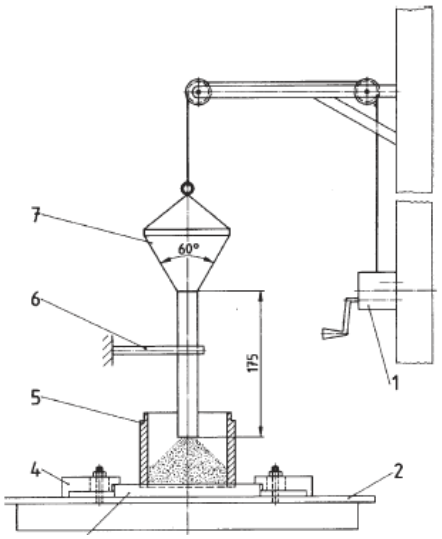
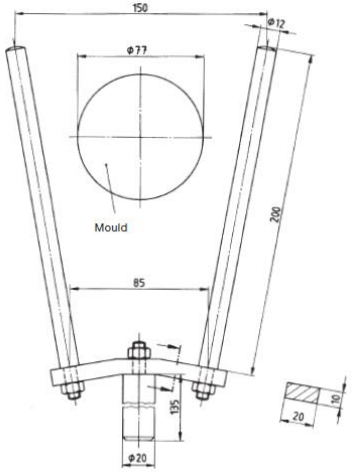
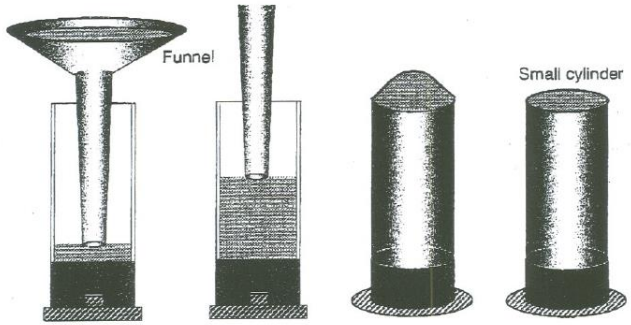
Influence of max/min dry density measurements on density index

