PARAMETERIZED PROCESS MODELS FOR UNDERWATER MUNITIONS EXPERT SYSTEM

MR-2647
Carl T. Friedrichs
Virginia Institute of Marine Science
In-Progress Review Meeting
May 15, 2018

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MR-2647: Parameterized Process Models for Underwater Munitions Expert System

Performer: Carl Friedrichs, VA Inst. of Marine Sci.

Technology Focus

- *Support of the Underwater Munitions Expert System (UnMES) for Remediation Guidance through development of observation-based parameterized models for burial, re-exposure and movement.*

Research Objectives

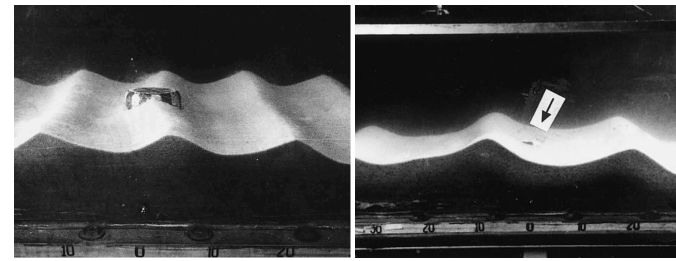
- *Synthesize and parameterize effects of far-field bed processes: (1) Effects of bedforms on munitions, (2) Effects of bed fluidization.*

Project Progress and Results

- *Progress in Year 2 has focused on a synthesis and simple model formulation for burial of munitions-like objects by bed fluidization associated with wave-induced liquefaction of sand.*

Technology Transition

- *Transfer additional parameterized models to MR-2645 "Underwater Munitions System for Remediation Guidance" (Rennie, PI), following successful precedent set by Friedrichs's previous project MR-2224.*



Burial by bedform migration
(Voropayev et al. 1999)

Burial by bed fluidization
(Catano-Lopera, Demir & Garcia 2007)

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Social Media Content

Results of Friedrichs's present (MR-2227) and previous SERDP Munitions Response project, MR-2224 "Simple Parameterized Models for Predicting Mobility, Burial, and Re-Exposure" have been highlighted on the web:

- *Findings available to lay audience via SERDP & ESTCP Webinar*

  https://www.serdp-estcp.org/Tools-and-Training/Webinar-Series/05-07-2015

- *All of Friedrichs's past SERDP presentations (10 to date) are downloadable at his lab (Coastal Hydrodynamics and Sediment Dynamics) website:*

  http://www.vims.edu/chsd

- *Rennie, Brandt & Friedrichs (2017) "Initiation of motion and scour burial of objects undewater". Ocean Engineering, Vol. 131: 282-294 was highlighted on SERDP Munitions Response social media, e.g.:*

  https://www.facebook.com/serdpestcpMR/15 on February 2, 2017

- *Friedrichs's SERDP 2017 Project of the Year Award for Munitions Response was highlighted on the News & Events page of the SERDP-ESTCP website:*

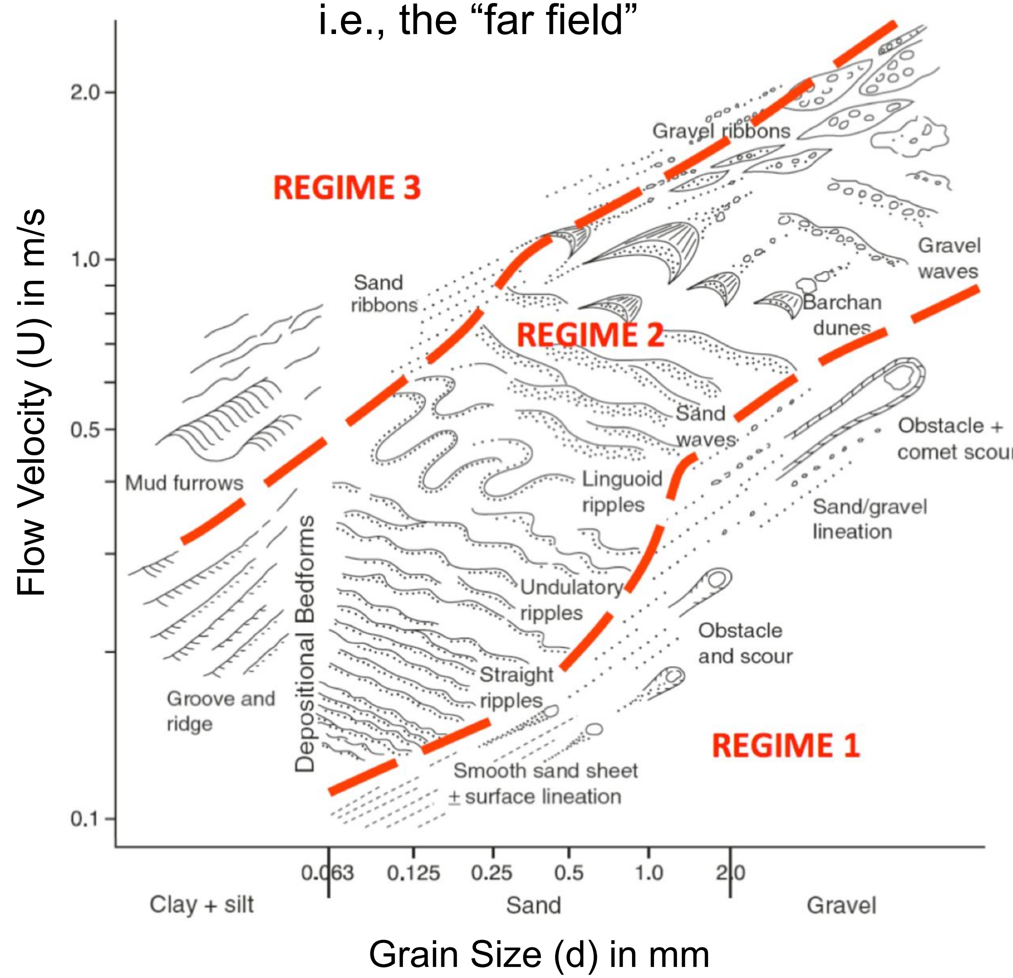
  https://www.serdp-estcp.org/News-and-Events/Blog/Simple-Parameterized-Models-for-Predicting-Mobility-Burial-and-Re-exposure-of-Underwater-Munitions

Problem Statement

- Problem being addressed:
  Existing data and approaches for evaluating the potential effects of far-field bed movement (e.g., bedforms and bed fluidization) on the mobility, burial and re-exposure of unexploded ordnance (UXO) and UXO-like objects have not been adequately compiled and synthesized in the past.

- Limitations of previous approaches:
  Recent data mining (Friedrichs MR-2224) has helped constrain near-field interactions of flow with UXO (e.g., equilibrium burial by scour and initiation of UXO motion). However, relatively less literature review and synthesis has focused on interactions of far-field of flow and sediment with UXO (e.g., effects of bedforms, effects of bed fluidization).

Better understand the role of independent bed movement i.e., the "far field"



Bed regimes as a function of flow and grain size
(Modified from Stow et al. 2009)

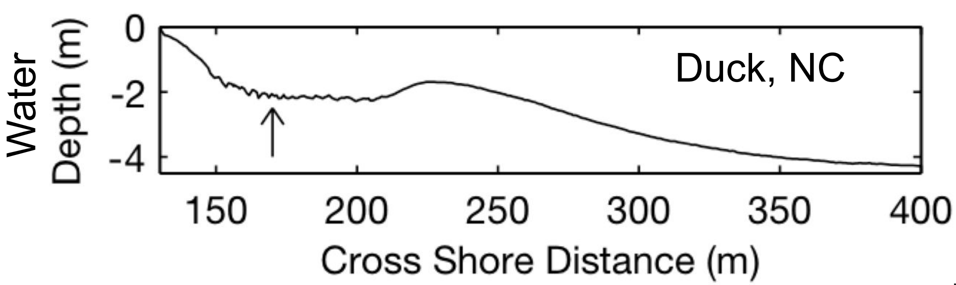
Technical Objectives

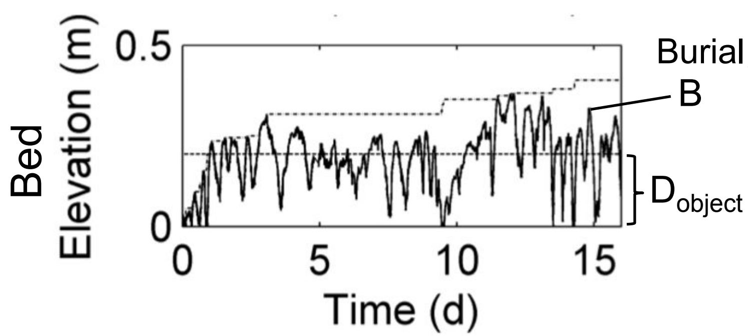
- 1) To identify and compile existing data and analyses regarding far-field sediment effects on UXO-like objects: (1) interaction with bedforms, (2) bed fluidization.
- 2) To utilize these data and analyses to further develop and constrain simple, logical, parameterized relationships for these processes;
- 3) And to provide these improved parameterized relationships to other SERDP/ESCTP investigators for use within UnMES as well as providing them to the larger DoD, coastal engineering and scientific communities.

