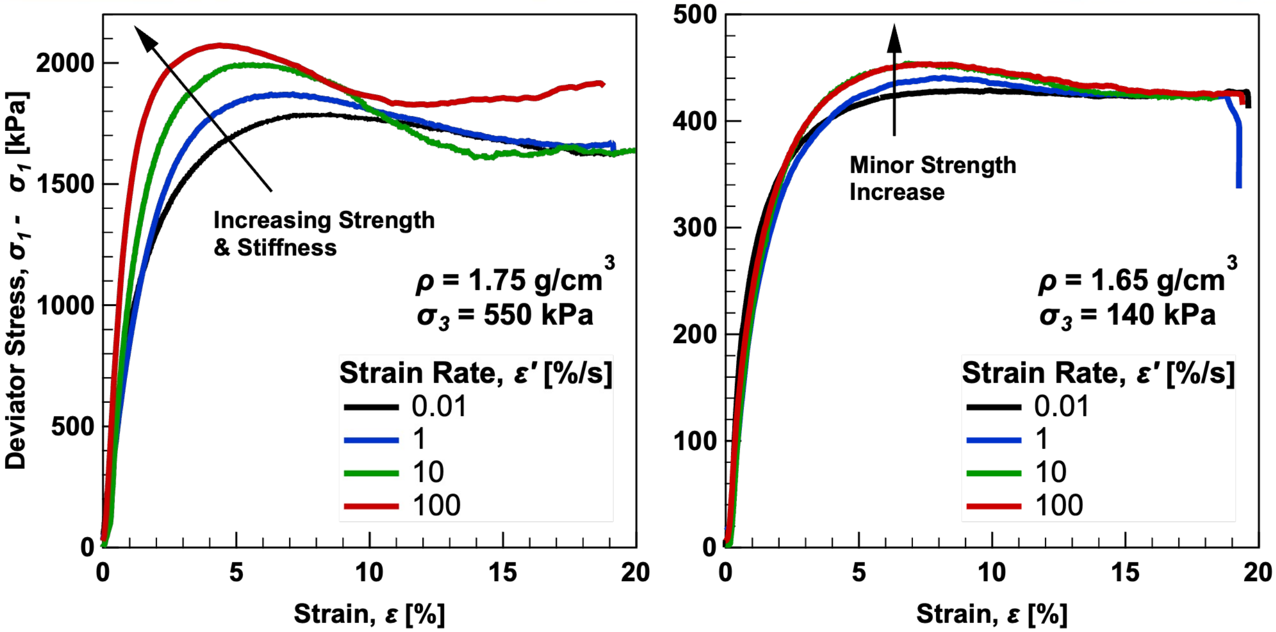




**New Method for Quantifying High Strain Rate Effects in Soils**

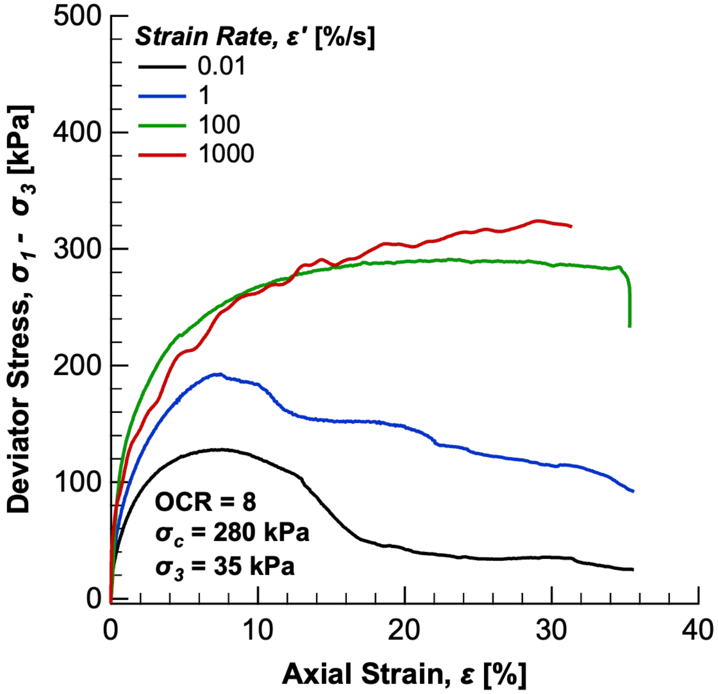
High-rate loading frame data can be better understood by correcting for the inertia of the machine.

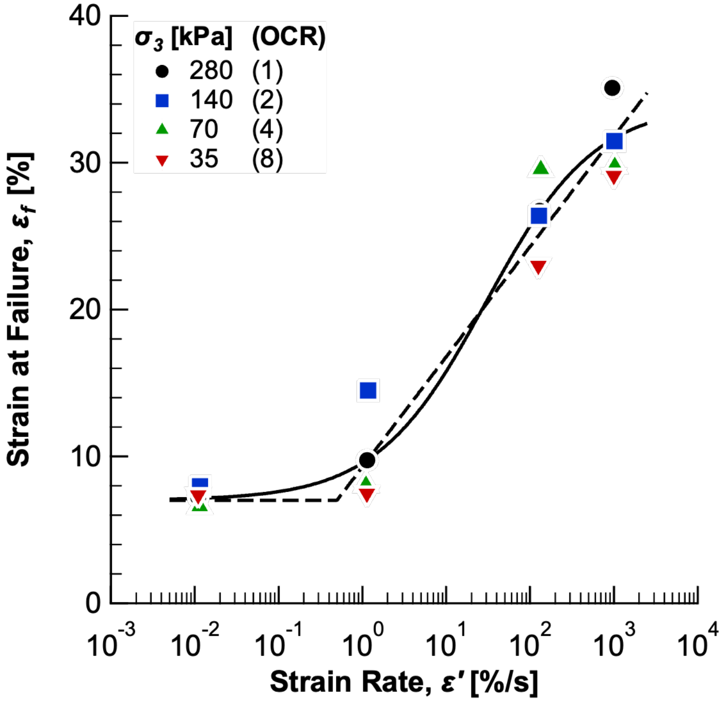
# HSR Effects in Sand



**Strength of sands elevated at HSR, more significant in dense sands under high confinement**

# HSR Effects in Clay





## In cohesive soils rate effects are significant

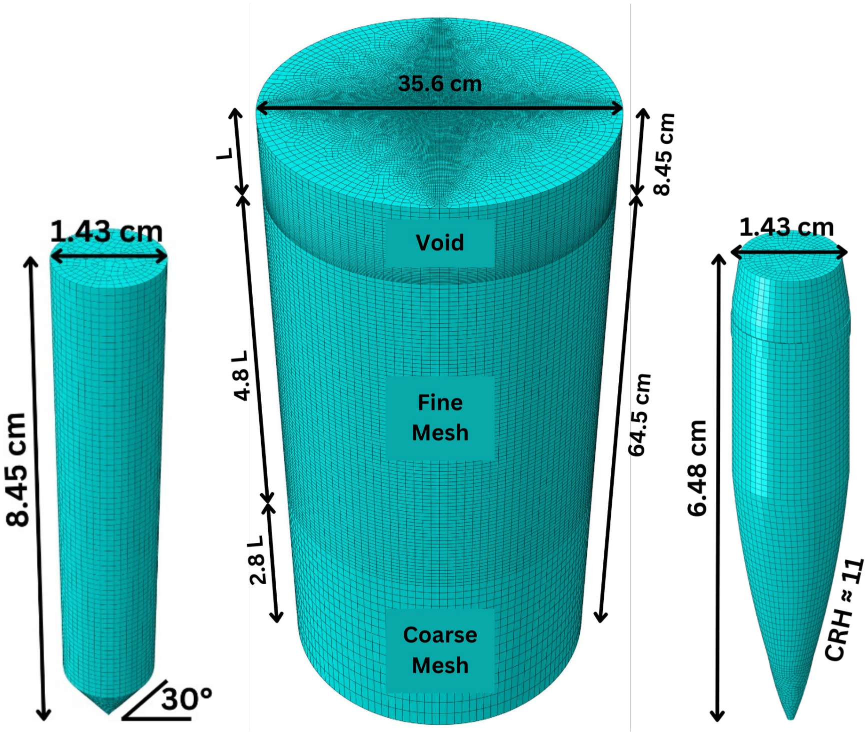
# Centrifuge Tests (Planned)

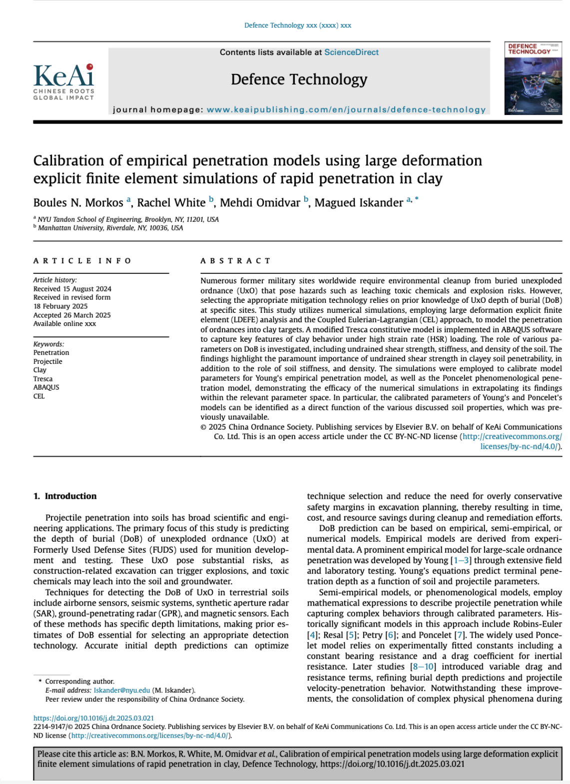
- Tests to be conducted at NYU facility in Abu Dabi in Fall 2025.
- Goal: show that geoPoncelet approach works at larger scale that might be affected by higher geostatic stresses.

# FEM Simulations

## Abaqus/Explicit Analysis

- Coupled Eulerian-Lagrangian approach
- User-defined constitutive models for clay and sand, considering:
  - Strain rate effects
  - Strain softening effects
- Comparisons with data now give us  confidence in the accuracy of these simulations.





ARTICLE IN PRESS

Defence Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Defence Technology

journal homepage: www.keaipublishing.com/en/journals/defence-technology

**Calibration of empirical penetration models using large deformation explicit finite element simulations of rapid penetration in clay**

Boules N. Morkos [a], Rachel White [b], Mehdi Omidvar [b], Magued Iskander [a, *]

[a] *NYU Tandon School of Engineering, Brooklyn, NY, 11201, USA*
[b] *Manhattan University, Riverdale, NY, 10036, USA*

A R T I C L E I N F O

*Article history:*
Received 15 August 2024
Received in revised form
18 February 2025
Accepted 26 March 2025
Available online xxx

*Keywords:*
Penetration
Projectile
Clay
Tresca
ABAQUS
CEL

A B S T R A C T

Numerous former military sites worldwide require environmental cleanup from buried unexploded ordnance (UxO) that pose hazards such as leaching toxic chemicals and explosion risks. However, selecting the appropriate mitigation technology relies on prior knowledge of UxO depth of burial (DoB) at specific sites. This study utilizes numerical simulations, employing large deformation explicit finite element (LDEFE) analysis and the Coupled Eulerian-Lagrangian (CEL) approach, to model the penetration of ordnances into clay targets. A modified Tresca constitutive model is implemented in ABAQUS software to capture key features of clay behavior under high strain rate (HSR) loading. The role of various parameters on DoB is investigated, including undrained shear strength, stiffness, and density of the soil. The findings highlight the paramount importance of undrained shear strength in clayey soil penetrability, in addition to the role of soil stiffness, and density. The simulations were employed to calibrate model parameters for Young's empirical penetration model, as well as the Poncelet phenomenological penetration model, demonstrating the efficacy of the numerical simulations in extrapolating its findings within the relevant parameter space. In particular, the calibrated parameters of Young's and Poncelet's models can be identified as a direct function of the various discussed soil properties, which was previously unavailable.