Lone Krogh, DONG Energy Wind Power







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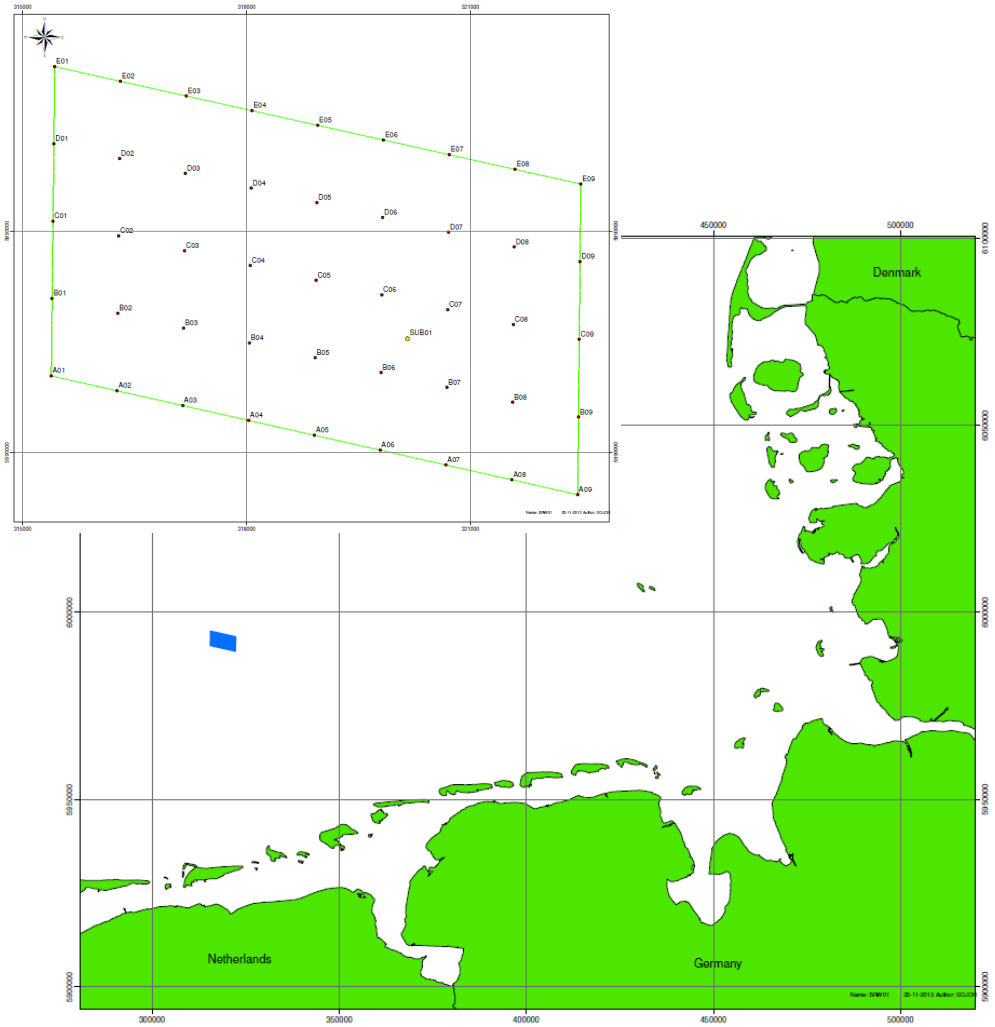
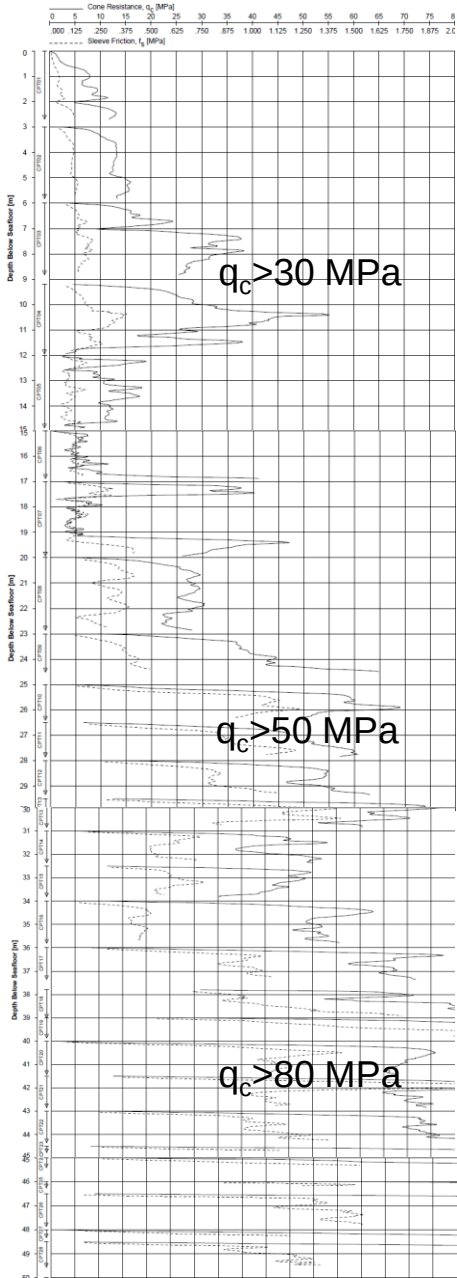
Borkum Riffgrund West 01 – dense to very dense sands

- Project BRW01:
  45 6.0 MW WTGs on
  monopile foundations



- Sand
  - pleistocene
  - fine-medium
  - d_{50}=0.2-0.3 mm
  - C_U~2
  - FC≤5%
  - primarily quartz

