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Characterisation of the behaviour of liquefaction triggering in a cyclic undrained simple shear test setting

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ABSTRACT

The definition of appropriate calibration criteria for liquefaction-simulating constitutive models in sands is essential to properly simulate a liquefied state under seismic ground motions, enabling an adequate estimation of the liquefaction hazard. Therefore, a thorough quantitative characterisation of the behaviour of liquefaction is necessary to define liquefaction-triggering criteria that can describe a liquefied state in terms of stress and deformation. This paper presents a benchmark characterisation study of the behaviour of liquefaction, where liquefaction-triggering criteria, in terms of pore pressure ratio (r_u) and shear strain (γ), were determined using two cyclic undrained direct simple shear test databases of Ottawa F-65 sand. The behaviour of liquefaction was analysed considering variations of initial state, confinement pressure (σ'_{v0}) and cyclic shearing (CSR) conditions. The onset of liquefaction-triggering markers was evaluated in terms of moment of occurrence. The research concluded that liquefaction-triggering markers $r_u \approx 0.95$ and $\gamma = 3\%$ could be used simultaneously to indicate the initiation of liquefaction in loose and dense Ottawa F-65 sand under various initial and cyclic shearing conditions.

Keywords: seismic liquefaction, liquefaction-triggering criteria, Ottawa F-65 sand

1. INTRODUCTION

The assessment of the liquefaction hazard is an intrinsic part of the seismic analysis and design of a structure when saturated sandy and silty deposits are present. Depending on the seismicity in the region, as well as the compositional and state characteristics of the deposits, this hazard will fluctuate between non-existent, minimal, and extremely likely and is more commonly observed in younger deposits, which correspond to shallower depths. However, liquefaction hazard may extend towards deeper deposits if certain combinations of seismic loading and compositional and state conditions are present.

For this reason, engineers need to have a proper understanding of the cyclic undrained behaviour of sandy and silty deposits to adequately apply it to the calibration of constitutive models used in the seismic assessment and design of any type of foundation. In recent years, several studies on liquefaction triggering and behaviour have been performed through both cyclic testing (simple shear and triaxial) and centrifuge testing programmes executed in relation to the Liquefaction Experiments and Analysis Projects (LEAP) using the standardised Ottawa F-65 sand. References to the laboratory test and centrifuge programmes are described in Parra (2016), Vasko et al. (2018), El Ghoraiby et al. (2018), Carey et al. (2018), El Ghoraiby and Manzari (2018), Carey et al. (2018), Kokkali et al. (2018), Kutter et al. (2015), Kutter et al. (2018), Manzari et al. (2018), Tobita et al. (2018), Zhou et al. (2018), among others. The results obtained from these prior works were instrumental in the investigation of pre-liquefaction and liquefaction triggering behaviour of clean sands under diverse initial state and shearing conditions.

The purpose of this paper is to present a benchmark study to quantitatively describe the behaviour of the onset, or triggering, of liquefaction under diverse initial state and shearing conditions in clean sands in terms of both stress and strain. The aim of the quantitative assessment was to define liquefaction-triggering criteria in terms of stress (r_u) and strain (γ) which are most suited for the identification of a liquefied state in clean sands subjected to specific initial states and shearing conditions. These criteria would be of use in calibration methodologies of constitutive models, such as UBC Sand (Beaty and Byrne, 2011) and the PM4Sand (Boulanger and Ziotopoulou, 2017), used in geotechnical earthquake engineering practice when performing detailed liquefaction potential analyses in the framework of seismic design.

2. TRIGGERING OF LIQUEFACTION

To be able to quantitatively assess the onset of liquefaction, one must first define what mechanical process and state qualify as liquefaction. Many researchers, such as Armstrong (2018), Idriss and Boulanger (2008), and Sriskandakumar (2004), have proposed various definitions of what constitutes a liquefied state in sands and have defined its onset based on markers of r_u and γ (Portugal, 2019; Wu et al., 2004). However, a disadvantage of these definitions is that they are solely based on a single liquefaction triggering criterion, instead of 2 or more, leading to some confusion in practice. This confusion is increased further by broad, and only qualitative, definitions of liquefaction presented by institutions like ASCE and the NRC (Wu et al., 2004).