Technical Approach

- Identify and compile existing data and analyses on interaction of UXO-like objects with bedforms and bed fluidization:

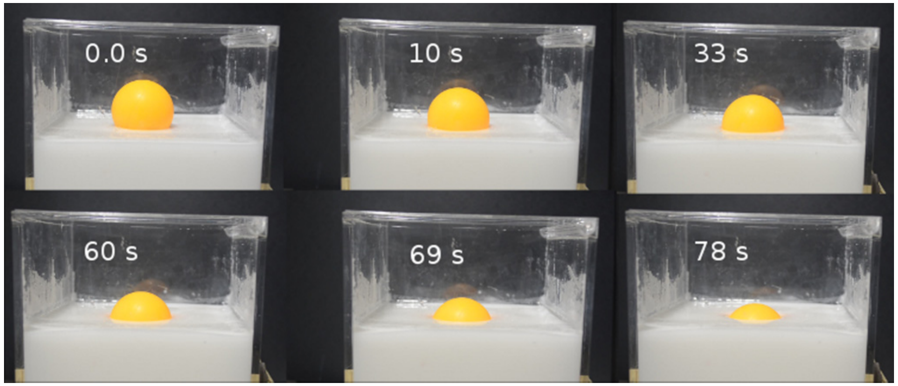
-- Internet searches (Google Scholar, Google), VIMS electronic journal and dissertation subscriptions, VIMS library, pdf reprint requests, Researchgate, interlibrary loan…





Envelope and frequency of object burial by megaripples
(Gallagher et al. 2007)

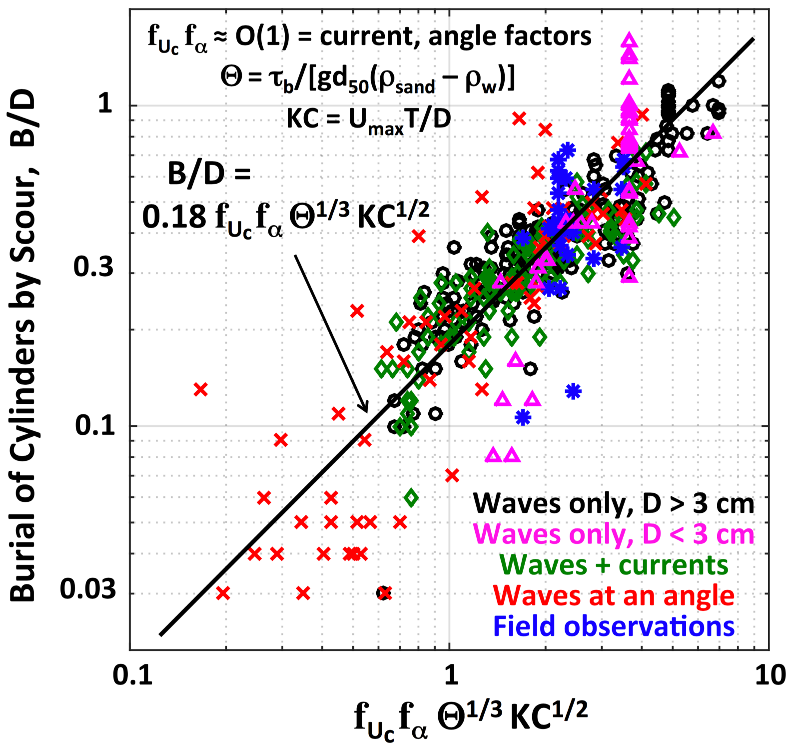
Sinking of sphere into saturated granular soil liquefied by vibration
(Clément et al. 2018)



Technical Approach (cont.)

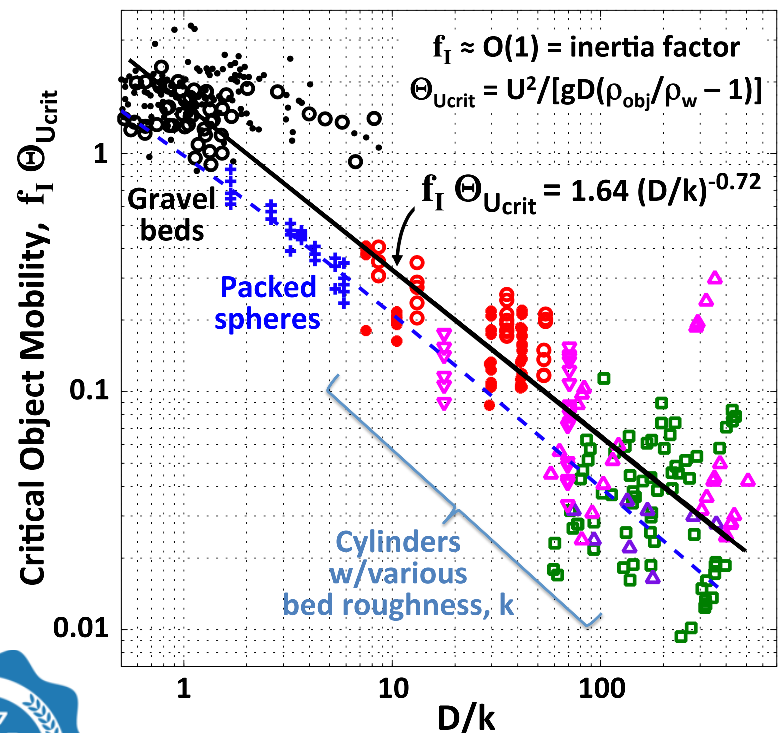
- Further develop parameterized relationships for UXO mobility, burial and re-exposure;
- Provide these improved relationships for use within UnMES as well as providing them to the larger DoD, engineering and scientific communities.
- Previous SERDP projects MR-2224 (Friedrichs) and MR-2227 (Rennie) provide precedent.

Equilibrium Scour Burial Depth



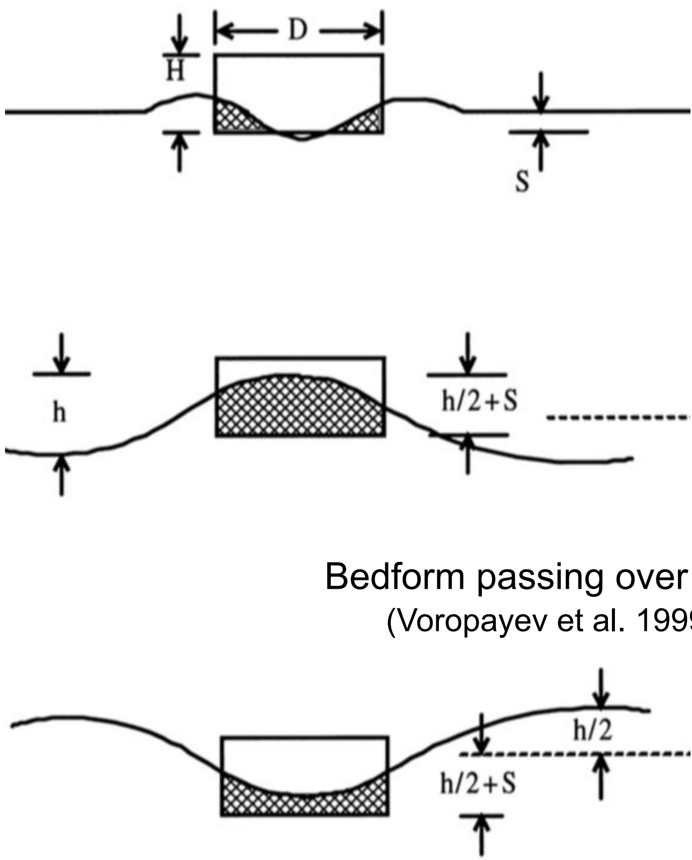
(Friedrichs, Rennie & Brandt 2016)