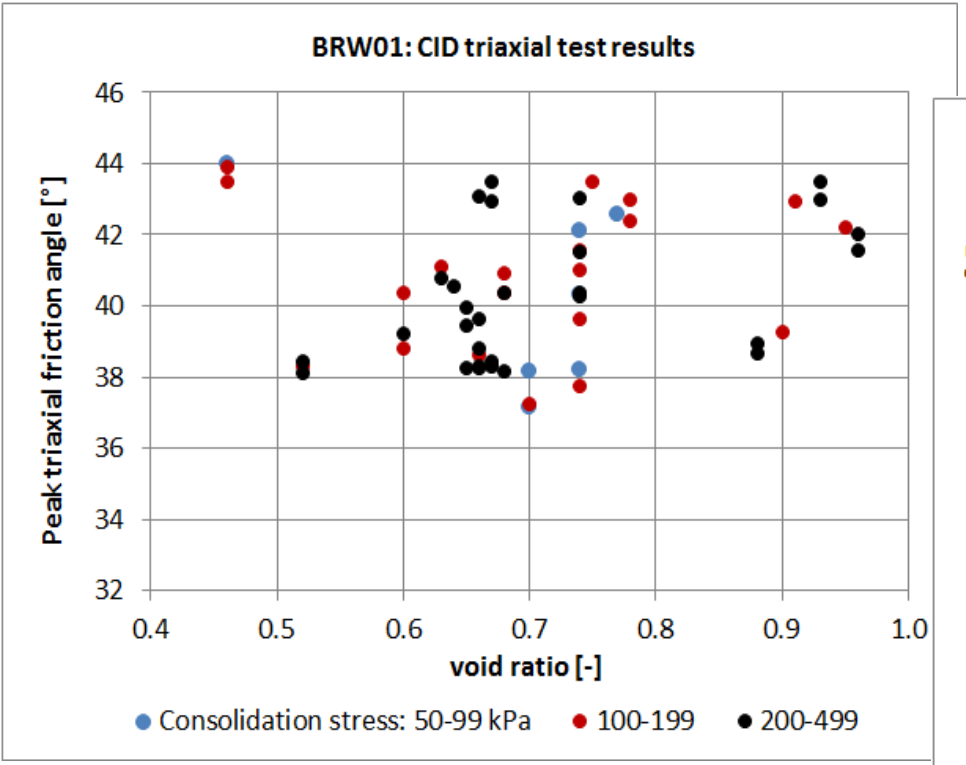


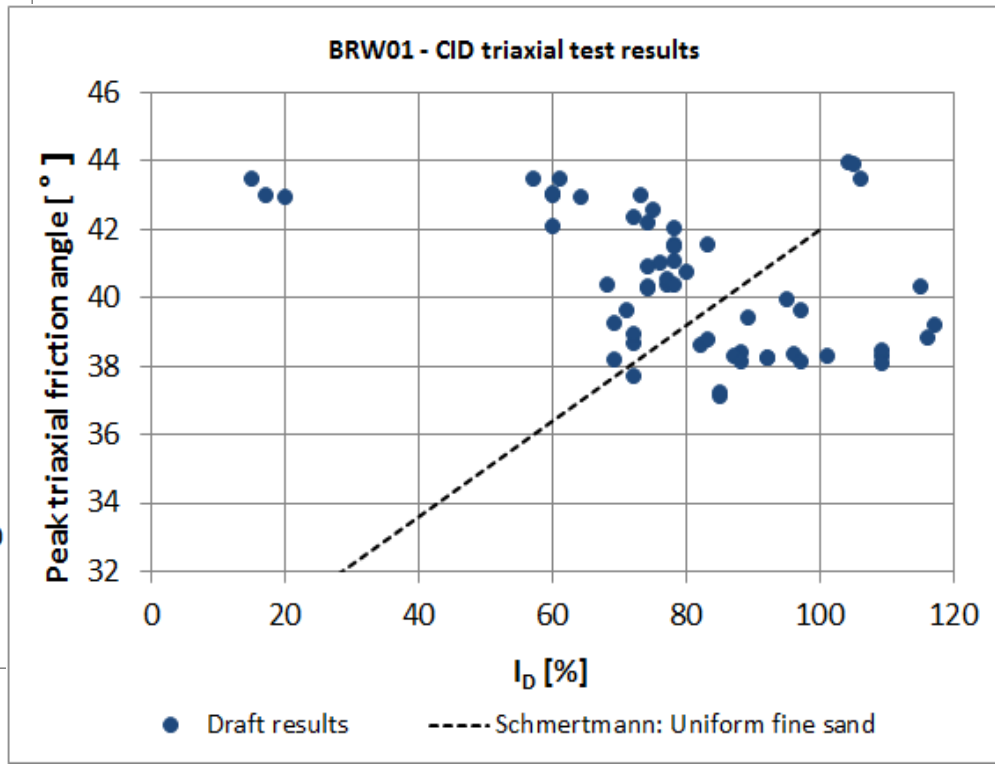
BRW01 – derivation of sand strength properties