© 2025 China Ordnance Society. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

**1. Introduction**

Projectile penetration into soils has broad scientific and engineering applications. The primary focus of this study is predicting the depth of burial (DoB) of unexploded ordnance (UxO) at Formerly Used Defense Sites (FUDS) used for munition development and testing. These UxO pose substantial risks, as construction-related excavation can trigger explosions, and toxic chemicals may leach into the soil and groundwater.

Techniques for detecting the DoB of UxO in terrestrial soils include airborne sensors, seismic systems, synthetic aperture radar (SAR), ground-penetrating radar (GPR), and magnetic sensors. Each of these methods has specific depth limitations, making prior estimates of DoB essential for selecting an appropriate detection technology. Accurate initial depth predictions can optimize technique selection and reduce the need for overly conservative safety margins in excavation planning, thereby resulting in time, cost, and resource savings during cleanup and remediation efforts.

DoB prediction can be based on empirical, semi-empirical, or numerical models. Empirical models are derived from experimental data. A prominent empirical model for large-scale ordnance penetration was developed by Young [1–3] through extensive field and laboratory testing. Young's equations predict terminal penetration depth as a function of soil and projectile parameters.

Semi-empirical models, or phenomenological models, employ mathematical expressions to describe projectile penetration while capturing complex behaviors through calibrated parameters. Historically significant models in this approach include Robins-Euler [4]; Resal [5]; Petry [6]; and Poncelet [7]. The widely used Poncelet model relies on experimentally fitted constants including a constant bearing resistance and a drag coefficient for inertial resistance. Later studies [8–10] introduced variable drag and resistance terms, refining burial depth predictions and projectile velocity-penetration behavior. Notwithstanding these improvements, the consolidation of complex physical phenomena during

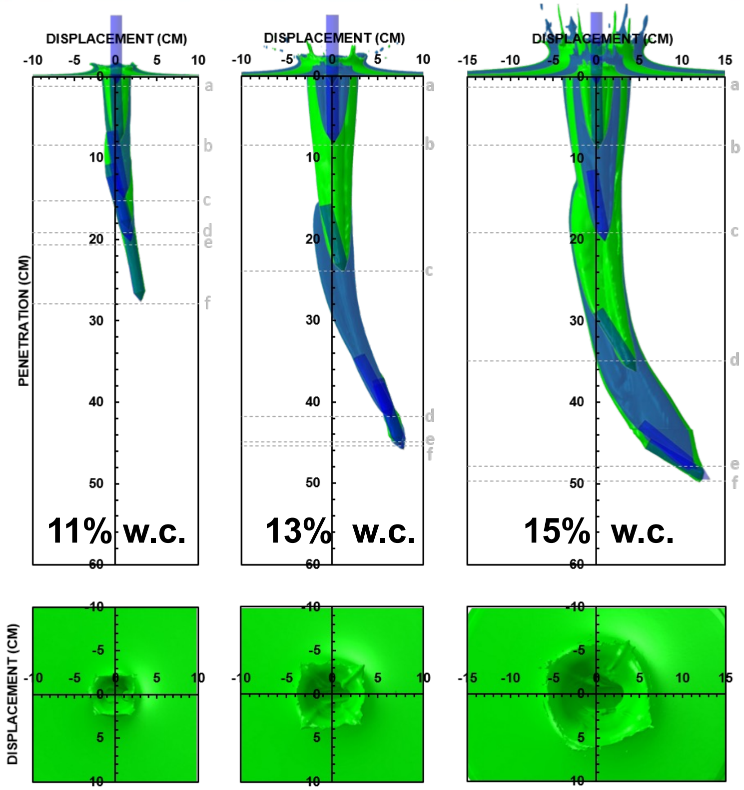
---

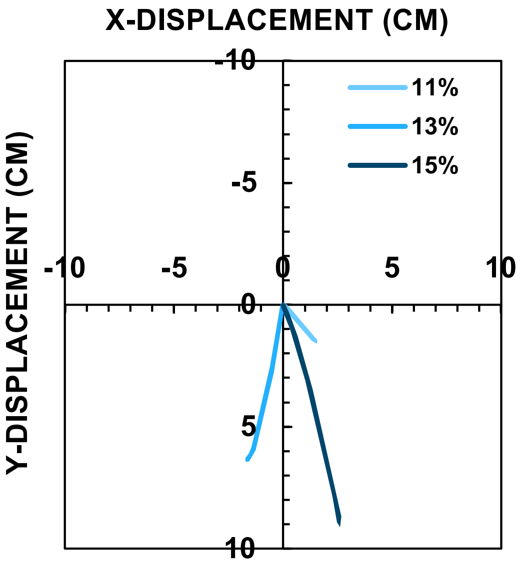
* Corresponding author.
*E-mail address:* Iskander@nyu.edu (M. Iskander).
Peer review under the responsibility of China Ordnance Society.

https://doi.org/10.1016/j.dt.2025.03.021
2214-9147/© 2025 China Ordnance Society. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Please cite this article as: B.N. Morkos, R. White, M. Omidvar *et al.*, Calibration of empirical penetration models using large deformation explicit finite element simulations of rapid penetration in clay, Defence Technology, https://doi.org/10.1016/j.dt.2025.03.021