Initiation of Object Motion

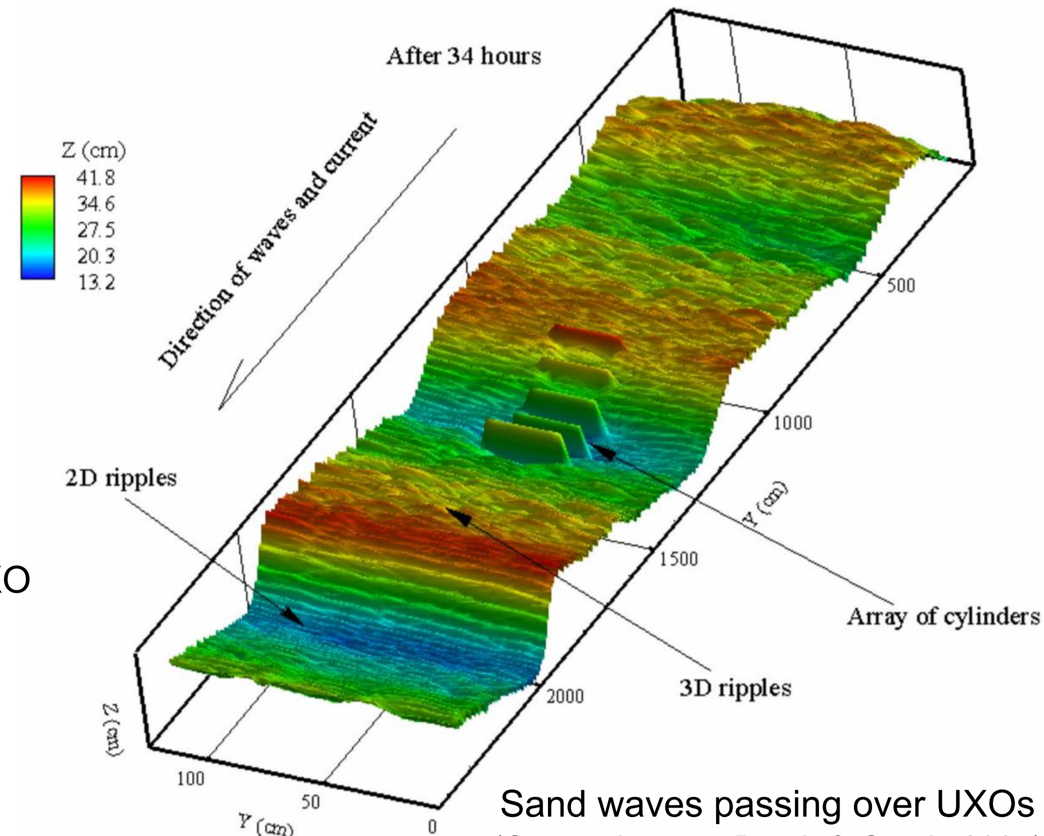


(Rennie, Brandt & Friedrichs 2017)

Results: 1. Bedforms – Process & Importance



Bedform passing over UXO
(Voropayev et al. 1999)

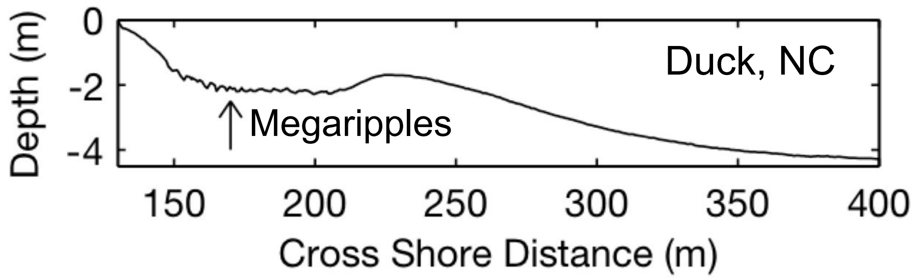


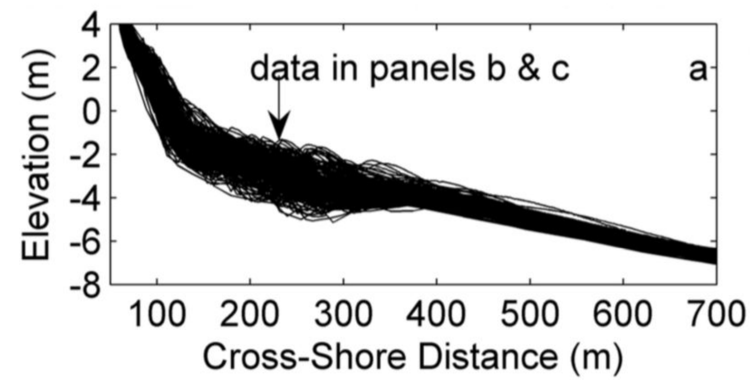
Sand waves passing over UXOs
(Catano-Lopera, Demir & Garcia 2007)

- Burial of object by bedform crest; additional object scour occurs in bedform trough.
- Net elevation of periodically buried object is lower due to passage of bedform.

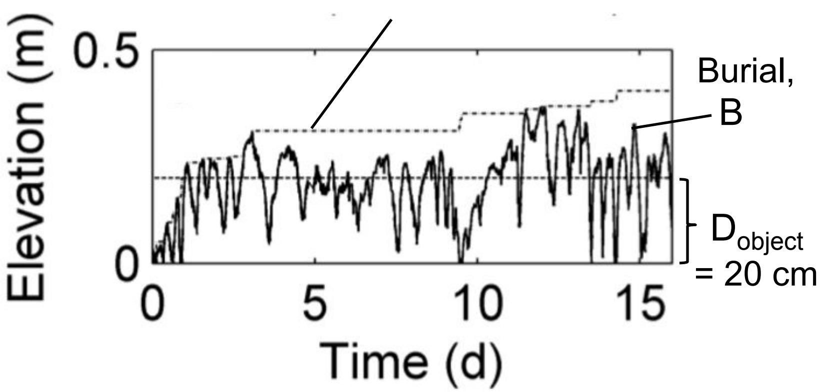
Results: 1. Bedforms – Bed Envelope Concept

(Gallagher et al. 2007)

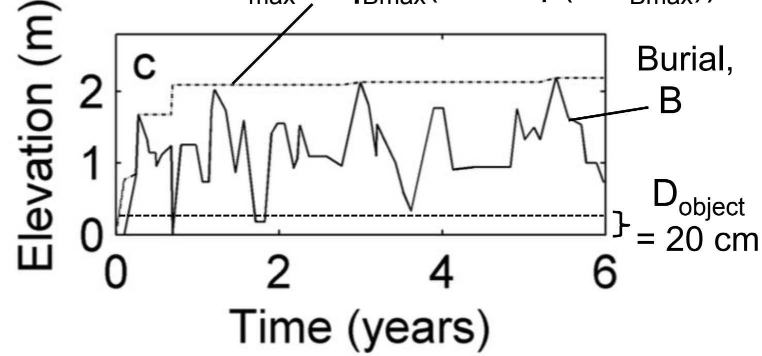




Bed Envelope thickness = $B_{max} \approx \eta_{Bmax}(1 - \exp(-t/T_{Bmax}))$



$B_{max} \approx \eta_{Bmax}(1 - \exp(-t/T_{Bmax}))$

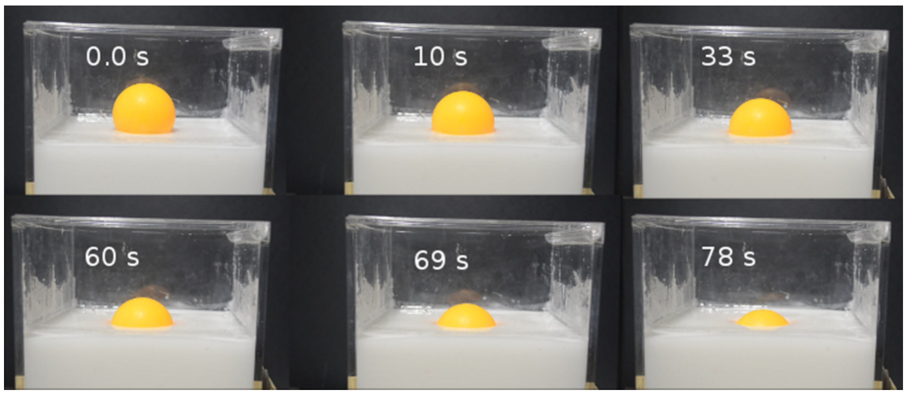


- As deeper troughs pass, object elevation continues to drop, but less frequently.
- Potential $B_{max}(t) \sim \eta_{Bmax} (1 - \exp(-t/T_{Bmax}))$ follows exponential taper in time.
- η_{Bmax} ~ dominant bedform height, T_{Bmax} ~ bedform cycle time.
- Envelopes are superimposed, with larger bedforms dominant at longer time-scales.