- In-situ testing: CPT $q_c \rightarrow I_D = I_D(q_c, \sigma)$
- Laboratory strength testing: $\varphi'_p = \varphi'_p(I_D)$

$$I_{D,triax} = \frac{e_{max} - e_{triax}}{e_{max} - e_{min}}$$

- I_D is the **link** between in-situ and lab measurements





BRW01 – increased focus on testing details

Focus: Quality of triaxial testing
- sample preparation, testing performance etc.

Focus: Maximum/Minimum dry density testing
- how are these test performed?

$$e = \frac{\rho_s \gamma_w}{\gamma_d} - 1$$

- Very different testing methods apply !
  - $\gamma_{d,max}$: vibrating hammers, vibrating tables, falling weights, "impactor test"

- German Regulations require DIN testing
  - how is a removal of fines influencing the test result?
  - is $\Delta e_{DIN}=e_{max}-e_{min}$ small compared to other methods?

- Many correlations, eg. $I_D=I_D(q_c)$ are based on results of ASTM testing?

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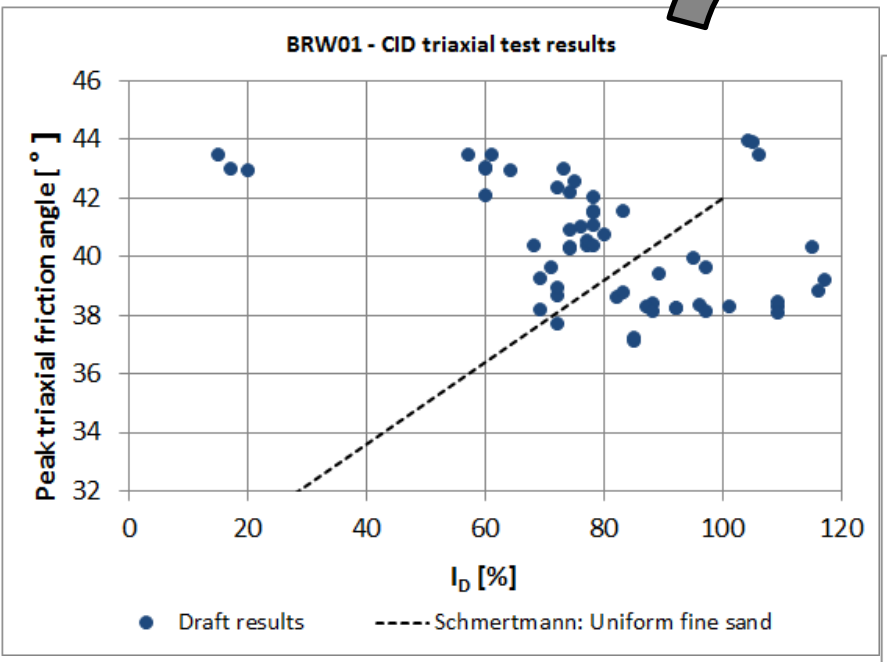
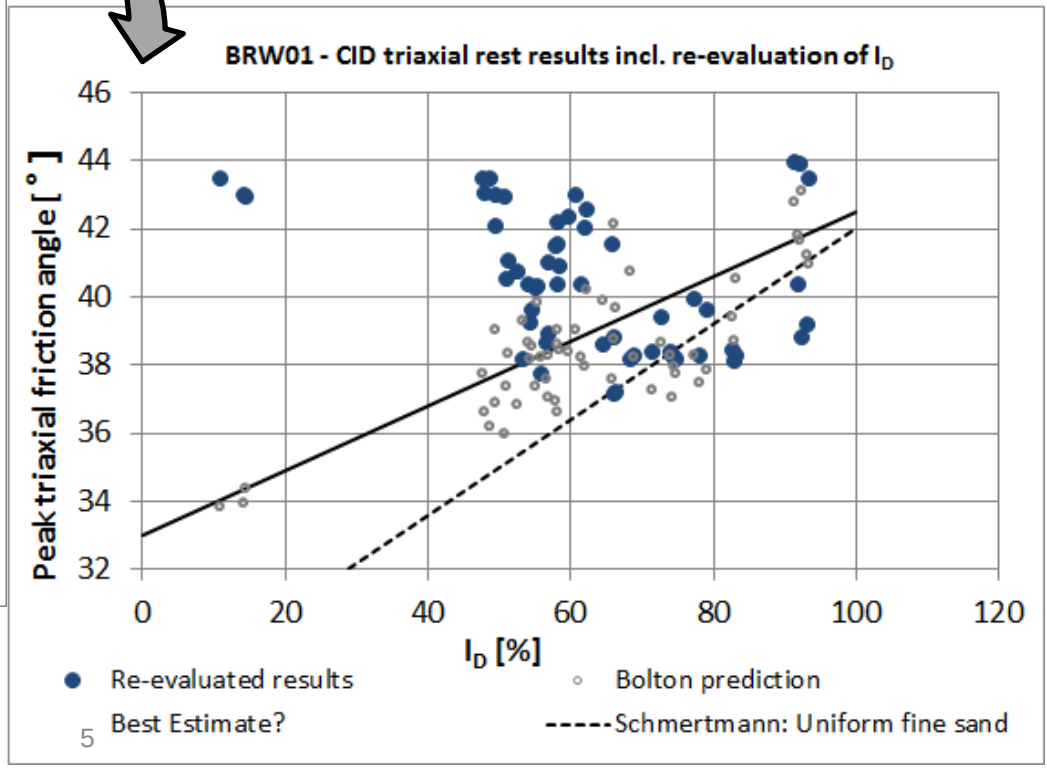
BRW01 – re-evaluation of density index

Analyse and comparison of testing results →
small adjustment of DIN measured $\gamma_{d,max}$

5% increase of $\gamma_{d,max}$

Small adjustment – large impact!