# FEM Simulations: Instability in Clay



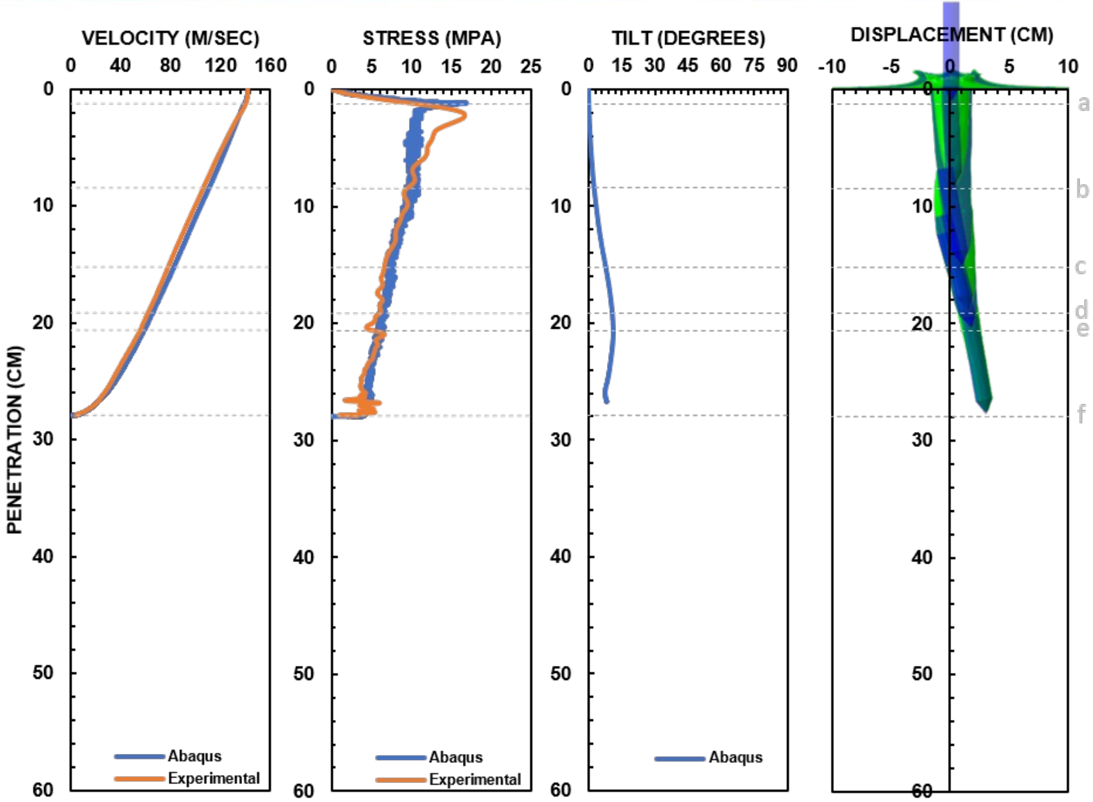


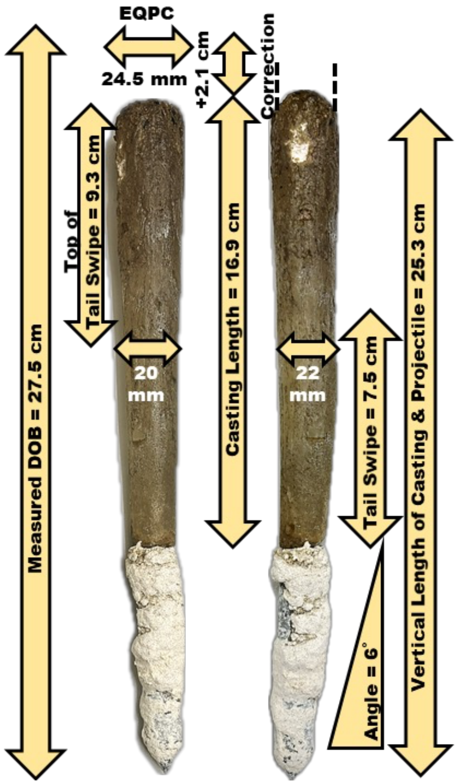
Top View

Early onset
AoA causes
tail swipe

# FEM Simulations: Penetration in Clay

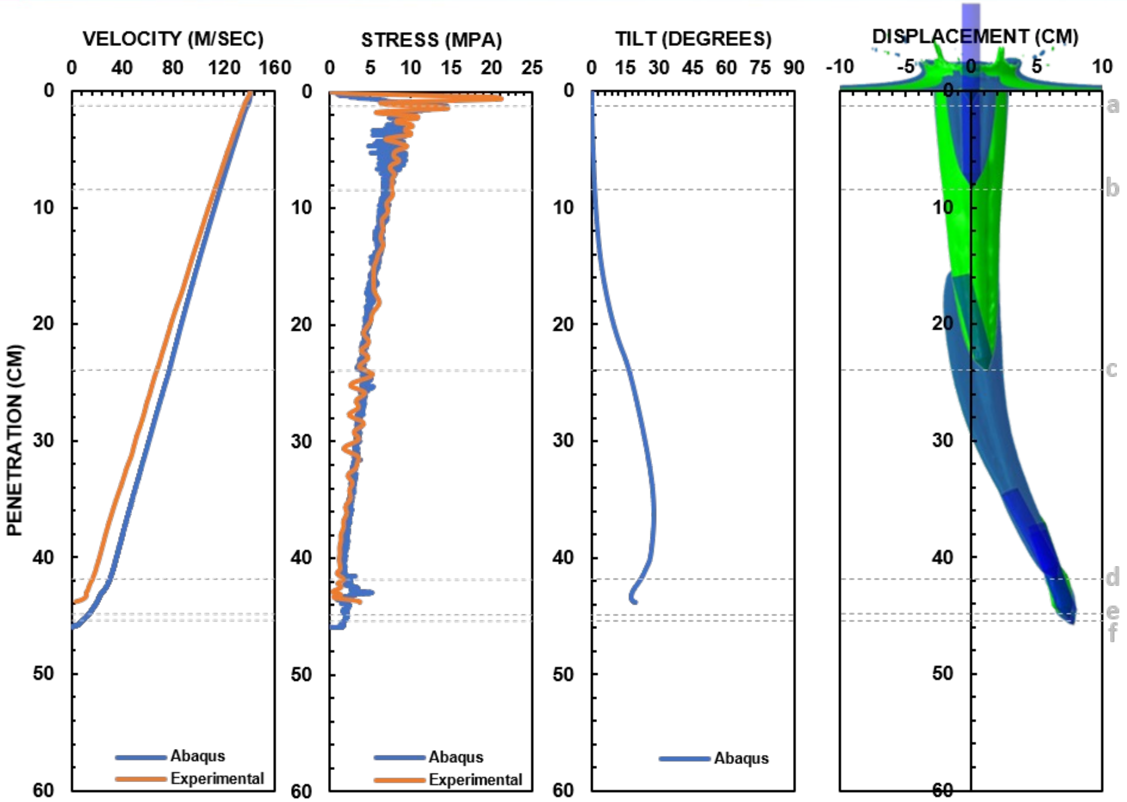
## (11% WC Clayey Sand)

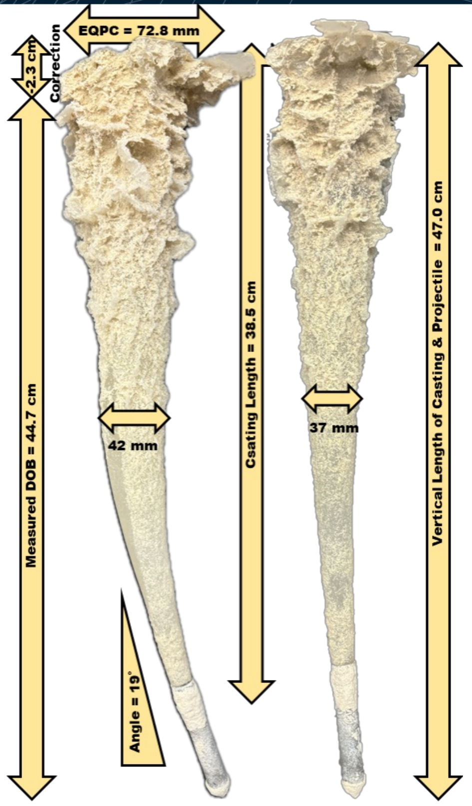




SERDP

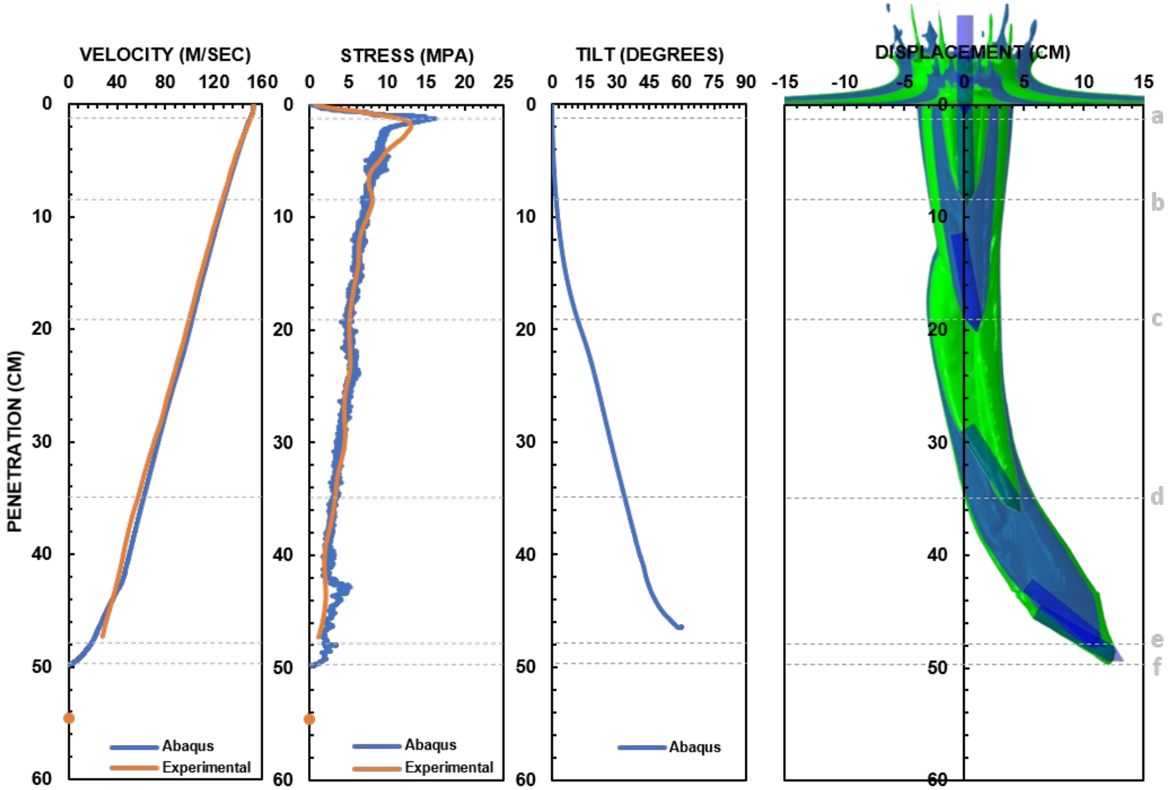
# FEM Simulations: Penetration in Clay
## (13% WC Clayey Sand)



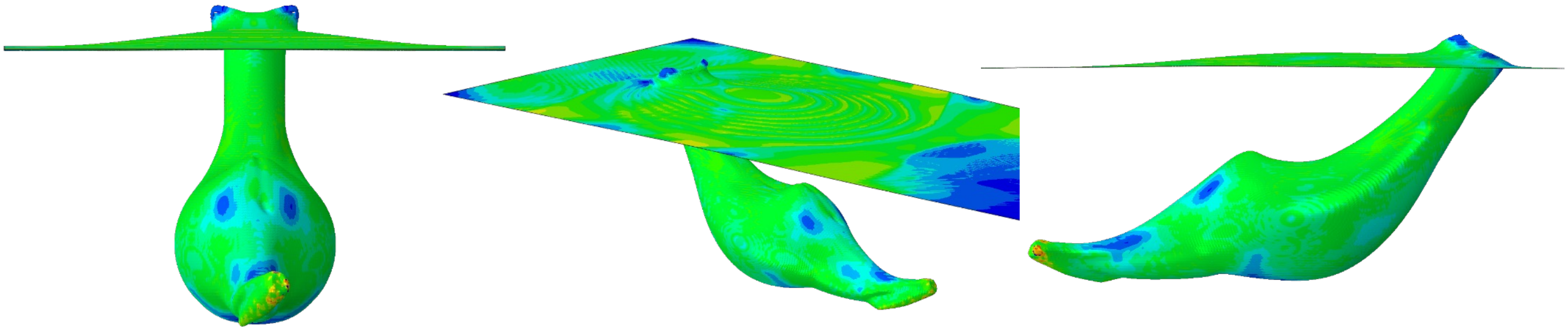


# FEM Simulations: Penetration in Clay

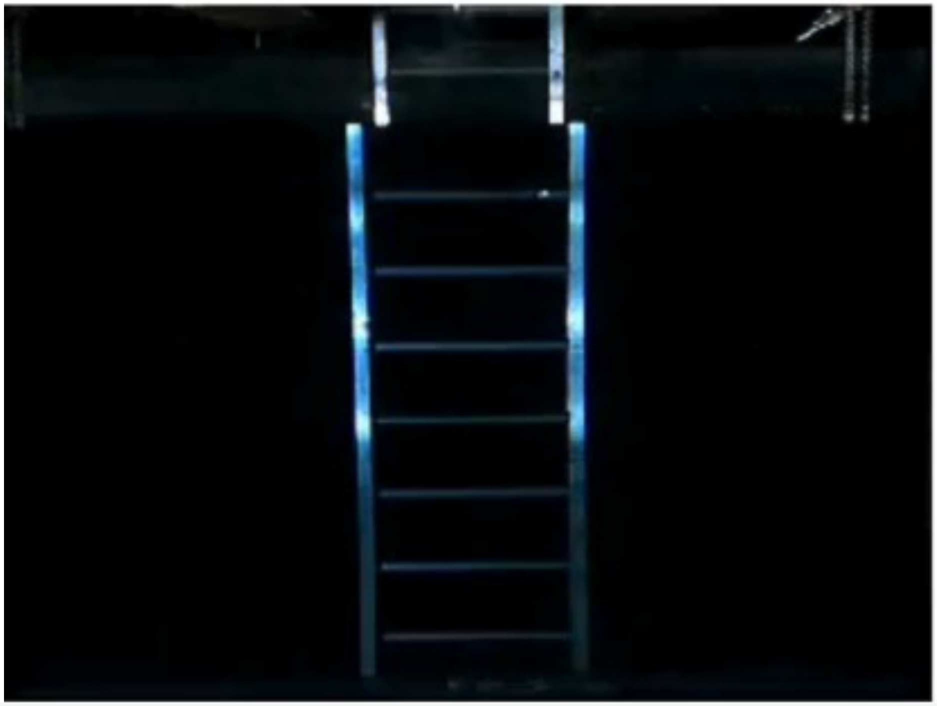
## (15% WC Clayey Sand)