Results: 2. Liquefaction – Process & Importance

Lab: Sinking of sphere into saturated granular soil liquefied by vibration

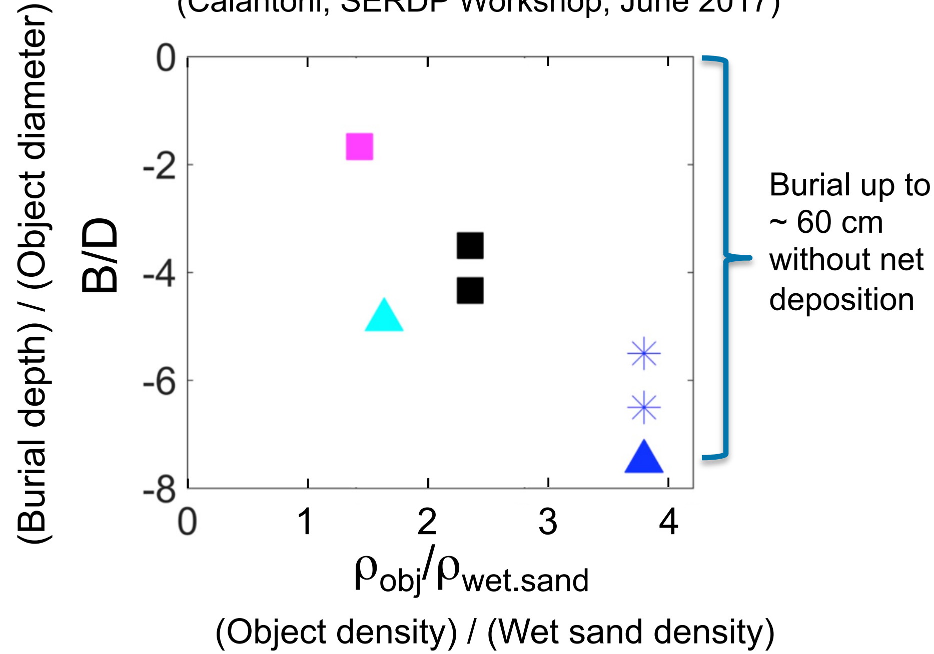
(Clement et al. 2018)



Rate of sinking is determined by a balance between buoyancy and frictional drag

Field observations: model munitions burial by storm at Duck, NC, Feb 2015, h = 6 to 8 m

(Calantoni, SERDP Workshop, June 2017)

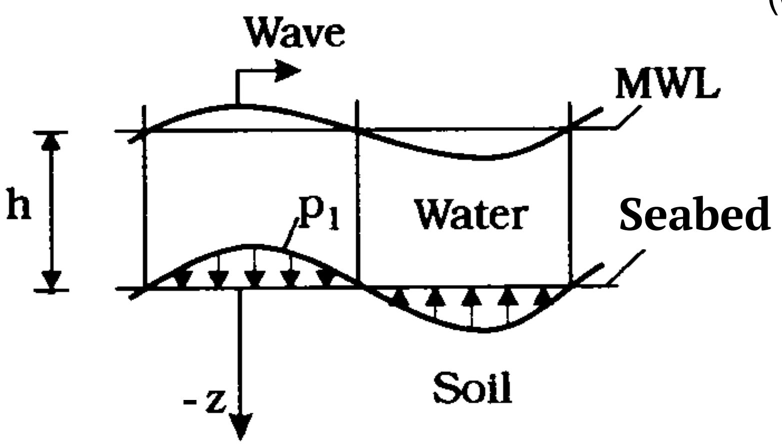


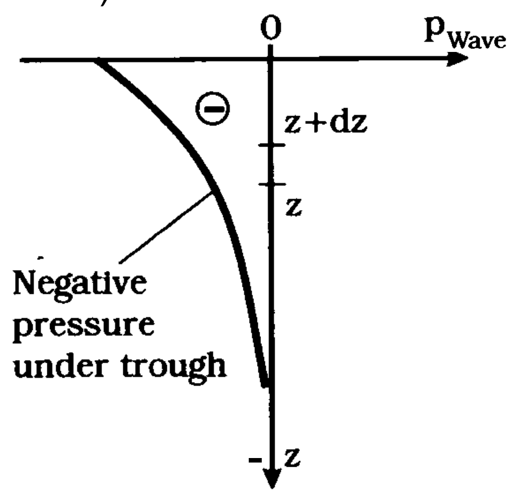
- Earthquake liquefaction experiments suggest simple force balance governs sinking.
- Burial/Diameter (B/D) of munitions-like objects in storms increases with object density (ρ_{obj}).
- Is simple formulation suggested by lab experiments consistent with field observations?

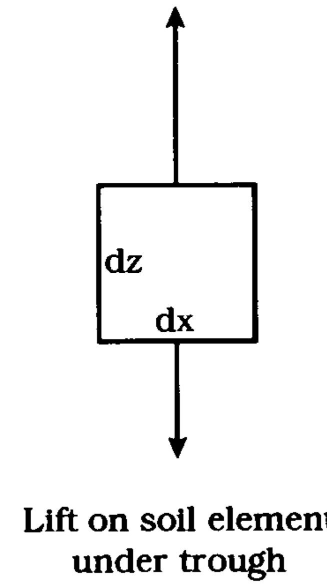
Results: Liquefaction

- What is (momentary) wave-induced liquefaction of a sand bed?

(Sumer 2014)







Criteria for wave-induced liquefaction of sand:

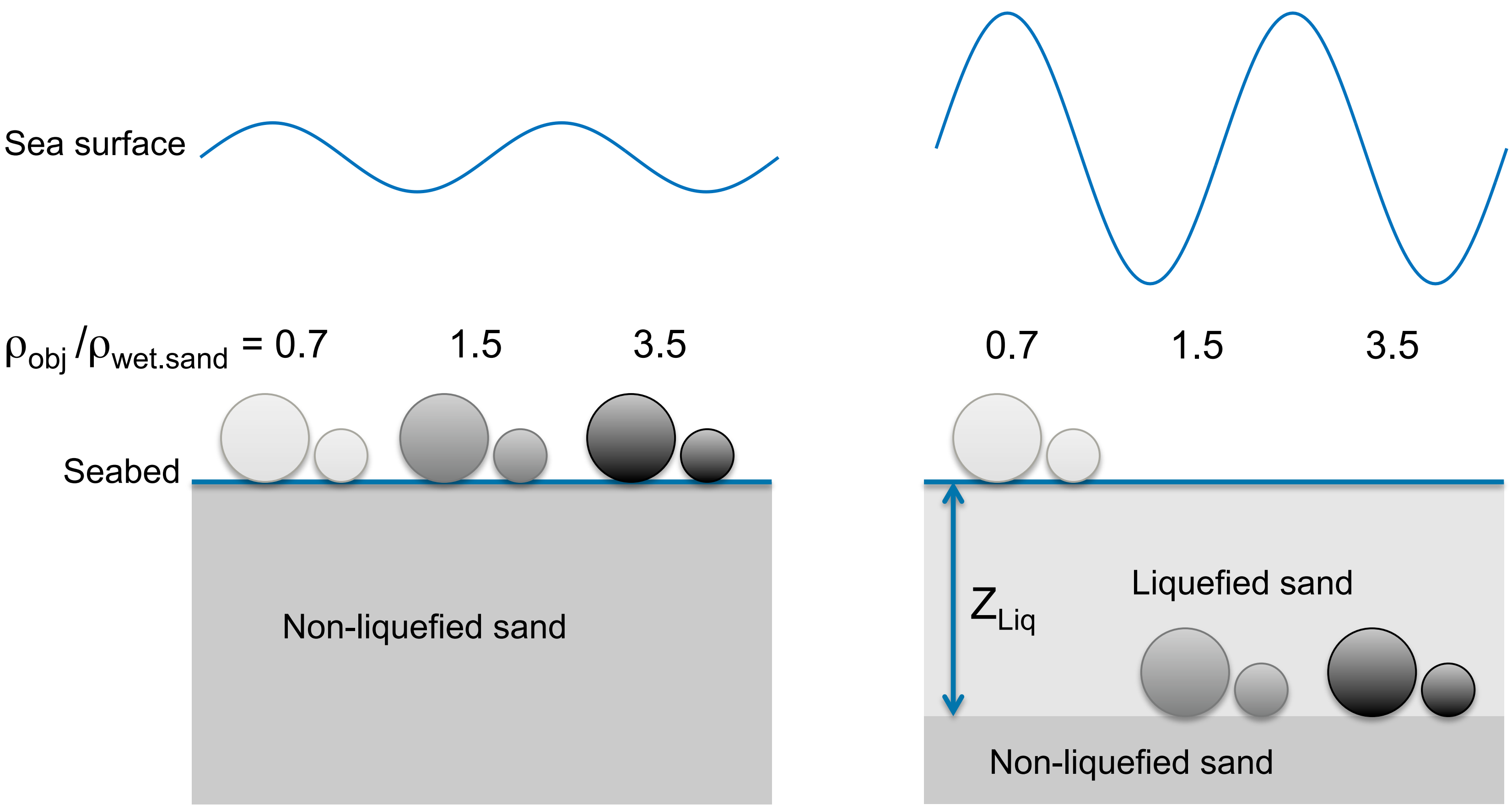
$$-\frac{\partial p_{\text{wave}}}{\partial z} > (\rho_{\text{wet.sand}} - \rho_{\text{water}})\, g$$

- Occurs when the upward gradient in wave-induced excess pore pressure exceeds the buoyant specific weight of the saturated soil skeleton.