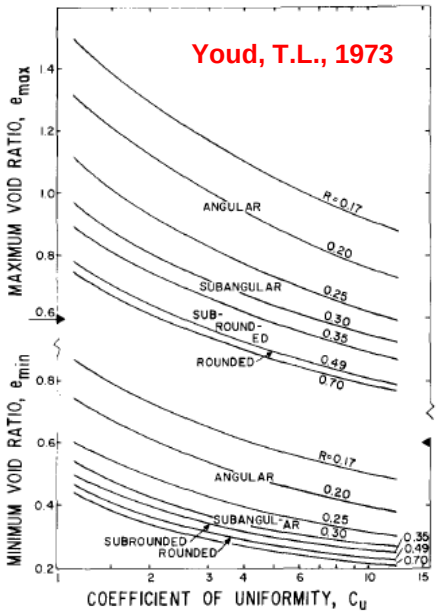


Max/min dry density/void ratio correlations

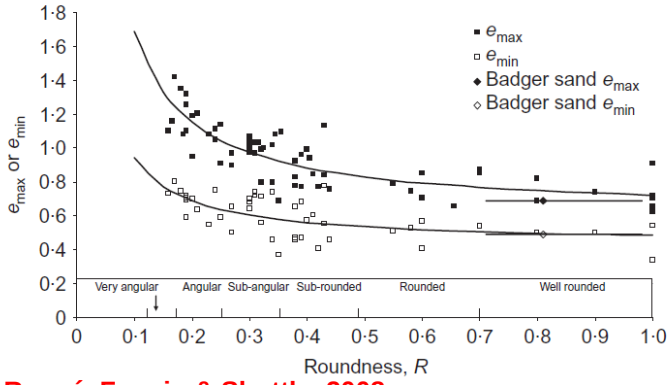
- Comparison with results from neighbouring projects

- Predictions/correlations exist for determining e_{min} and e_{max} or Δe based on various databases related to:

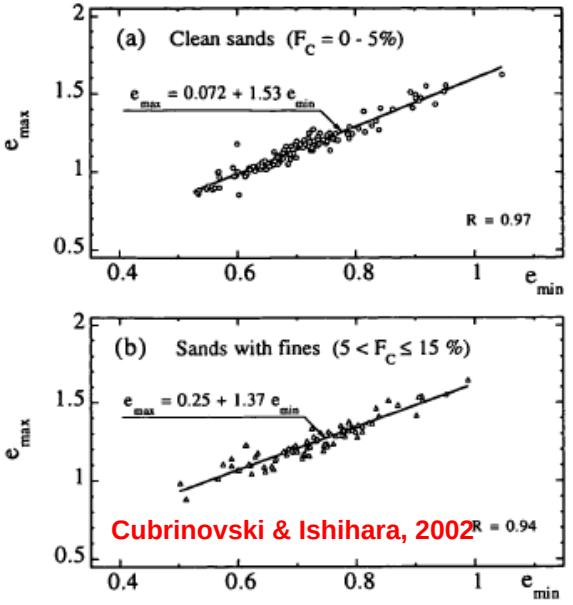
  - Particle size (d_{50})
  - Particle shape (sphericity S, angularity R)
  - Sorting (C_U)
  - Fines content (FC)