# Oblique impact of M-107 (in progress)



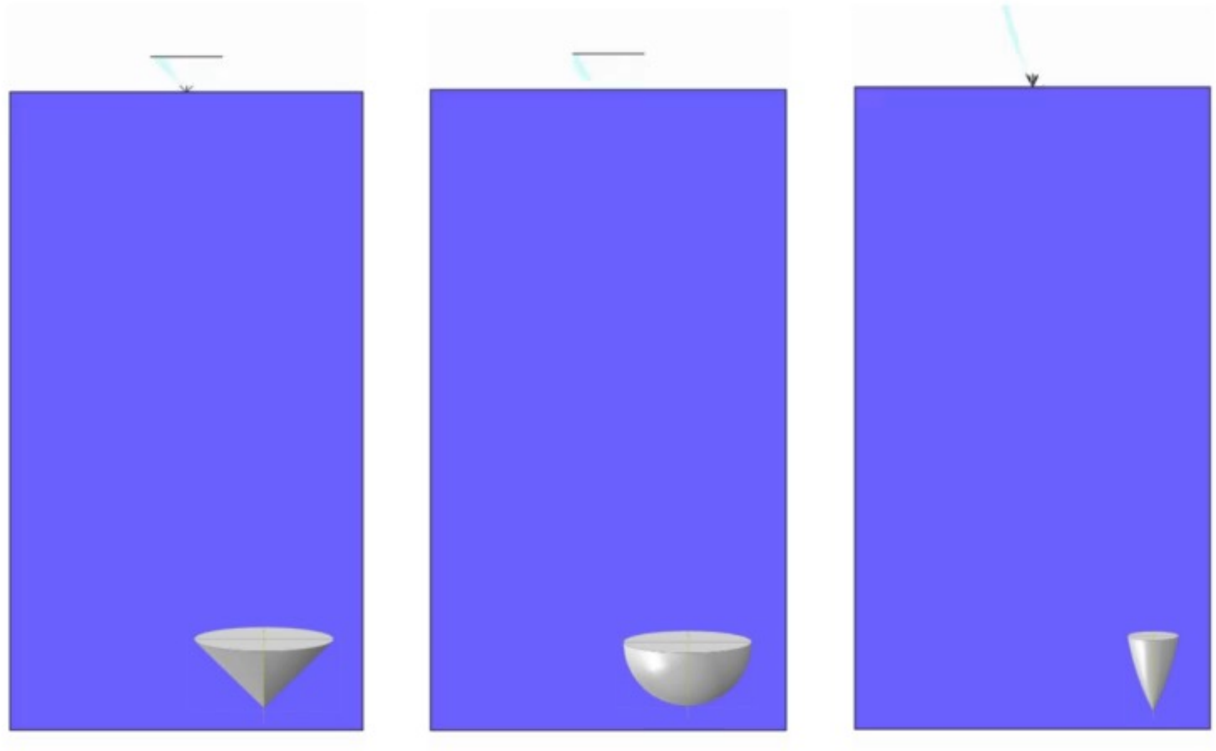
# Water Impact Phenomena



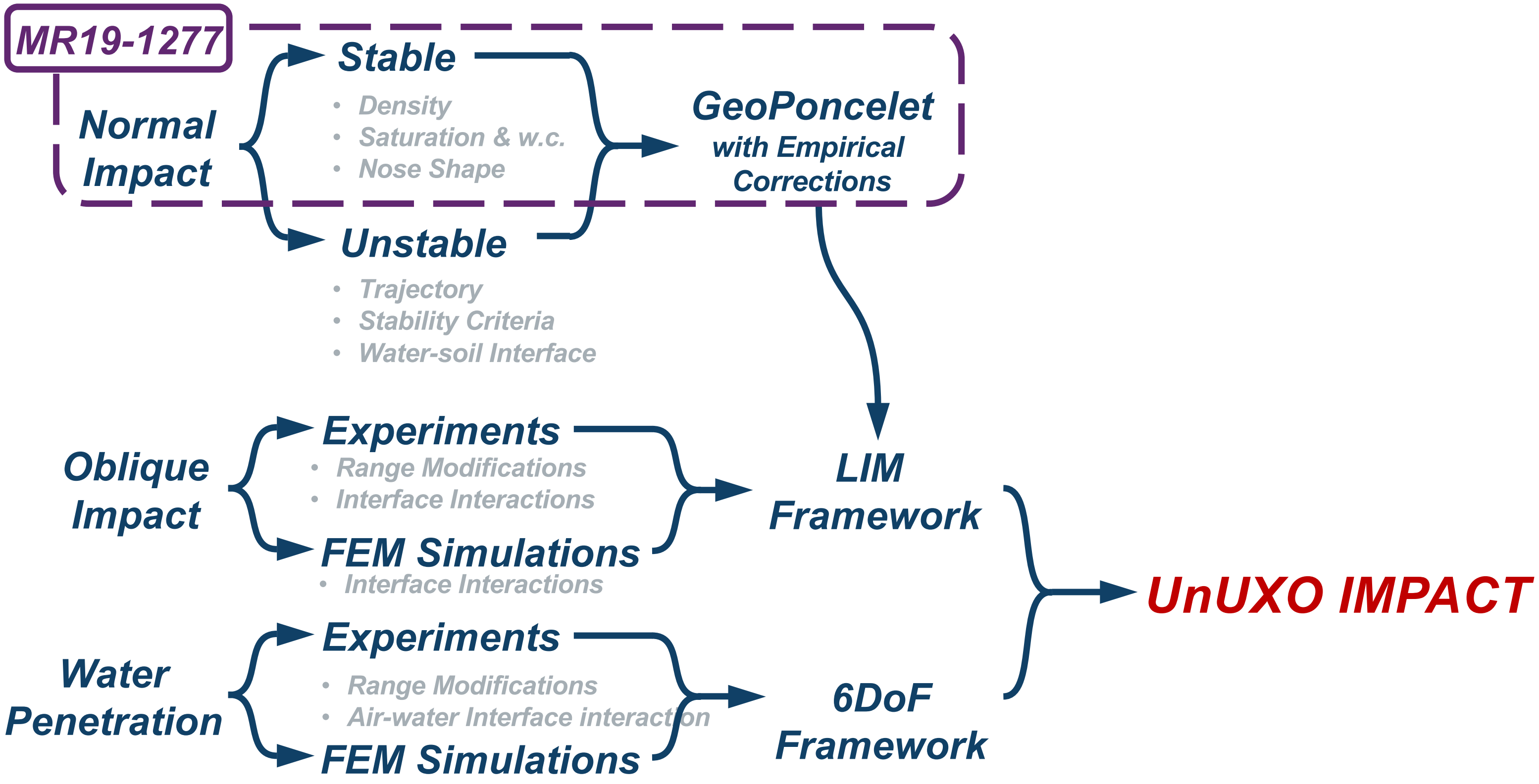
**No fins**

**With fins**

# Water Impact Simulation



# Penetration Model Development



MR19-1277

Normal Impact

Stable
- Density
- Saturation & w.c.
- Nose Shape

Unstable
- Trajectory
- Stability Criteria
- Water-soil Interface

GeoPoncelet
with Empirical Corrections

Oblique Impact

Experiments
- Range Modifications
- Interface Interactions

FEM Simulations
- Interface Interactions

LIM Framework

Water Penetration

Experiments
- Range Modifications
- Air-water Interface interaction

FEM Simulations

6DoF Framework

UnUXO IMPACT

# GeoPoncelet (GP) Model

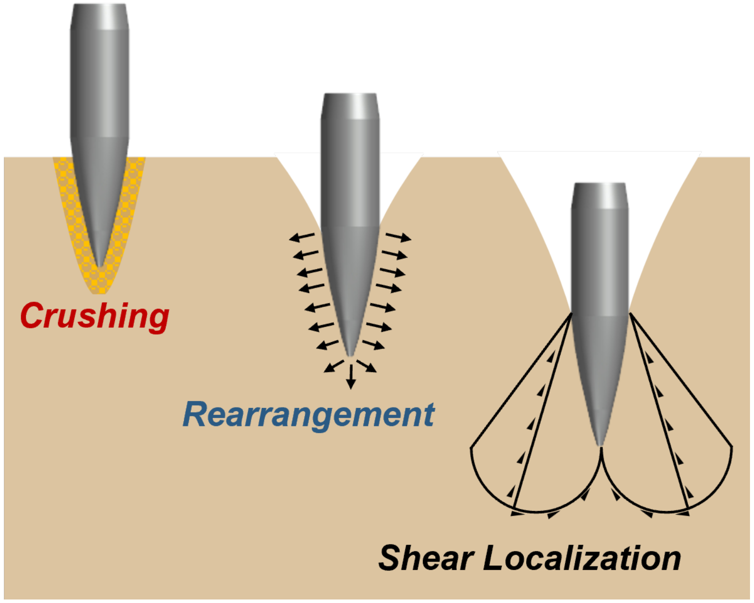
$$\boldsymbol{v_{i+1} = v_i - \frac{q_i}{m v_i} \Delta z,}$$

$$q_i = \begin{cases} C_1 \rho_i v_i^2 + \zeta_n \zeta_{r,i} q_{t,i}\,, q_i \geq q_{tr} \\ C_2 \rho_i v_i^2 + \zeta_n \zeta_{r,i} q_{t,i}\,, q_i < q_{tr} \end{cases}$$

$$\zeta_r = 1 + \mu \log\left[\frac{v/D}{(v/D)_{\mathrm{CPT}}}\right]$$

## Geo Poncelet Accounts for

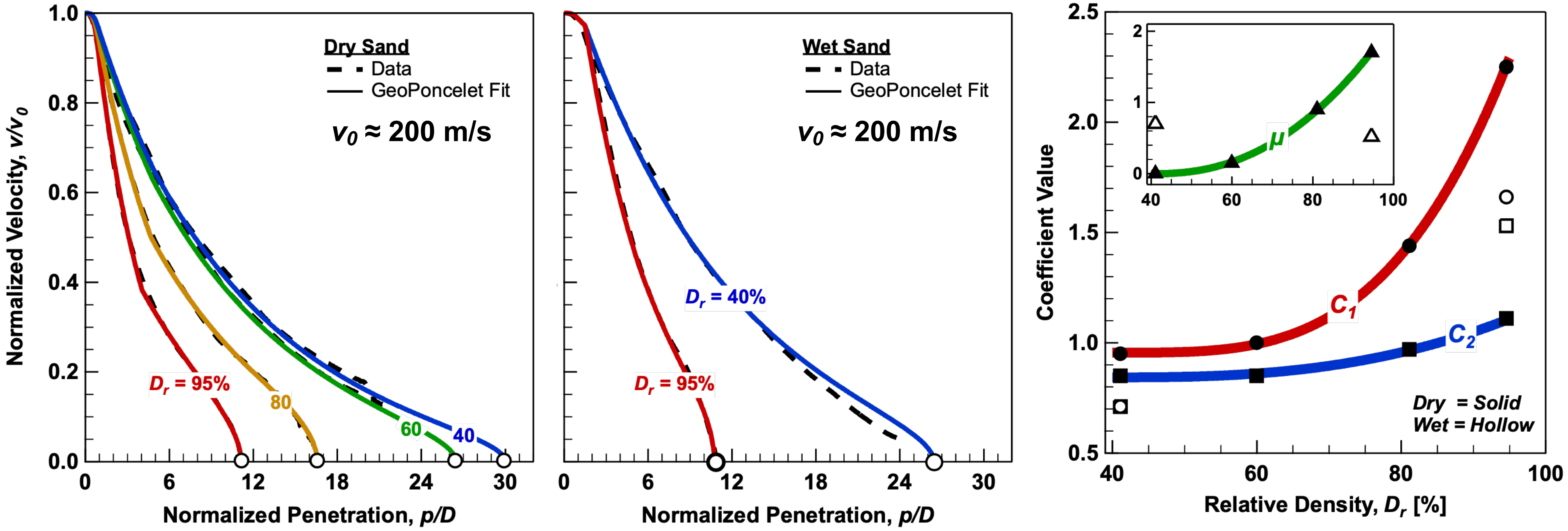
- Incremental implementation to account for depth dependent parameters
- Variable projectile X-sectional area during impact
- Use of *in-situ* cone tip stresses
- Piece-wise drag implementation