(e.g., Yeh & Mason 2014; Qi & Gao 2015, 2018)

Liquefaction: Classic Response

- What is the simple classic expectation of object response to liquefaction?
- Ans: Sink down to bottom of liquefied layer if $\rho_{obj} / \rho_{wet.sand} > 1$

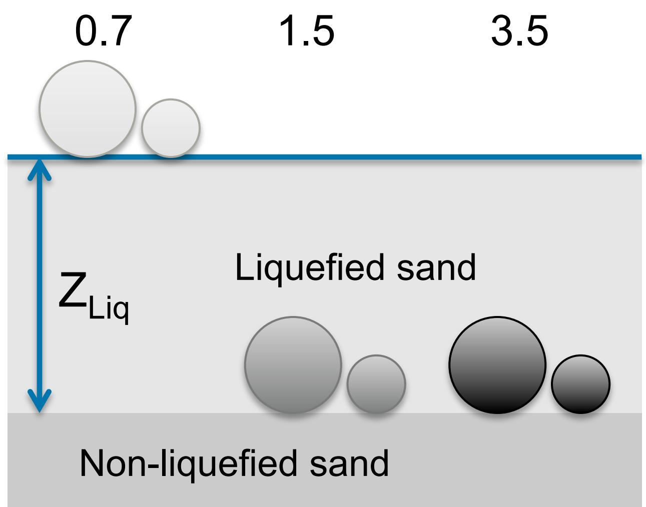


($\rho_{wet.sand} \approx$ 1900 kg/m^3 for both liquefied and non-liquefied sand.)

- Simple classic response does not agree with field observations

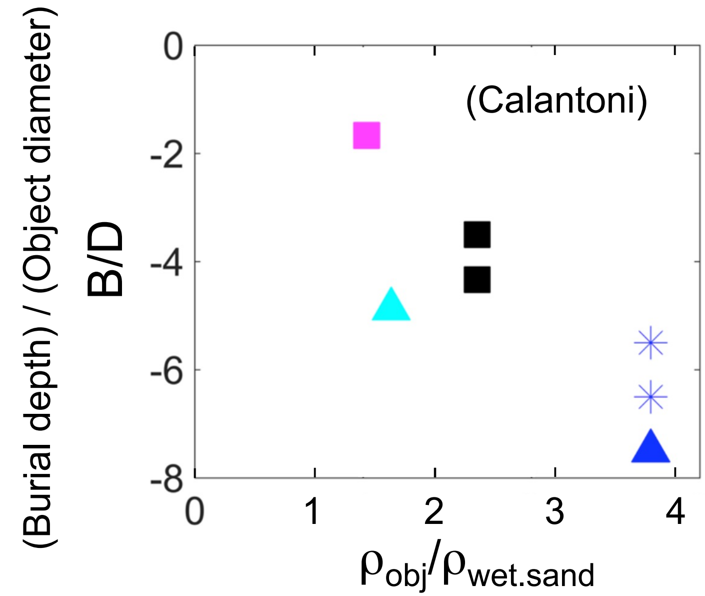
Expected result:

$\rho_{obj} / \rho_{wet.sand}$ =



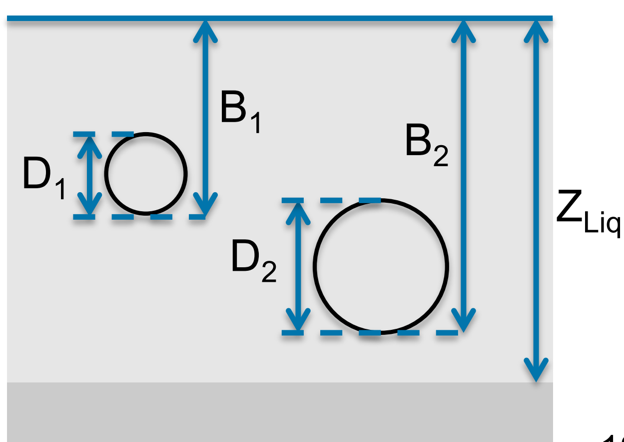
Observed result:

Storm at Duck, NC, Feb 2015, H_{sig} > 4 meters



Observations (Calantoni) ≠ Expectations:

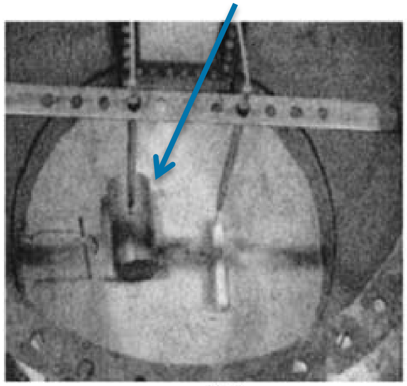
- Burial depth (B) continues to increase with $\rho_{obj} / \rho_{wet.sand} > 1$
- B ≠ Z_{liq} and B from one event is often much less than Z_{liq}
- B is observed to scale with with object diameter (D)
- B/D ~ $\rho_{obj}/\rho_{wet.sand}$

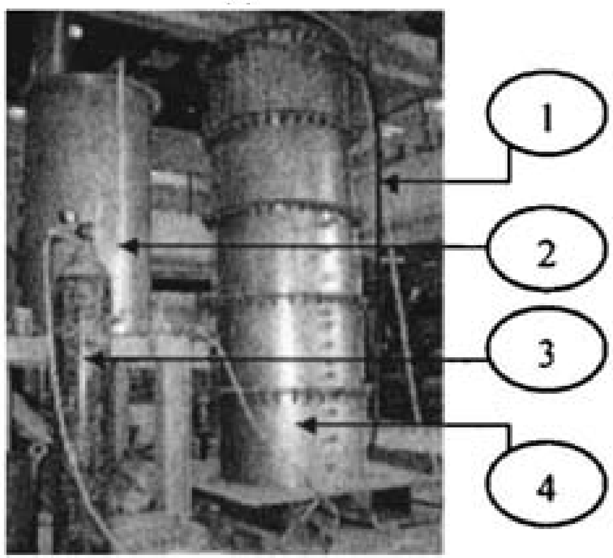


- Simple classic response does not agree with lab observations.

(Chowdhury et al. 2006)

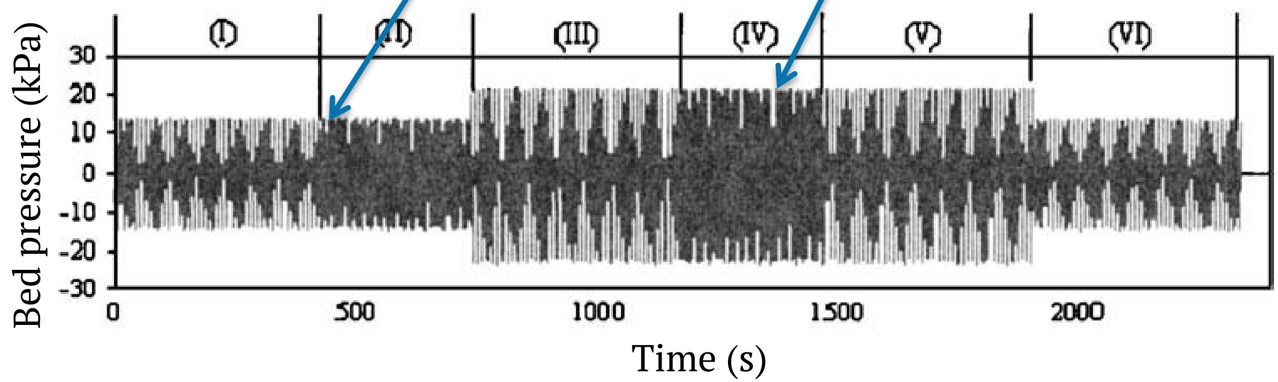
Object (D = 10 cm)

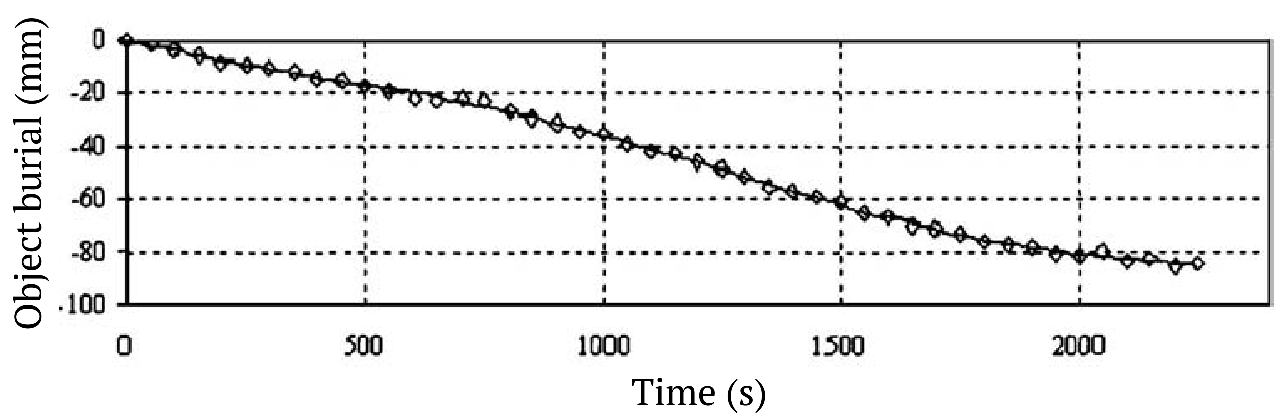




(1) Hydraulic hose for cyclic loading
(2) Water de-airing system
(3) CO2 cylinder
(4) One-dimensional cylindrical tank

