Quality Control of Vibro-compacted Carbonate Sands by means of CPT

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Large land reclamation works – Hydraulic Fill
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- Massive sand placement by dredging equipment
- Quality depending on local availability (fines content, mineralogy, …)
- Quality in part depending on dredging technique and segregation in reclamation
- (Relative) Densities depending on installation method and above or below water installation
Requirements

- **Material**
  - PSD: size and amount of large particles; fines content; Uniformity
  - Mineralogy (e.g. carbonates content)
  - Plasticity

- **Relative density / Compaction**
  - Minimum relative density; may be different above and below water; often higher in top 1 or 2 m
  - Target $q_c$-line
  - Liquefaction resistance $F_oS_L$

- **Shear strength: friction angle $\varphi'$**

- **Bearing Capacity under defined loads on foundations**

- **Settlements**
  - Overall settlements under (service) loads / Differential settlements
  - Residual settlements (consolidation of natural layers; secondary settlements)
  - Earthquake induced settlements
Requirements

Ground Improvement

Ground improvement techniques typically used for granular fill

- Vibroflotation
- Dynamic compaction
- RIC
- HEIC
- Roller compaction
- Stone columns

Technique selected depending on fill material characteristics, layer thickness and on requirement

QA: Measure execution parameters!
Carbonate sand

Calcareous sand or Carbonate sand

- Sand with (broken) shells
- Sand particles are microscopic small shells or shell debris
- Sand particles are porous
- Sand particle density: test material or porous individual particles?
- Up to 100% CaCO₃
- Minimum CaCO₃-value?

Occurs in many places in the world
Is locally available and has to be used
Carbonate sand

Many different calcareous or carbonate sands are found in the world!
Calcareous sand

Some consequences

► Crushable material
► Effect on compaction: zone of influence / change in PSD / less permeable mantle around the probe
► Effect on testing: CPT / MDD / other?
► How to interpret CPT?
► How to perform lab testing: proctor vs vibratory table?
► Min and Max densities are lower in absolute value compared to silica sand: gives ‘uncomfortable’ feeling
► Effect on shear strength : angularity: $\phi'$ >>
► Effect on stiffness : lower stiffness
► Effect on liquefaction potential : + or - : is unclear
► Often fines are mineralogically the same non plastic material – product of particle degradation
Quality Control *with calcareous sand*

**Sampling and shallow testing**
- **PSD** – attention not to further desintegrate the material
- **In situ density** – Sand replacement method
- **Defining MDD** – No dynamic tests; prefer vibratory table according to ASTM

**Deep testing**
- **CPT with Shell Correction Factor**
- **BH with SPT – SCF??** No literature available

**Further evaluation based on CPT**
- **Material type and layering**
- **Relative density**
- **Liquefaction assessment**
Quality Control with calcareous sand

CPT and Shell Correction Factor

- SCF = $q_{c,silica} / q_{c,carbonate}$
- Has been demonstrated by multiple researchers
- Depends on Carbonate sand type
- Depends on Relative density
- Depends on stress state
- Depends on Carbonates content
- Need for project dependent calibration
- Use of a constant value of 1.3 is not correct
Quality Control *with calcareous sand*

**QC CPT in Vibroflotation practice**

- Compaction in triangular grid
- Quality control by means of CPT: where to perform?
- One CPT in center of grid: ‘worst’ location’
- One CPT at 1/3 distance between compaction points: ‘best location’

*Remark: Quality assurance during VC execution; measure all execution parameters – required power at end of each compaction level is good control parameter*
Quality Control with calcareous sand

Evaluation of CPT’s

- Analysis of CPT result – presence of ‘unsuitable’ layers in the fill
- Allowable ‘inclusions’:
  - Max layer thickness: 0.2m to 0.3m
  - Sum of all inclusions: max 10% to 15% of total fill thickness / sometimes not allowed above the water table or in top x m
  - No influence on settlement and BC requirements
- CPT-handling for further analysis
  - Horizontal averaging; sometimes allowed only for relative density, not for liquefaction analysis – is considered very conservative approach
  - Vertical running averaging (over 1m or 0.5m): is generally allowed but discussion wrt averaging height
- SBT $I_c$ parameter for fines content: not reliable! Always sampling needed for ‘contractual’ evaluation of fines content
Quality Control with calcareous sand

CPT analysis for Soil Behavior Type $I_C$

- No fully reliable link with fines content; is called ‘apparent’ fines content by Robertson
- Gives different result when one compares the $I_C$ from pre to post compaction CPT’s
- Important factor for automatic liquefaction assessment
- One should combine pre compaction $I_C$ with post compaction CPT: how to do this?
Case study: how to define relative density

How to define relative density?

► Typical relative density correlations (Baldi, Jamiolkowski, …) not valid for carbonate sand and different correlations show large scatter

► Use of SCF is a solution, but we went for more correct approach: site specific calibration

► Calibration Chamber tests at ISMGEO

► Centrifuge testing: CPT in the flight: cover the whole stress range in the flight

► Testing of 3 different relative densities

► Practical test procedure for quick and economical testing during project execution
Case study: Calibration chamber test results

cone resistance $q_c$ (MPa)

vertical effective stress $\sigma'_v$ (kPa)

Dr=43% -- 57% -- 66%

Fit according to Jamiolkowski et al. (2001)

$C_0 = 12.81$, $C_1 = 0.25$, $C_2 = 2.84$
Case study: SCF

- Relative density definition is OK with site specific calibration: discussion solved
- Practical approach for liquefaction assessment: with SCF
- Is dependent on the relative density formula used (Jamiolkowski et al, 2001 is taken as reference)
- Is dependent on the relative density and stress level
- What about dependence on PSD, $C_u$ or carbonates content? Mayne: when CC > 42% independent

$$SCF = (0.002 \times RD + 0.4628) \times \sigma'_{v0}^{0.23} \geq 1$$
Case study - Post compaction CPT evaluation – relative density

- Dr = 50%, w = 0.15%
- Dr = 62%, w = 0.15%
- Dr = 82%, w = 0.15% (based on agreed correlation)
Case study - Post compaction CPT evaluation – Liquefaction

- Dr = 50%, w = 15%
- Dr = 62%, w = 15%
- Dr = 82%, w = 15% (based on agreed correlation)

Graphs showing:
- $q_v$ [MPa]
- Friction ratio [%]
- $u$ [MPa]
- $I_c$
- Factor of Safety

(depth in m CD)
Conclusions / Considerations

► Mineralogy of the reclamation material is important: need for CaCO$_3$-content!
► Adapted quality control methods for specific crushing behavior
► Use of SCF: remains a point of discussion with client/consultant but also from theoretical point of view (for different reasons)
► Site Specific correlations for relative density will help for RD, not for liquefaction assessment
► Remain realistic when evaluating such large earthworks below and above the water table: allowance for ‘unsuitable’ inclusions; certain margin on ‘non-conformity’ is unavoidable unless ‘clean’ Borrow Area is found
► Preference for ‘Performance Requirements’: do not only focus on material testing, but overall behavior testing (e.g. zone load tests, embankment tests, …)
► When one wants to avoid the use of SCF for liquefaction assessment: more advanced testing such as cyclic TX or cyclic DSS or in situ testing by means of Seismic CPT, PMT or DMT – need for further research in these fields with calcareous sands
► Liquefaction assessment: why is Liquefaction Potential Index not used in practice (e.g. to overcome issues with limited thickness failing silty sand layers)?
► Engineering Review / Engineering Judgment remains key in these projects
Thank you for your attention