**Where:**

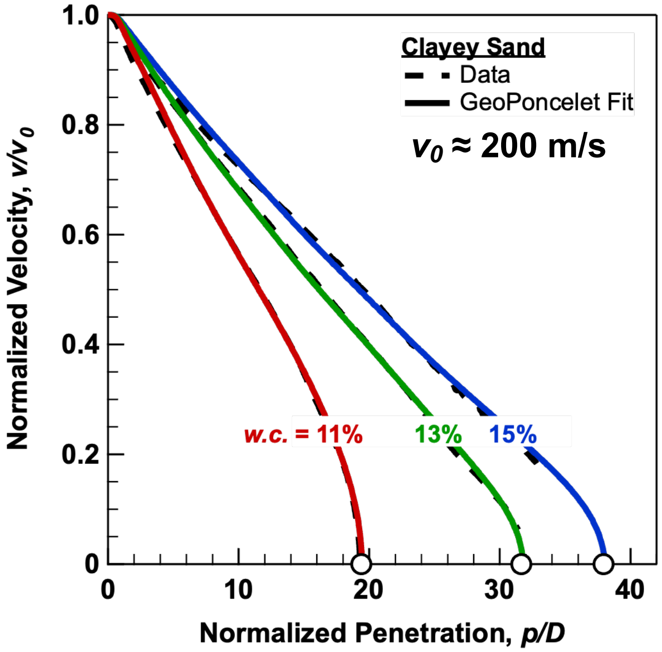
$v$ : projectile velocity
$m$ : projectile mass
$\rho$ : soil density
$A$ : projectile area
$q_t$ : CPT stress at a depth $z$
$\Delta z$ : penetration depth increment
$C_1$ : crushing drag coefficient
$C_2$ : rearrangement drag coefficient
$q_{tr}$ : crushing transition stress
$\zeta_n$ : bearing stress nose shape factor
$\zeta_r$ : bearing stress rate factor
$\mu$ : Rate strengthening coefficient

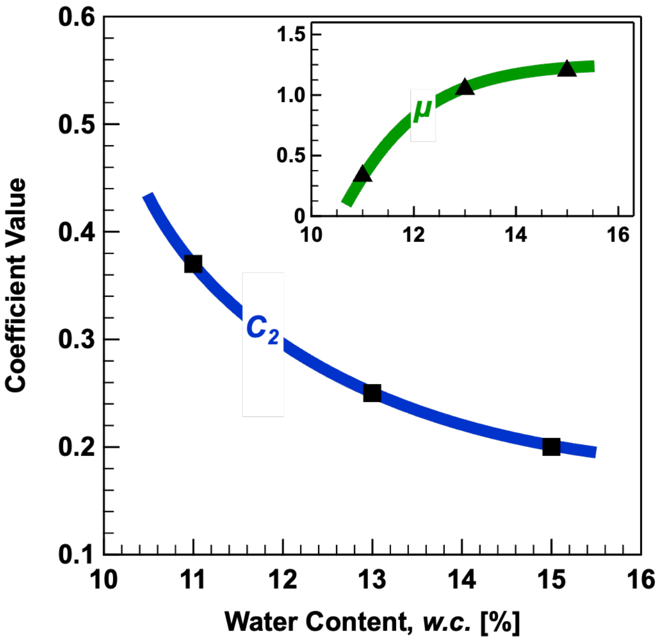
# GeoPoncelet Model Demonstration: Sand



**The model can describe penetration data with high fidelity**

# GeoPoncelet Model Demonstration: Clay

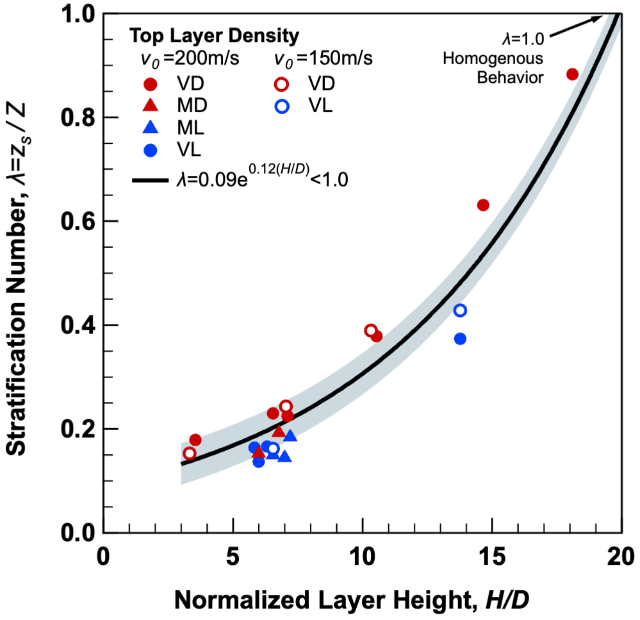


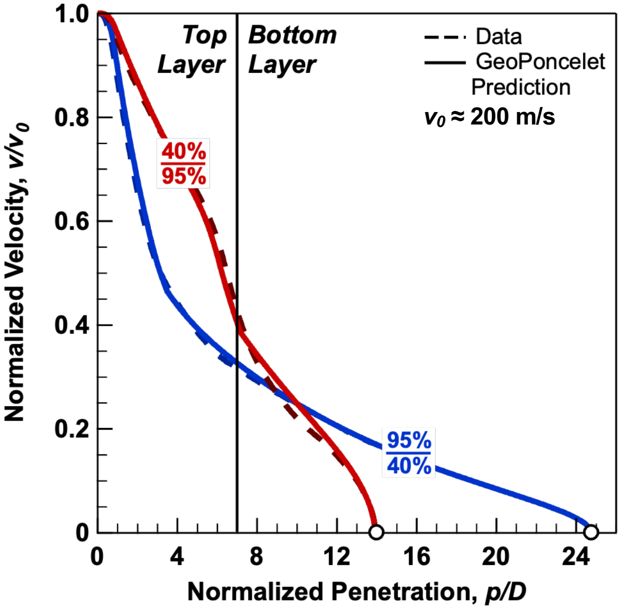


Note: No crushing in clays. Only $C_2$ is sufficient.

**The model can describe penetration data with high fidelity**

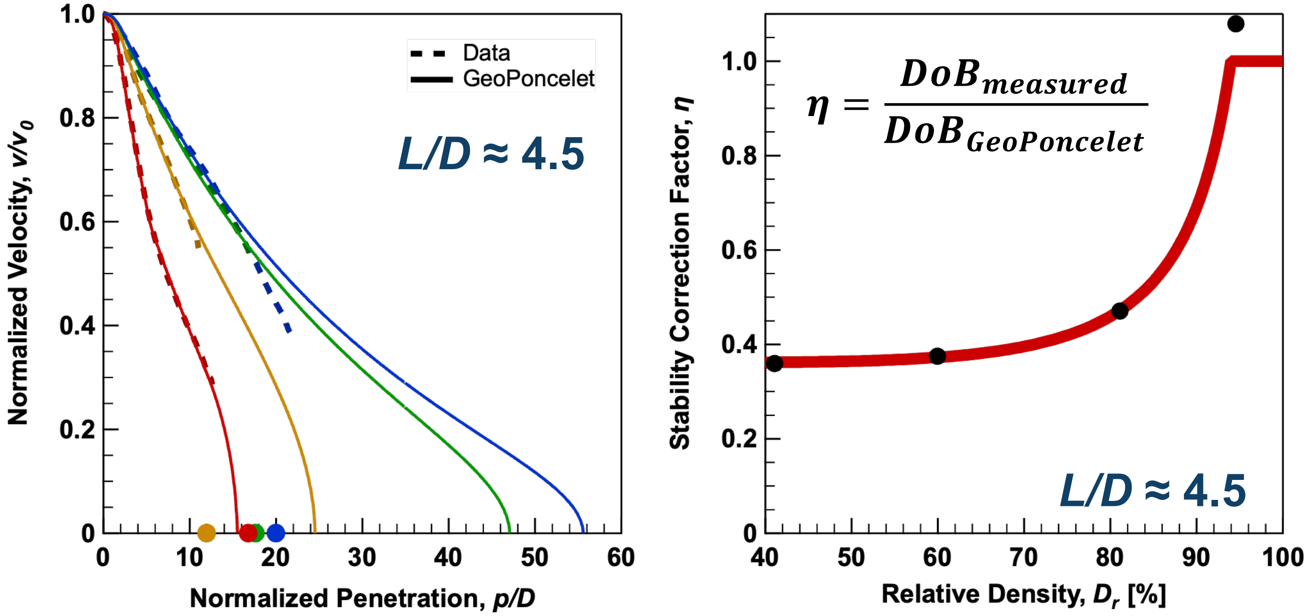
# GeoPoncelet Model for Layered Sand





## DoB in layered sands predicted from calibration in uniform sands

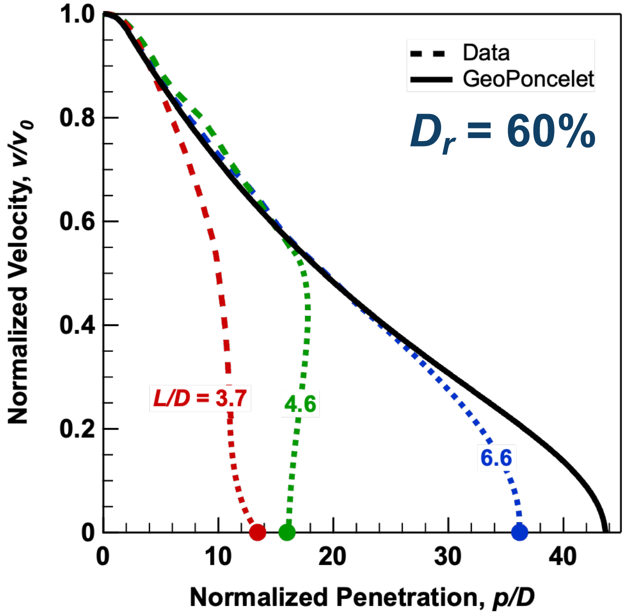
# Model Instability Correction Factors for Relative Density