Equivalent wave height: 2.6 meters 4.4 meters

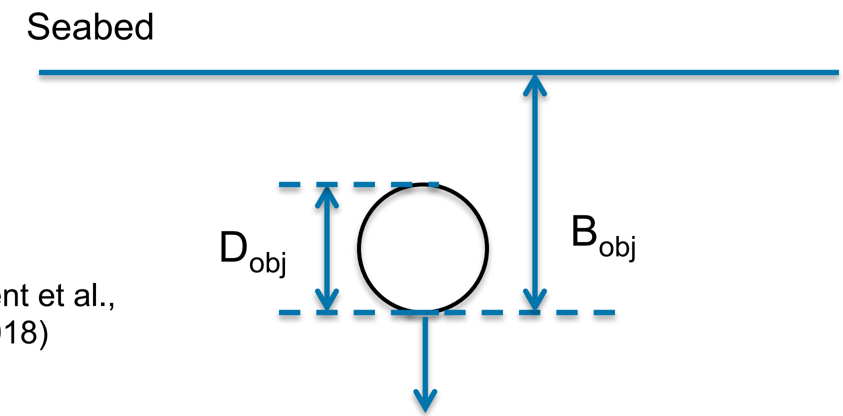




Object sinking is <u>not</u> necessarily rapid:

80 mm/2000 sec ≈ 1.4 cm/hour

Results: Force Balance



Force balance between buoyancy and drag:

$$F_{buoy} = Volume_{obj} \, (\rho_{obj} - \rho_{sed,wet}) \, g$$

$$F_{drag} = frict_{coeff} \;\; \rho_{sed,wet} \, g \, Area_{obj} \, Vel_{obj}$$

ρ = density
g = gravity

(Clement et al., 2018)

Set $F_{buoy} = F_{drag}$ and solve for sinking velocity, Vel_{obj}:

$$Vel_{obj} = (D_{obj}/frict_{coeff}) \, (\rho_{obj}/\rho_{sed,wet} - 1)$$

$$Vel_{obj} = d(B_{obj})/dt$$

Integrate in time over liquefaction event to solve for B_{obj}:

$$B_{obj} = (D_{obj}/frict_{coeff}) \, (\rho_{obj}/\rho_{sed,wet} - 1) \, T_{liquef}$$

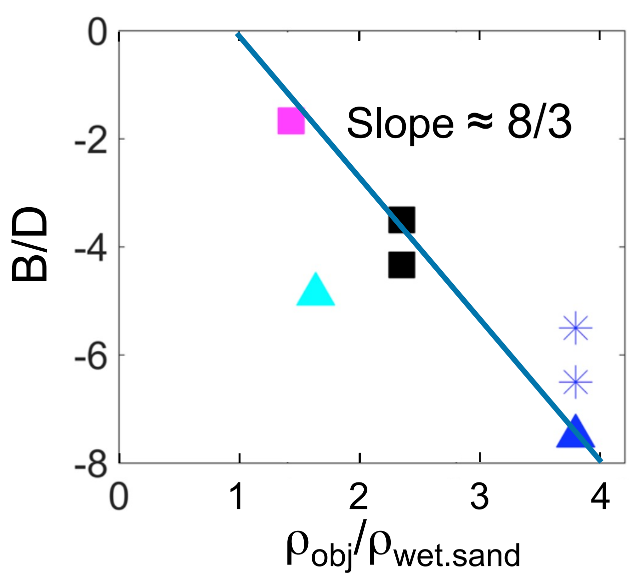
T_{liquef} = duration of liquefaction event

Results: Form Consistent with Observations

Fit to slope in model formulation to observations from Duck, NC:

Field observations: model munitions burial by storm at Duck, NC, Feb 2015

(Calantoni, SERDP Workshop, June 2017)



From previous slide:

$$B_{obj} = (D_{obj}/frict_{coeff})\ (\rho_{obj}/\rho_{sed,wet} - 1)\ T_{liquef}$$

Solve for (B/D) and fit to observations:

$$(B/D)_{obj} = \underbrace{(T_{liquef}/frict_{coeff})}_{\approx 8/3}\ (\rho_{obj}/\rho_{wet.sand} - 1)$$

Results: Model for Liquefaction Depth

Liquefaction criteria: $$-\frac{\partial p_{\text{wave}}}{\partial z} \geq (\rho_{\text{wet.sand}} - \rho_{\text{water}})\, g$$

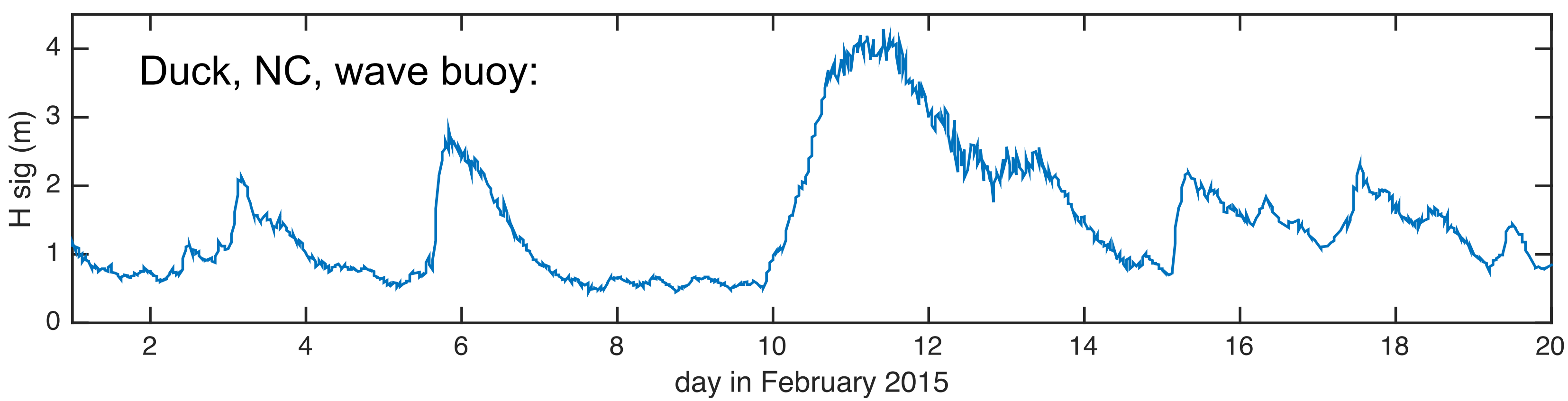
gives liquefaction depth: $$z_L = \frac{p_0}{\gamma'} - \frac{1}{a\,(1-b\,)}$$ (Qi & Gao, 2015)

p_0 = Amplitude of wave-induced pressure at seabed (~ wave height = H_{sig})

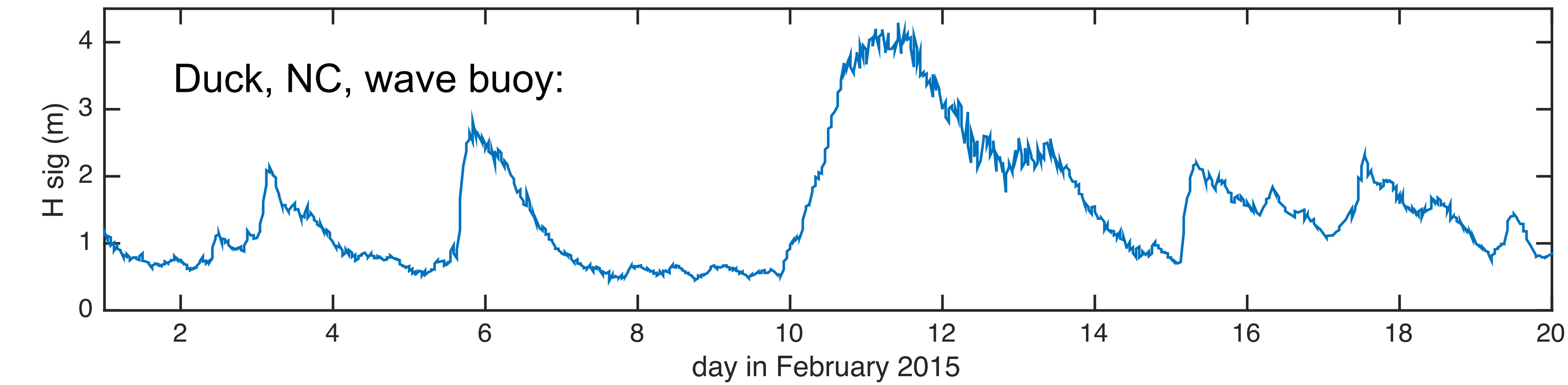
γ' = $(\rho_{obj} - \rho_{sed,wet})$ g = Submerged wet weight of sand bed