- **Any literature on how results of the various testing methods compare?**



Rousé, Fannin & Shuttle, 2008

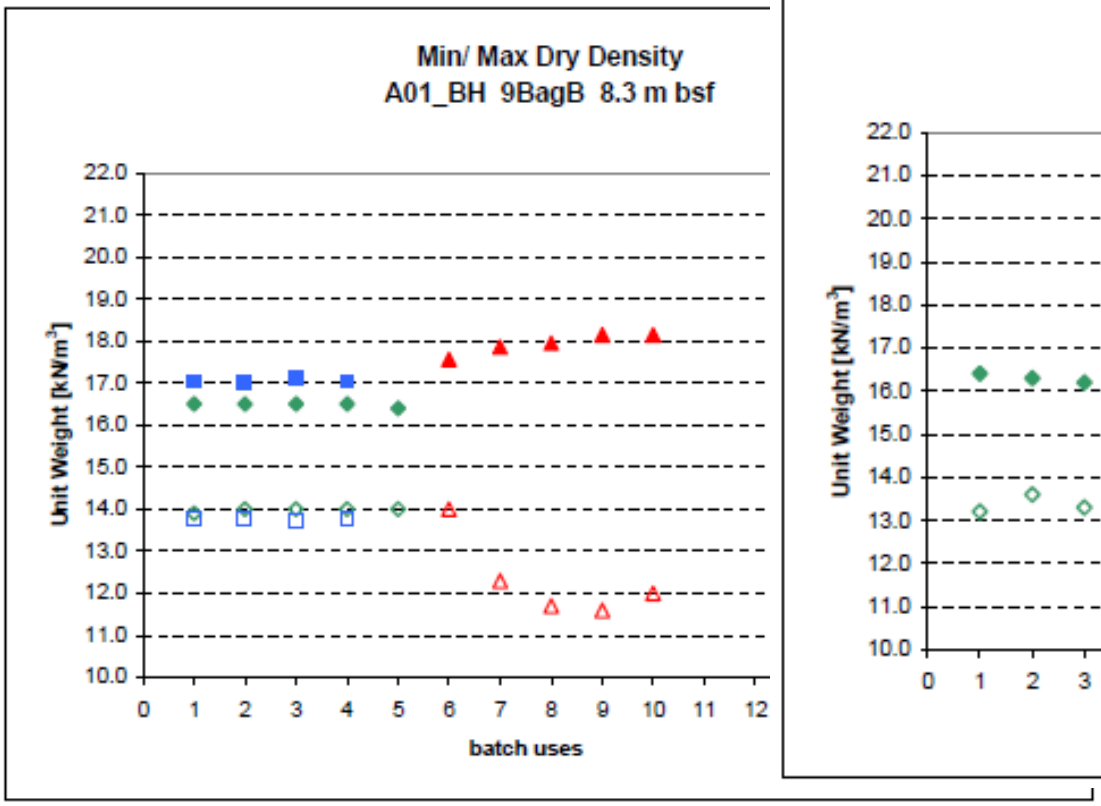


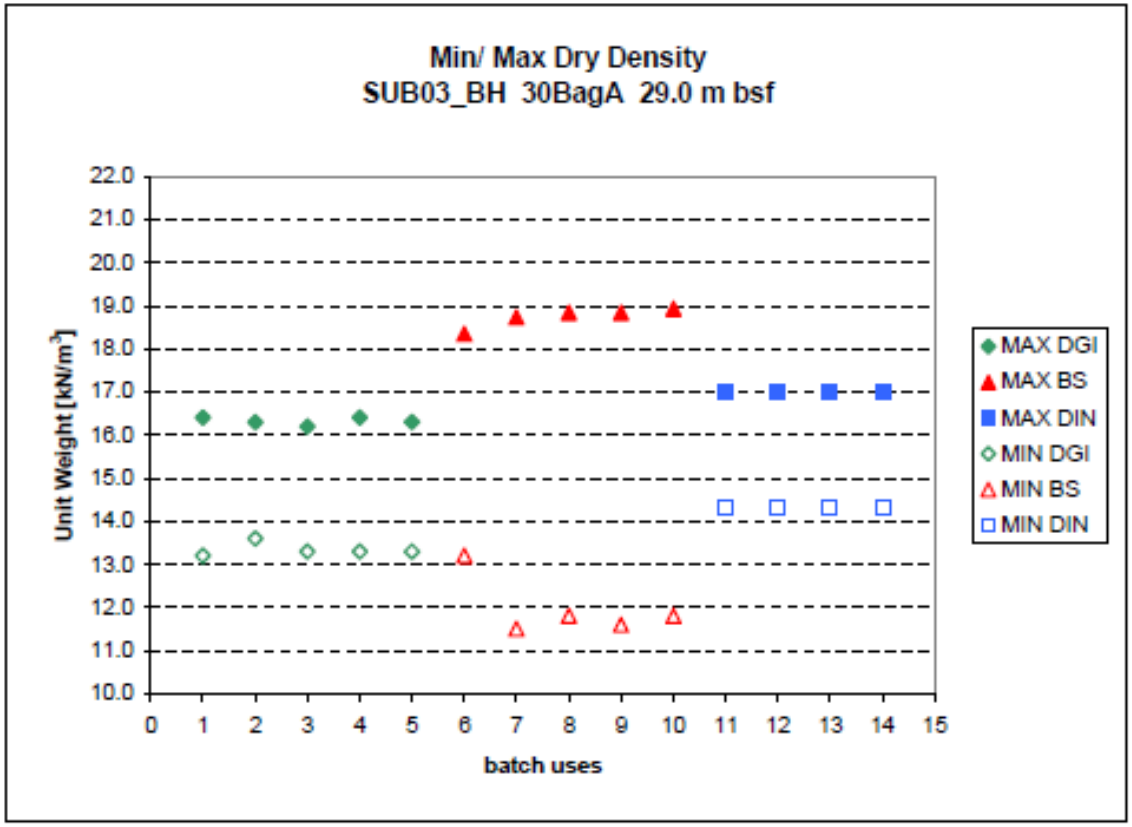
Cubrinovski & Ishihara, 2002

BRW01 – Min/max dry density comparison testing

- Interesting observations **and** new questions arising …

  - methods return different values and different windows
  - DIN + DGI methods show good repeatability, but mod. BS involves grain crushing?
  - methods more in line for $\gamma_{d,min}$ than $\gamma_{d,max}$
  - $\gamma_{d,min,BS}$ decreasing with increasing fines content?





Future focus related to derivation of sand properties

- Ok, issues with the lab density index determination! What to do about it?

- Determine the friction angle directly from CPT measurements?
  - eg. use correlations as proposed by Robertson & Campanella, Kulhawy & Mayne and others

- Develop a CPT based design method for holding capacity of laterally loaded piles?