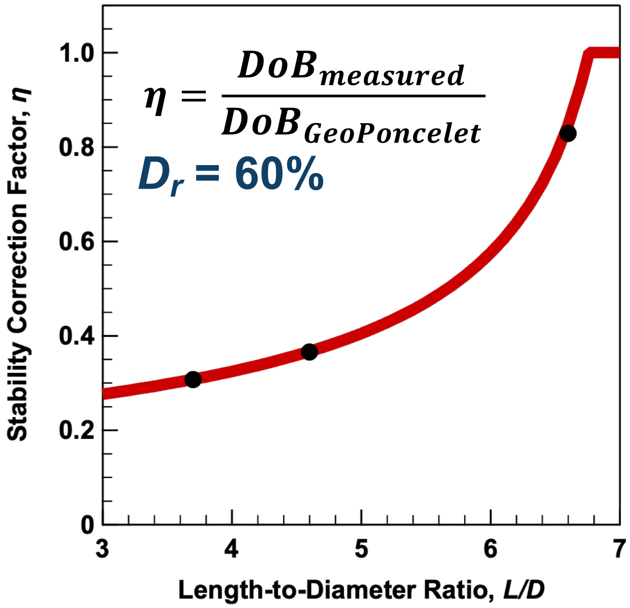


**Empirical correction factor *η* corrects for decreased DoB**

*η* is influenced by both density and *L/D*

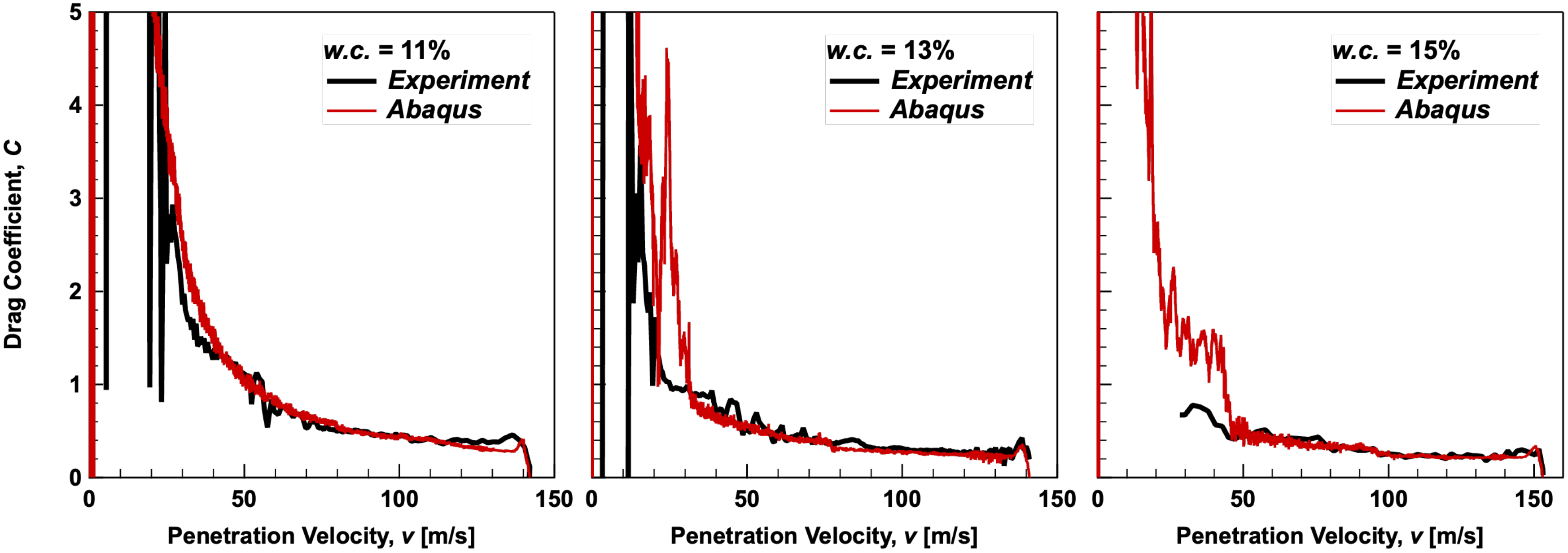
# Model Instability Correction Factors for Projectile Shape (L/D)





**Length-to-diameter (*L/D*) ratio identified is key stability parameter**

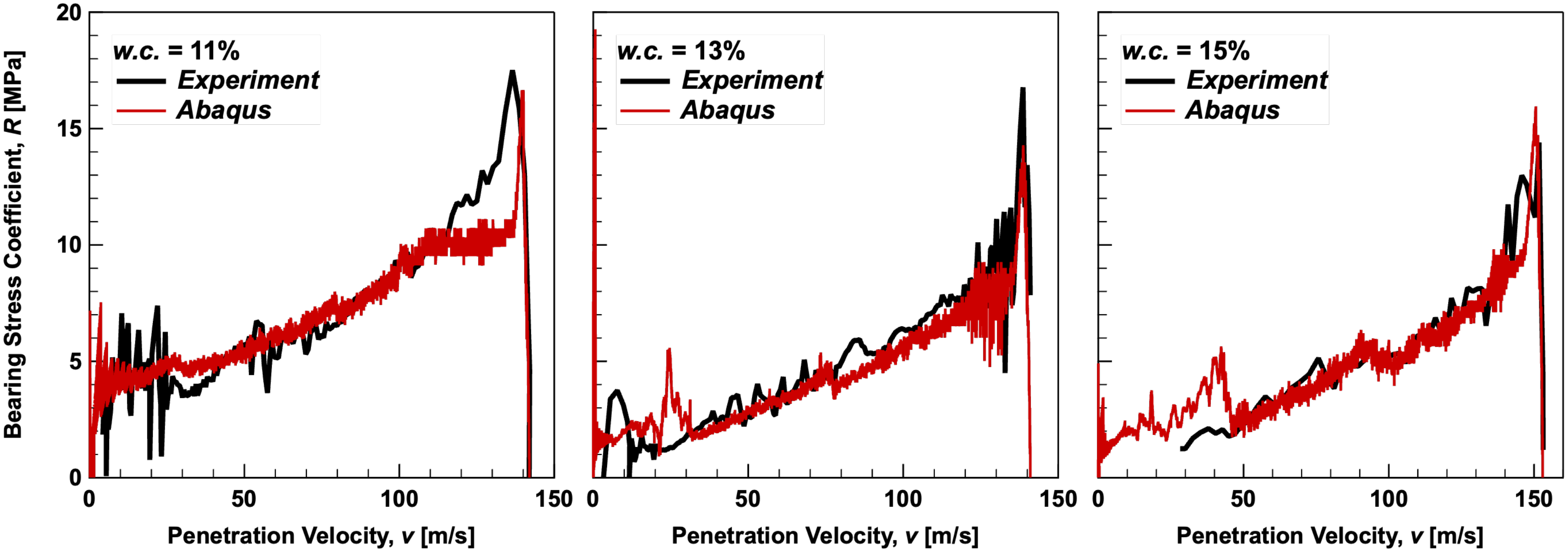
# Abaqus Correctly Computes Poncelet Parameters: Drag



**Excellent Match between experimental & numerical results**

High-speed, drag-dominated penetration

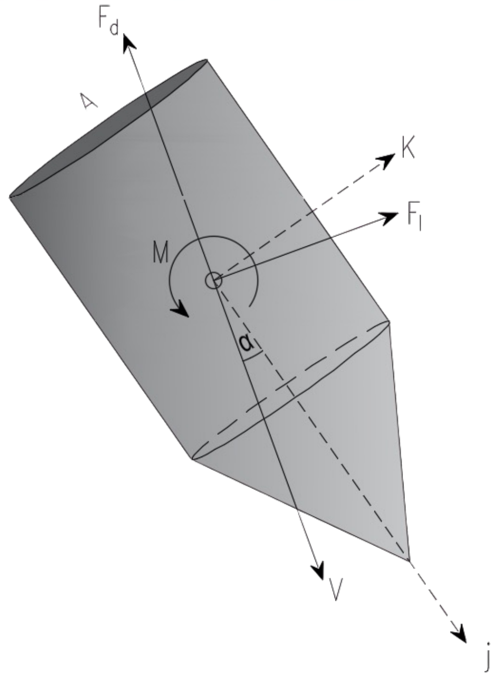
# Abaqus Correctly Computes Poncelet Parameters: Bearing



**Excellent Match between experimental & numerical results**

Low-speed, strength-dominated penetration

# 6DoF UnUXO Model (Water)



**6DoF model accounts for global drag, lift, and torque, in water**

## Equation of Motion (Translational Motion)

$$m\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = \boldsymbol{F_d} + \boldsymbol{F_l}$$

$$|\boldsymbol{F_d}| = \frac{1}{2}C_d\rho_w A\boldsymbol{V}^2$$

$$|\boldsymbol{F_l}| = \frac{1}{2}C_l\rho_w A\boldsymbol{V}^2$$

**Where:**

$F_d$: Drag Force
$F_l$ : Lift Force
$C_d$: Drag Coefficient
$C_l$ : Lift Coefficient

## Moment of Momentum Equation (Rotational Motion)

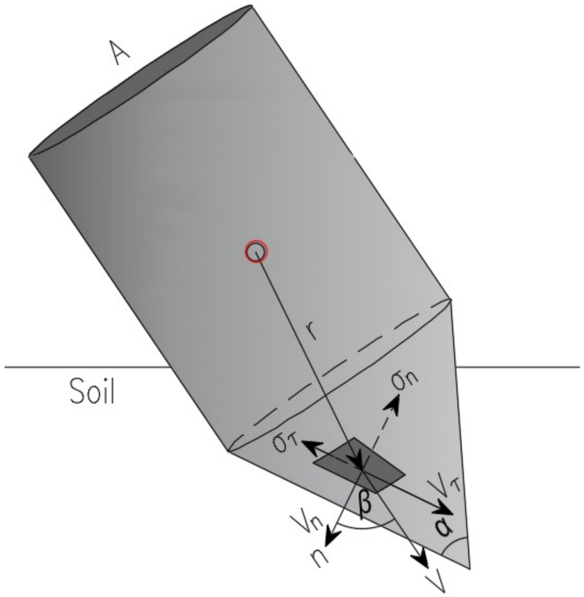
$$\boldsymbol{J}\cdot\frac{\mathrm{d}\boldsymbol{\Omega}}{\mathrm{d}t} = \boldsymbol{M}$$

$$|\boldsymbol{M}| = \frac{1}{2}C_m\rho_w LA\boldsymbol{V}^2$$

**Where:**

$J$: Projectile gyration tensor
$\Omega$: Projectile angular velocity
$M$: Torque on Projectile
$C_m$: Torque Coefficient

# LIM UnUXO Model (Soil)



Equation of Motion

$$\boxed{m\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = \boldsymbol{F}}$$

$$\boxed{\boldsymbol{F} = \oiint (\boldsymbol{\sigma_n} + \boldsymbol{\sigma_\tau})\mathrm{d}A}$$

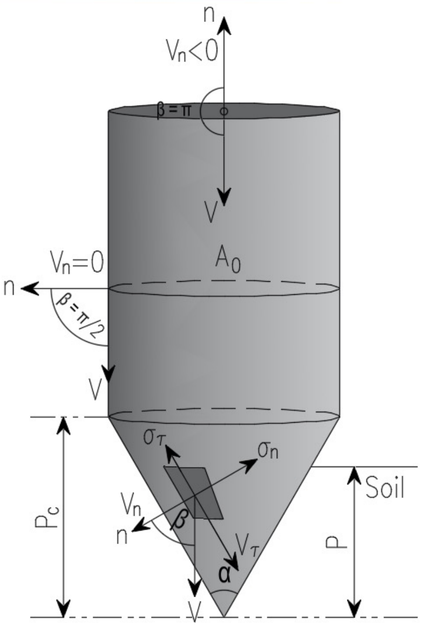
Moment of Momentum Equation

$$\boxed{\boldsymbol{J}\cdot\frac{\mathrm{d}\boldsymbol{\Omega}}{\mathrm{d}t} = \boldsymbol{M}}$$

$$\boxed{\boldsymbol{M} = \oiint r(\boldsymbol{\sigma_n} + \boldsymbol{\sigma_\tau})\mathrm{d}A}$$

**In soils, the localized interaction model (LIM) computes resultant stresses by integration of stresses on differential areas.**