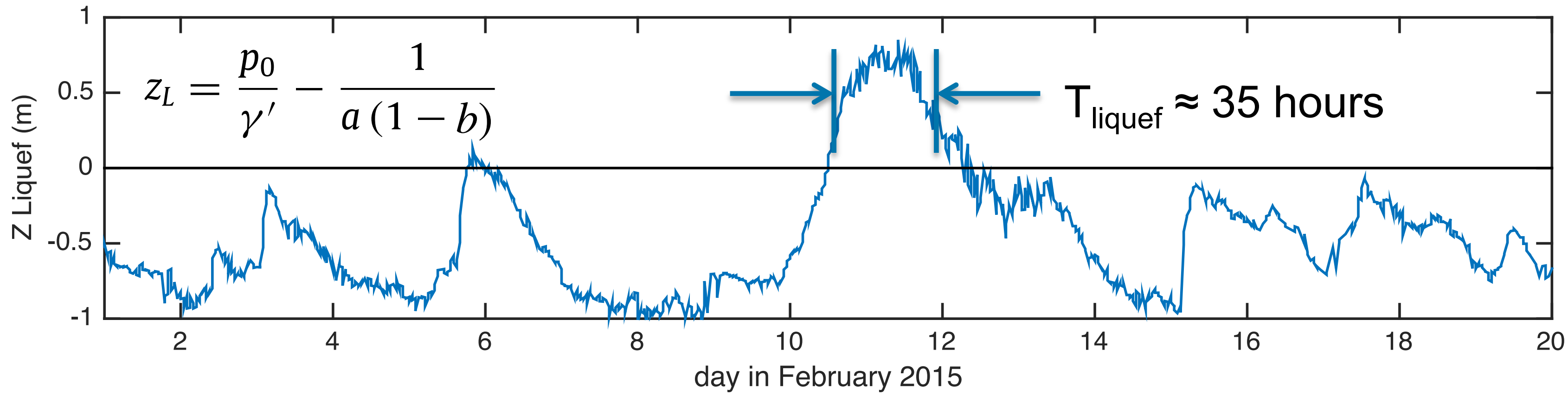
a = Vertical wave number in the bed, funct($Period_{wave}$, bed consolidation)

b = Bed compressibility coeff, funct(sand saturation = S_r, permeability)



Apply liquefaction depth model to Duck observations:





Parameters as in Qi & Gao (2015), with h = 8 m.

Tuned via saturation, using S_r = 0.993.

(If $Z_L < 0$, then no liquefaction)

Recall:

$$(B/D)_{obj} = \underbrace{(T_{liquef}/frict_{coeff})}_{\approx\, 8/3}\ (\rho_{obj}/\rho_{wet.sand} - 1)$$

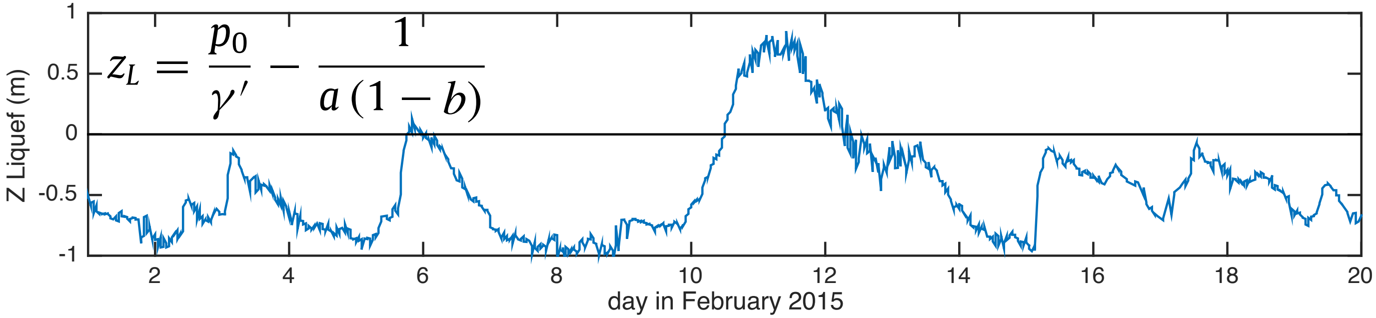
So: $frict_{coeff} \approx (3/8)$ (35 hours) $\approx$ 13 hours

Results: Time-Series for Modeled Burial

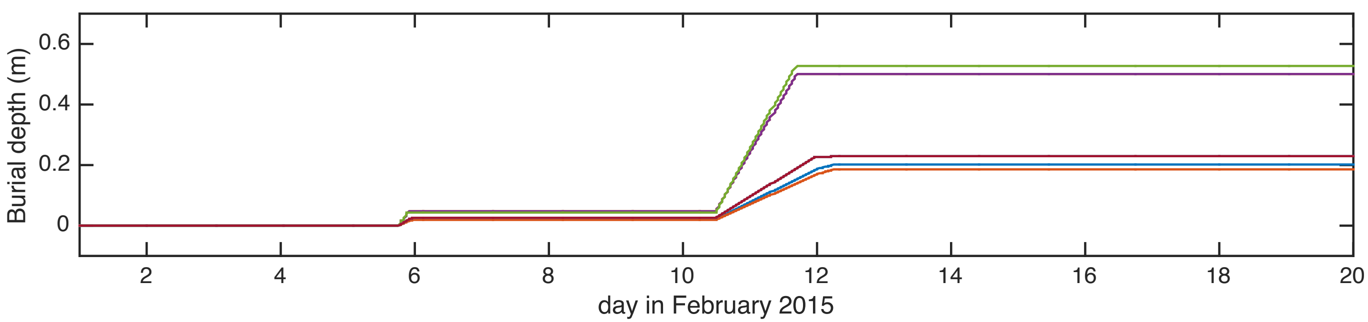
<u>Calculate time-series of object burial using:</u> $Vel_{obj} = (D_{obj}/frict_{coeff})\ (\rho_{obj}/\rho_{sed,wet} - 1) = \Delta B_{obj}/\Delta t$

So (1) $\Delta B_{obj}(t) = (D_{obj}/frict_{coeff})\ (\rho_{obj}/\rho_{sed,wet} - 1)\ \Delta t$ if $B_{obj} < Z_L$; and (2) $\Delta B_{obj}(t) = 0$ if $B_{obj} < Z_L$

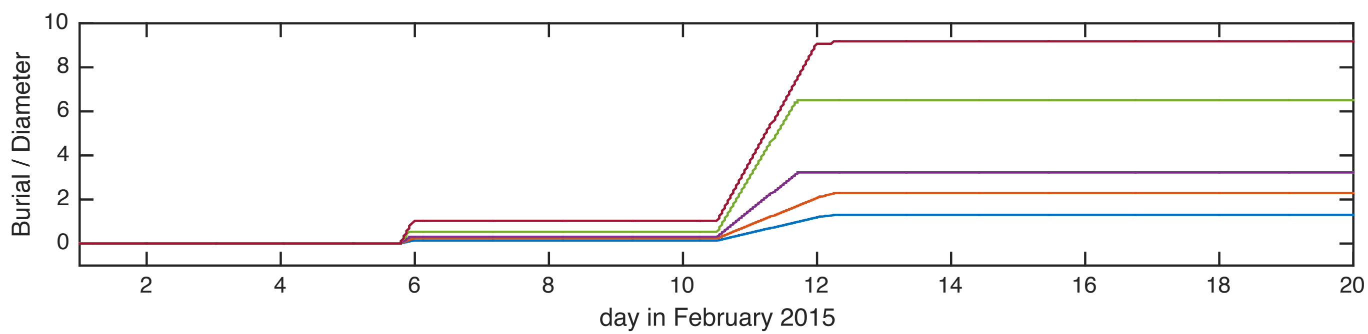
Z_L



B_{obj}



B/D



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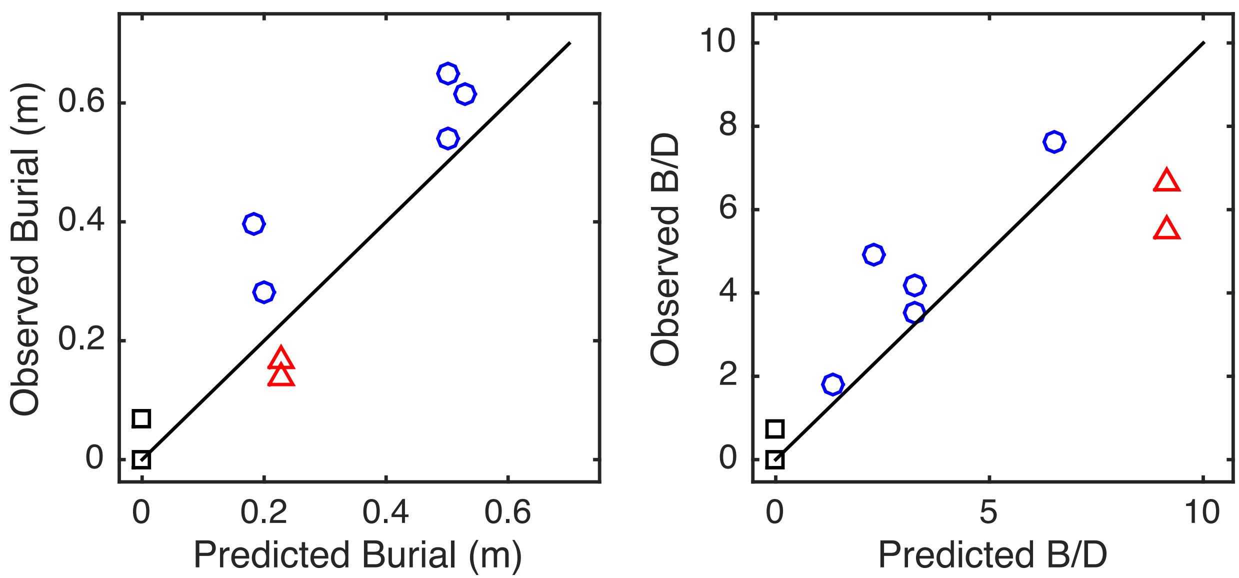
Results: Predicted Final Burial Depth