- Identify a new link between the in-situ testing and laboratory testing?
  - eg. specific in-situ density – maybe based on RI cone measurements?

- Stick to the existing method and work on improving the reliability of the density index value?

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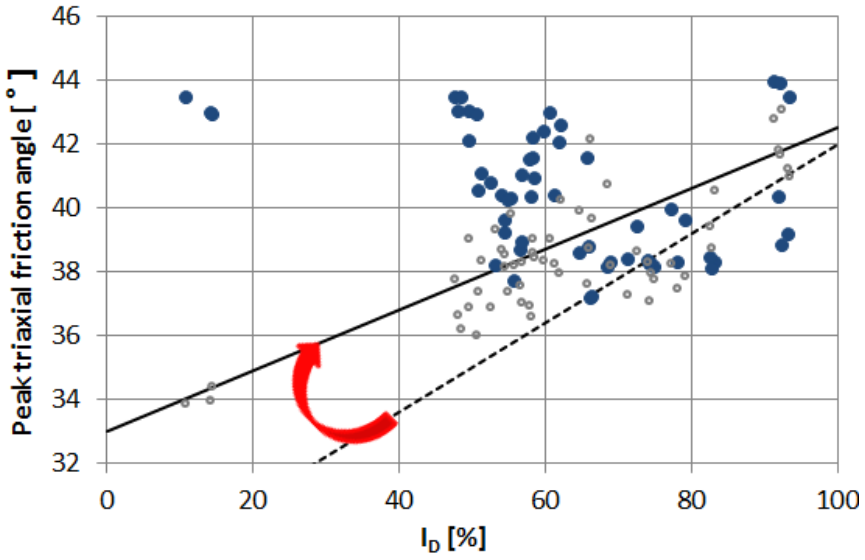
BRW01 – monopile sensitivity study

- More reliable estimates of $\gamma_{d,max}$ and $\gamma_{d,min}/e_{min}$ and e_{max} allow for:



+ $\gamma'=\gamma'(I_D)$

Large Cost Savings!

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Joint Industry Project – max/min dry density comparison

- Partnering project with NGI and Geolabs

- Objective:
  A database with results of the most common laboratory test methods/standards for different sand types
  - identify trends and patterns
  - prepare recommendations for future works

- Sand types:
  - sands from DONG Energy OWF sites
  - well-known "reference sands"
  - silty and calcareous sands

- Test methods:
  - DIN, DGI, BS, ASTM
  - NGI in-house, Fugro in-house