# LIM Model Applied to Rectilinear Project Ballistic Data (1D motion)

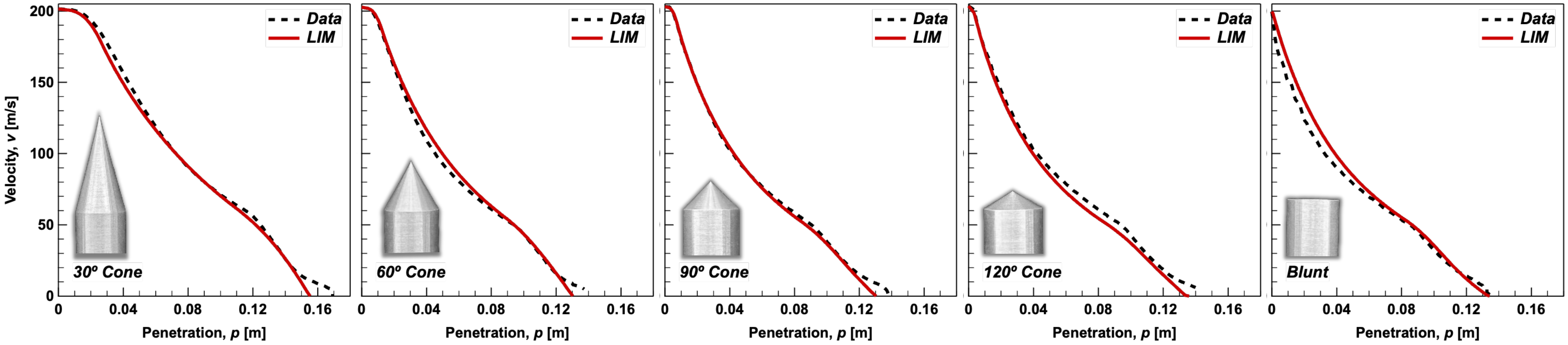


$$-m\frac{dV}{dt} = \left[ C_\sigma \rho V^2 \left( \begin{array}{c} \sin\left(\frac{\alpha}{2}\right) \\ +k_f \cos\left(\frac{\alpha}{2}\right) \end{array} \right) + R_\sigma \left( 1 + k_f \cot\left(\frac{\alpha}{2}\right) \right) \right] A(P)$$

| Test ID | Projectile Nose Apex Angle (α) | Impact Velocity $V_0$ (m/s) | Poncelet Parameters | |
|---|---|---|---|---|
| | | | C | R (MPa) |
| **PDV50** | 30° Cone | 201.4 | 1.4 | 3.0 |
| **PDV49** | 60° Cone | 202.7 | 2.1 | 1.7 |
| **PDV53** | 90° Cone | 203.1 | 2.1 | 1.5 |
| **PDV54** | 120° Cone | 203.5 | 2.0 | 1.6 |
| **PDV51** | Blunt | 199.6 | 2.0 | 1.5 |

**Initial implementation is in 1D to be followed by 3D to predict a more comprehensive trajectory**

# LIM Performance (1D)



**LIM captures experimental data with good fidelity for a variety of cone angles**

# Next Steps (for next 12 months)

- Laboratory experiments for calibration of trajectory instability models.
  - Water
  - Transparent soils
  - Sands and clays
- Comprehensive set FEM simulations for calibration of instability models and behavior at interfaces.
- Development of UnUxO-Impact model to incorporate both GeoPoncelet and LIM model features.
- Centrifuge experiments to investigate scaling.
- Interim progress report: August 2025.
- Milestone 1 demonstration field test: Summer 2026

# Technology Transfer

- We are working with US Army ERDC-GSL, Vicksburg MS and U.S. Army Engineering and Support Center, Huntsville to carry out a field test demonstration and present results in a form amenable to implementation by site managers.
- 11 Journal publications to date
- 5 Presentations at conferences
- Web tool for stochastic assessment of site variability + user guide

# Issues

- Laboratory work is behind schedule due to need for breech repair.
- DoD funding has been late forcing NYU to issue risk accounts twice so far. This has also affected staffing.
- Model development relies on field verification (Milestone 1). SERDP directed us to apply to ESTCP Demonstration of Munitions Response Technologies for Underwater Environments at Live Sites per ESTCP FY 2026 Solicitation (Released Jan 7, 2025), which we did. If approved, the schedule will be 12 months later than we had anticipated in the original contract schedule. For this reason, we may need a no cost extension.

# Thank You

Exhumed false nose in front of blunt projectile

iskander@nyu.edu

sbless@nyu.edu

omidvar@manhattan.edu

pcchu@nps.edu

# BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

# UnUXO High Speed Model: Water Impact

## Drag, Lift, and Torque Coefficients as functions of Reynolds Number ($R_e$) and AoA (α)

$$|\boldsymbol{F_d}| = \frac{1}{2} C_d \rho_w A V^2 \qquad C_d = 0.02 + 0.35 e^{-2\left(\alpha - \pi/2\right)^2} \left(\frac{R_e}{R_e^*}\right)^{0.2} + 0.008\Omega \sin(\theta)$$

$$|\boldsymbol{F_l}| = \frac{1}{2} C_l \rho_w A V^2 \qquad C_l = \begin{cases} 0.35 \sin(\theta_1) \left(\frac{R_e}{R_e^*}\right)^{0.2}, & \alpha \le \frac{\pi}{2} \\ 0.1 \sin(\theta_2) - 0.015\Omega \left(\frac{R_e}{R_e^*}\right)^{2} \sin\left(\theta_2^{0.85}\right), & \alpha > \frac{\pi}{2} \end{cases}$$

$$|\boldsymbol{M}| = \frac{1}{2} C_m \rho_w L A V^2 \qquad C_m = \begin{cases} 0.07 \sin(2\alpha) \left(\frac{R_e}{R_e^*}\right)^{0.2}, \alpha \le \frac{\pi}{2} \\ 0.02 \sin(2\alpha) \left(\frac{R_e}{R_e^*}\right)^{0.5}, \alpha > \frac{\pi}{2} \end{cases}$$

$$\theta = \operatorname{sign}(\pi - 2\alpha)\left(\pi^{2.2} - (\pi - |\pi - 2\alpha|)^{2.2}\right)^{\frac{1}{2.22}}$$

$$\theta_1 = \pi \left(\frac{2\alpha}{\pi}\right)^{1.8} \qquad \theta_2 = 2\pi \left(\frac{2\alpha}{\pi} - 1\right)^{0.7}$$

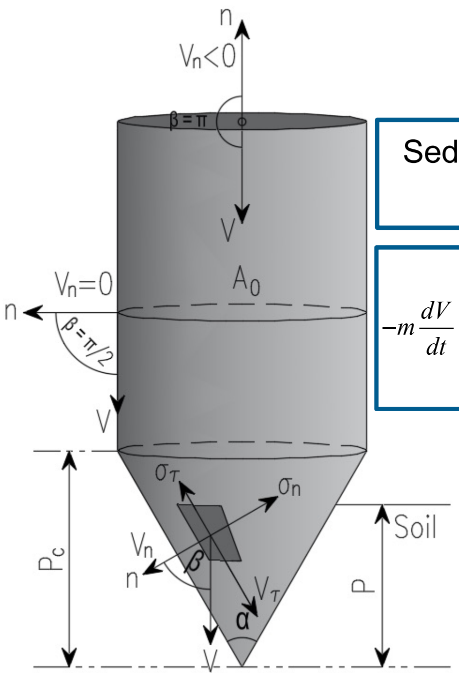
$R_e = \frac{VD}{v}$ → Reynolds Number

$R_e^* = 1.8 \times 10^7$ → Critical Reynolds Number

Based on $^{1}/_{12}$-scale Mk84 bomb tests at impact velocities of 305 m/s. New functions are being developed for M107 and Cones.

# Two UnUXO High Speed Soil Penetration Models

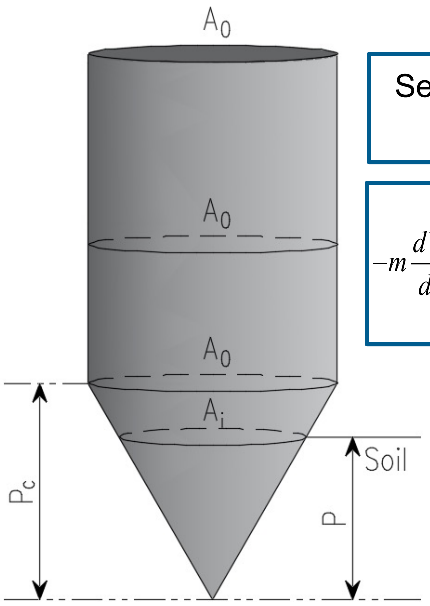
## Localized Interaction Model (LIM)



Sediment Resistant Stress on Projectile's
**Physical Surface**

$$-m\frac{dV}{dt} = \left[C_\sigma \rho V^2 \left(\sin\left(\frac{\alpha}{2}\right) + k_f \cos\left(\frac{\alpha}{2}\right)\right) + R_\sigma\left(1 + k_f \cot\left(\frac{\alpha}{2}\right)\right)\right] A(P)$$

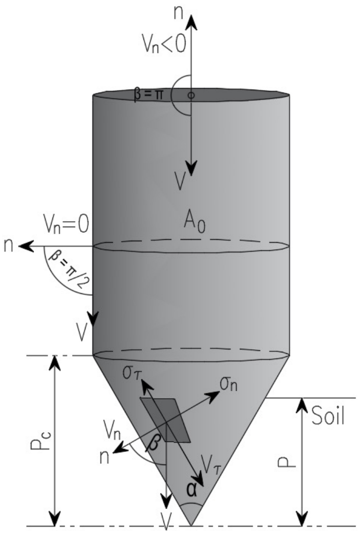
## Poncelet Model

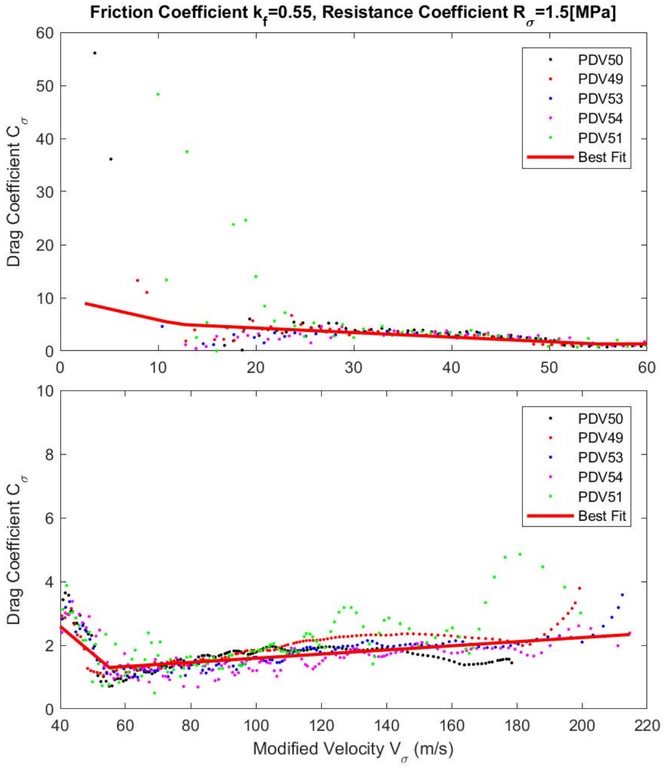


Sediment Resistant Stress on Projectile's
**Projected Surface**

$$-m\frac{dV}{dt} = \left[C\rho V^2 + R\right] A(P), \quad \begin{cases} A(P) = A_0\left(\frac{P}{P_C}\right)^2 & P < P_C \\ A(P) = A_0 & P \geq P_C \end{cases}$$