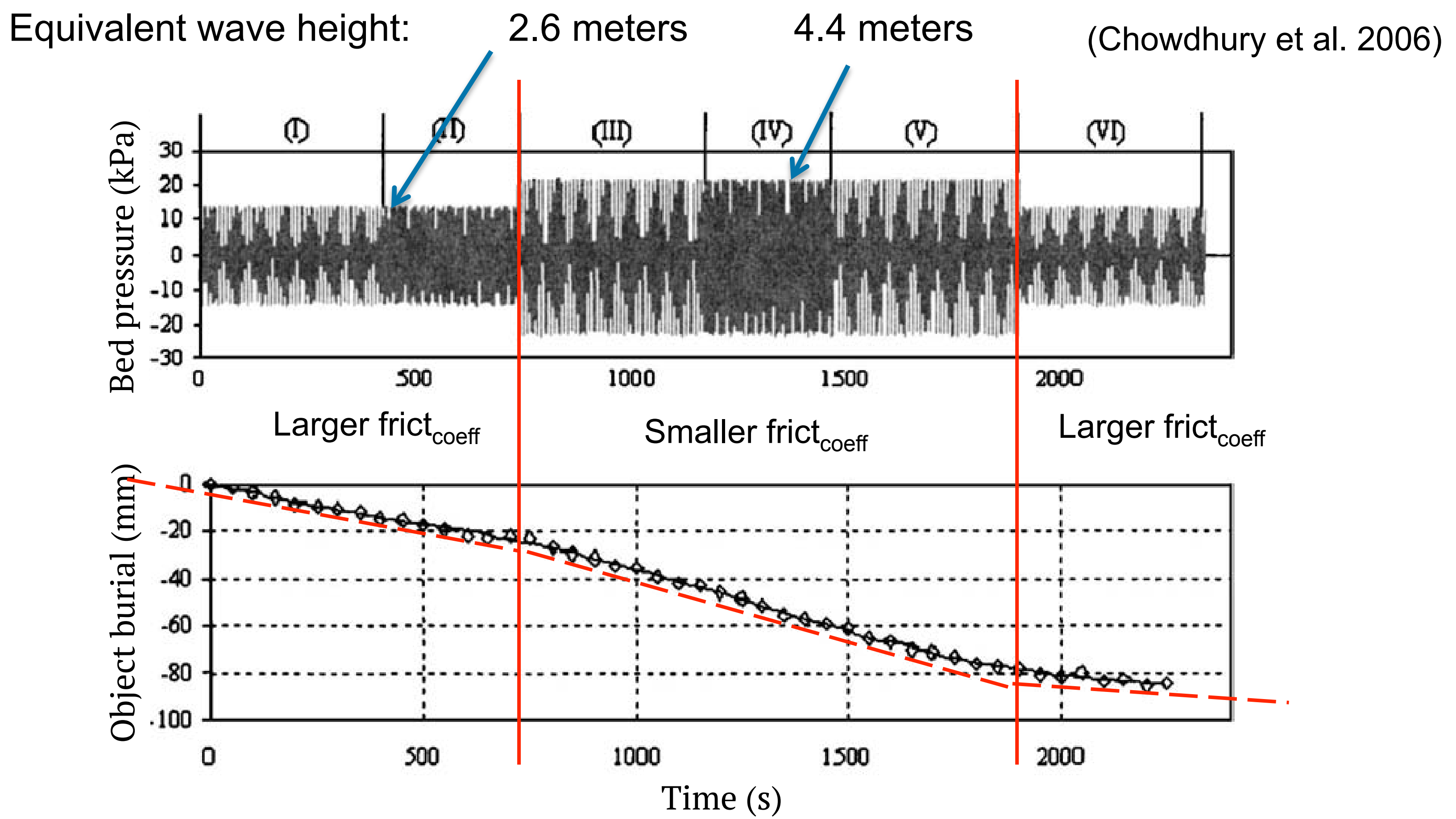
Integrated: $\Delta B(t) = (D_{obj}/frict_{coeff})\,(\rho_{obj}/\rho_{sed,wet} - 1)\,\Delta t$ for $B < Z_L$



Duck, NC, Feb ‘15, h = 8 m
Duck, NC, Feb ‘15, h = 6 m
(Calantoni)
Lab results (Chowdhury et al. 2006)

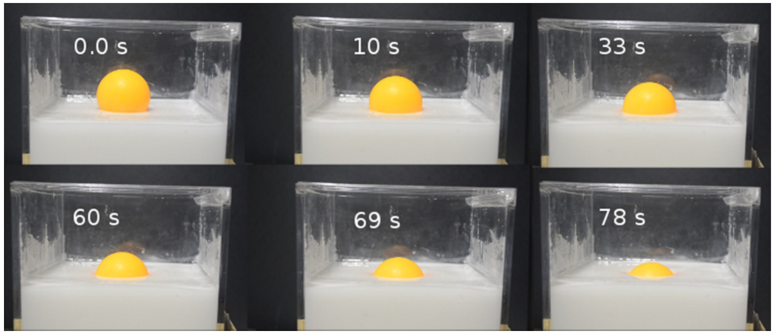
Results: What Does $frict_{coeff}$ Depend On?

$$Vel_{obj} = (D_{obj}/frict_{coeff})\,(\rho_{obj}/\rho_{sed,wet} - 1) = \Delta B_{obj}/\Delta t$$



- As amplitude of pressure fluctuations at bed (~ H_{sig}) increases, $frict_{coeff}$ decreases

Results: What Does $frict_{coeff}$ Depend On?



$$\Delta B(t) = (D_{obj}/frict_{coeff})\ (\rho_{obj}/\rho_{sed,wet} - 1)\ \Delta t$$

For "earthquake", Clément et al. (2018) found

$frict_{coeff} \sim 1/(\text{velocity of ground shaking})$

Possible scalings for $frict_{coeff}$:

- inverse with $(\partial p/\partial z)_{bed} / (\partial p/\partial z)_{liquef}$ (larger H_{sig}, higher bed saturation)
- inverse with $(\partial p/\partial x)_{bed}$ / sediment weight (i.e., Sleath Parameter)
- increasing with object depth within liquefied layer (i.e., B/Z_L)
- increasing with sediment angularity (i.e., grain angle of repose)
- increasing with bed grain size + grain density (i.e., grain settling velocity)

Transition Plan

- Useful interim products:

-- Outline of envelope prediction method $B_{max}(t) \approx \eta_{Bmax}(1 - \exp(-t/T_{Bmax}))$ to translate bedform properties into statistical time-dependence of future object burial.

-- Vertical force balance equation for depth of burial by fluidization gives

$$\Delta B(t) = (D_{obj}/frict_{coeff})\ (\rho_{obj}/\rho_{sed,wet} - 1)\ \Delta t \quad \text{for } B < Z_L$$

- Transition plan for research into field use:

-- This project (MR-2647) was planned and is being executed in close collaboration with the larger SERDP project MR-2645 by Rennie & Brandt from JHU-APL entitled “Underwater Munitions Expert System for Remediation Guidance”.

-- The parameterized model relationships being developed here are being passed to Rennie for incorporation into the UnMES System which is explicitly for field use in helping guide the on site evaluation/remediation of UXO sites.

Publications

- No journal publications have yet been submitted in association with MR-2647. However, two papers have appeared as a result of Friedrichs's similar, previous SERDP project, MR-2224, in collaboration with MR-2227:

- Friedrichs C.T., S.E. Rennie, and A. Brandt, 2016. Self-burial of objects on sandy beds by scour: A synthesis of observations. In: J.M. Harris, R.J.S. Whitehouse, and S. Moxon (eds.), Scour and Erosion. CRC Press, p. 179-189. http://dx.doi.org/10.1201/9781315375045-23

- Rennie, S.E., A. Brandt, and C.T. Friedrichs, 2017. Initiation of motion and scour burial of objects underwater. Ocean Engineering, 131: 282-294. http://dx.doi.org/10.1016/j.oceaneng.2016.12.029.