# Inertial Drag Coefficient – Velocity Dependent and for All the Five Cases





$$C_\sigma = \begin{cases} 10 - 0.4167V_\sigma & V_\sigma < 12 \\ 6.0326 - 0.0.086V_\sigma & 12 \le V_\sigma < 55 \\ 0.9434 + 0.0065V_\sigma & 55 \le V_\sigma \end{cases}$$

$$V_\sigma = V\sqrt{\cos\beta + k_f \sin\beta}$$

Using modified velocity, drag can be computed for any nose shape

# 23-3855: Depth of Burial of UXO in Estuary Environments

**Performers:** M. Iskander (NYU), S. Bless (NYU), M. Omidvar (MU), P. Chu (NPS)

## Technology Focus

- *Detection of UxO in FUDS*

## Research Objectives

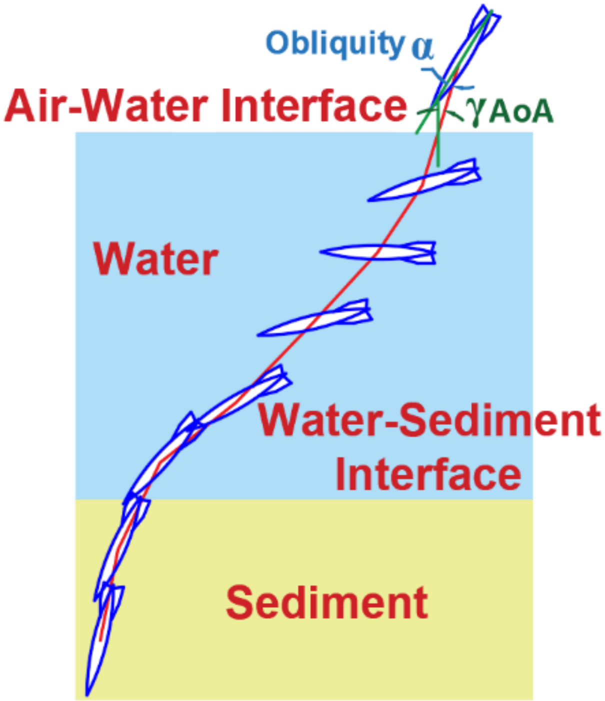
- *Develop a refined penetration model in soils and water that accounts for site specific conditions, including obliquity, AoA, and soil conditions*

## Project Progress and Results

- *Model is now able to account for soil properties, instability, and projectile nose shape*

## Technology Transition

- *We are working with US Army ERDC-GSL, Vicksburg MS and U.S. Army Engineering and Support Center, Huntsville to carry out a field test demonstration and present results in a form amenable to implementation by site managers.*



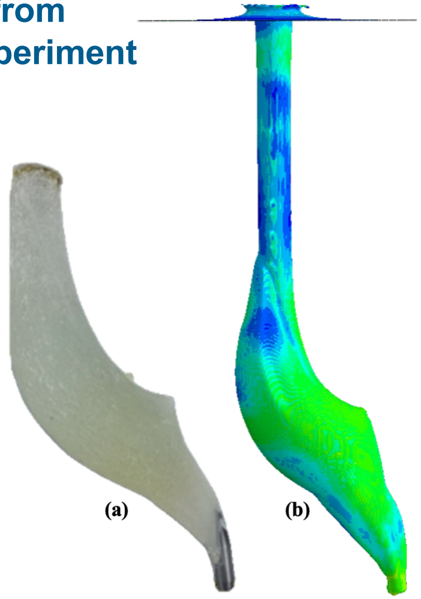
# Plain Language Summary

- The first step in remediation of hazards from buried Unexploded Ordnance (UxO) requires estimates of initial depth of burial (DoB). This is true for both terrestrial and underwater environments. A validated method for predicting DoB for UxO that may be deeply embedded does not exist.
- The research seeks to develop a method for accurate prediction of the DoB of UxOs based on laboratory tests and validated FEM simulations. The method employs site-specific field measurements of actual soil conditions and accounts for stochastic site variability.
- This work will contribute to a more efficient and cost-effective remediation of sites contaminated with UxO, thus facilitating their transfer to civilian use.

# Impact to DoD Mission

- Extensive data has been collected on projectile trajectory and instability in soils.
- The GeoPoncelet model is now able to account for projectile instability using an empirical stability criteria
- Projectile instability can reduce the DoB by up to 60, thus the new model yields far more realistic DoBs.
- This work will facilitate more effective and cost-efficient cleanup of FUDS.

**(a) Projectile trajectory from lab-scale ballistic test in clayey-sand. (b) Projectile trajectory and cavity from simulated ballistic experiment in clayey-sand**



# Action Items

- None.

# Status of Funds for Federal Performers

- Report on the status of funds for each MIPR received by a directly funded Federal performer. Provide information on each fiscal year for which there has not been 100% expenditure of funds. If you or your co-performer do not understand how to fill this out, contact your Program Manger in advance of the IPR.

| FY20XX Funds | | | |
|---|---|---|---|
| **Directly Funded Federal Performer(s)** | **Funds Received** | **Funds Obligated*** | **Percent Funding Obligated** |
| Federal Performer A<br>- Direct Cite MIPR | | | |
| Federal Performer A<br>- Reimbursable MIPR | | | |
| Federal Performer B<br>- Direct Cite MIPR | | | |
| Federal Performer B<br>- Reimbursable MIPR | | | |

* Funds put on contracts and/or purchase orders that have been issued, and funds associated with internal labor or travel expenses that have been incurred.

# Publications: Journals

**2025**

- Mercurio S, Iskander M, Omidvar M, and Bless S (2025) “Calibration of the GeoPoncelet penetration model for conical rod projectiles in cohesive soils, In press, *J. Geotechnical & Geoenvironmental Engineering*, ASCE.
- Dinotte J, Iskander M, Ads A, Bless S, Omidvar M (2025) “Use of hydraulic systems for high-rate compression testing,” https://doi.org/10.1007/s40799-025-00802-8, *Experimental Techniques*, Springer
- Dinotte J, Omidvar M, Bless S, Iskander M (2025) “CPT-informed model for rapid penetration into sand,” In press, *Canadian Geotechnical Journal*, dx.doi.org/10.1139/cgj-2024-0581
- Morkos B, White R, Omidvar M, and Iskander M (2025). “Calibration of empirical penetration models using large deformation explicit finite element simulations of rapid penetration in clay.” https://doi.org/10.1016/j.dt.2025.03.021, *Defense Technology*, Elsevier.
- Morkos B, Iskander M, Omidvar M, and Bless S (2025) “From Battlefield to Building Site: Probabilistic Analysis of UXO Penetration Depth for Infrastructure Resilience.” *Applied Sciences*, 15(6), 3259; https://doi.org/10.3390/app15063259, MDPI.
- Omidvar M, Dinotte J, Giacomo L, Bless S, Iskander M (2025) “Prediction of High-Speed Penetration in Layered Sand using Cone Penetration Tests,” *J. Geotechnical & Geoenvironmental Engineering*, Vol. 151, No.1, https://doi.org/10.1061/JGGEFK.GTENG-12760

# Publications: Journals Cont.

**2024**

- Mercurio S, Grace D, Bless S, Iskander M, and Omidvar M (2024) “Frequency-shifted photonic doppler velocimetry (PDV) for measuring deceleration of projectiles in soils,” *Acta Geotechnica*, https://doi.org/10.1007/s11440-024-02252-9, Springer Nature.
- Mercurio S, Bless S, Omidvar M, and Iskander M (2024) “Deceleration of projectiles in sand,” *Acta Geotechnica*, https://doi.org/10.1007/s11440-024-02408-7, Springer Nature
- Giacomo L, Grace D, Omidvar M, Bless S Iskander M (2024) “Vertical projectile launcher for study of rapid penetration into soil targets,” https://doi.org/10.1007/s40799-024-00732-x, *Experimental Techniques*, Springer Nature.
- Omidvar M, Dinotte J, Giacomo L, Bless S, Iskander M (2024) “Dynamics of sand response to rapid penetration by rigid projectiles,” *Granular Matter*, https://doi.org/10.1007/s10035-024-01440-4, Springer Nature.
- Omidvar M, Dinotte J, Giacomo L, Bless S, and Iskander (2024) “Photon doppler velocimetry for resolving vertical penetration into sand targets,” https://doi.org/10.1016/j.ijimpeng.2023.104827, *J. of Impact Engineering*, Vol. 185, 104827, Elsevier

# Publications: Conference Papers

**2025**

- Dinotte J, Giacomo L, Mercurio S, Omidvar M, Bless S Iskander M, (2025) “High-Speed Ordnance Penetration into Stratified Sandy Soils,” In: V. Eliasson et al. (eds.), Dynamic Behavior of Materials, Volume 1, SEM24 Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978- 3-031-85829-1_8, Springer Nature Selected as the best paper in the Dynamic Behavior of Materials track of the 2024 Society for Experimental Mechanics Annual Meeting.

**2024**

- Giacomo L, Dinotte J, Omidvar M, Bless S Iskander M, (2024) “An Investigation of Projectile Instability during Ballistic Penetration into Sandy Soils,” Accepted, SEM24: Society of Experimental Mechanics Annual Conference.
- Dinotte J, Giacomo L, Bless S, Iskander M, Omidvar M (2024) “Nose shape effects from projectile impact and deep penetration in dry sand”. In: Eliasson, V., Allison, P., Jannotti, P. (eds) Dynamic Behavior of Materials, Volume 1. SEM 2023. Conference Proceedings of the Society for Experimental Mechanics Series, pp 49–59, Springer, https://doi.org/10.1007/978-3-031-50646-8_7
- Mercurio S, Bless S, Ads A, Omidvar M, And Iskander M (2024) “Rate dependence of penetration resistance in a cohesive soil.” In: Eliasson, V., Allison, P., Jannotti, P. (eds) Dynamic Behavior of Materials, Volume 1. SEM 2023. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, pp 23–31,. https://doi.org/10.1007/978-3-031-50646-8_4
- Morkos B, White R, Omidvar M, Iskander* M and Bless S (2024). “Numerical Simulation of High-Speed Penetration of Munitions in Clay.” GSP No. 352, GeoCongress 2024 Geotechnical Data Analysis and Computation, pp. 82-91, https://doi.org/10.1061/9780784485347.009, ASCE

# Literature Cited

- See publication list

# Acronym List

- AoA – Angle of Attack
- CPT – Cone Penetration Test
- ERDC-GSL – USACE Engineer Research & Development Center, Geotechnical & Structures Laboratory,
- DoB – Depth of Burial
- DoF – Degrees of Freedom
- ERDC – (U.S. Army) Engineer Research and Development Center (Vicksberg, MS)
- FUDS – Formerly used defense sites
- NPS – Naval Postgraduate School
- UnMES – Underwater Munition Expert System
- USACE – US Army Corps of Engineers
- USDA-NRCS – US Department of Agriculture National Resources Conservation Service
- UxO – Unexploded Ordnance