In the past, the r_u-based liquefaction triggering criterion was more popular than the γ-based one, as it was thought that excessive soil deformation was solely a consequence of strength loss. However, this is a misconception that was debunked over the last decades, and it has now been established that shear deformations and pore pressure accumulation are closely interrelated (Wu et al., 2004). Therefore, it was considered of great importance to jointly evaluate the relationship between r_u and γ during the shearing process and their role in the triggering of liquefaction, as it would greatly improve our understanding of the onset of liquefaction and how to adequately model cyclic undrained behaviour in practice.

3. CHARACTERISATION OF LIQUEFACTION ONSET IN OTTAWA F-65 SAND

3.1. General specifications

This benchmark study used the stress-controlled cyclic undrained direct simple shear (CUDSS) test databases performed with Ottawa F-65 sand executed by Parra (2016) and El Ghoraiby and Manzari (2018), hereafter referenced as PB2016 and EG2018, respectively, as the basis for the characterisation of the onset of liquefaction. Specifically, only the normally consolidated (NC) samples without any pre-shear were considered for this assessment. The PB2016 tests included 25 poorly graded (Cu = 1.61) and clean (negligible fines content) NC samples with loose and dense initial relative densities ($D_{R0} \approx 41\%$ and 80%, respectively), no pre-shear, confined at 50, 100, and 400 kPa vertical confinement pressures (σ'_{v0}), and sheared at cyclic stress ratios (*CSR*) ranging from 0.075 to 0.228. The EG2018 tests included 17 poorly graded (Cu = 1.73) and clean NC dense ($D_{R0} \approx 70\%$) samples with no pre-shear, confined at σ'_{v0} of 40 and 100 kPa, and sheared at *CSR*s ranging from 0.076 to 0.150. Furthermore, the maximum (e_{max}) and minimum (e_{min}) void ratios of the evaluated tests ranged from around 0.80 to 0.51, respectively. These magnitudes fell well within reported values from other Ottawa F-65 sand characterisation studies found in the literature (Cooper Lab, 2013; Rufatto, 2013; Vasko et al., 2014). For more details, please refer to Portugal (2019).

To adequately evaluate the behaviour of liquefaction in clean sands, several r_u and γ thresholds were selected to analyse cyclic undrained behaviour of loose to dense sands sheared at various initial states and loading conditions. These thresholds were jointly evaluated based on their moments of occurrence during cyclic shearing. I.e., the moment of occurrence was quantitatively assessed in terms of number of uniform shearing cycles (*N*). This was chosen to identify possible relationships between stress and strain markers during the onset of liquefaction considering various testing conditions.

3.2. Liquefaction-triggering thresholds or markers used in the study

The magnitudes of the liquefaction-triggering thresholds or markers were defined based on recommended values found in literature and those used in the evaluated CUDSS test databases. The chosen magnitudes of r_u and γ are visually represented in Fig. 1 and 2 and summarised in Table 1.

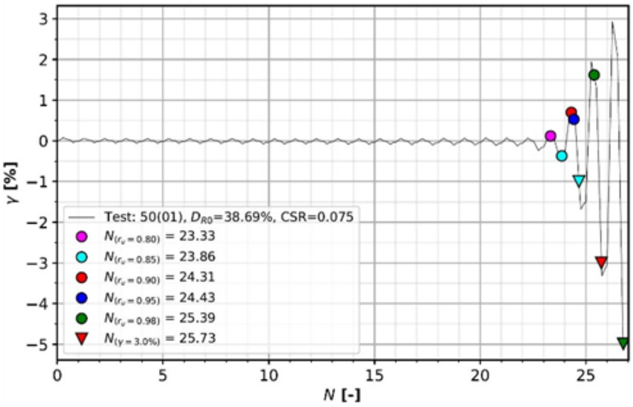

Figure 1: Moment of occurrence of r_u and γ markers in N-γ space in a loose sample, sheared at a low σ'_{v0} and *CSR*.

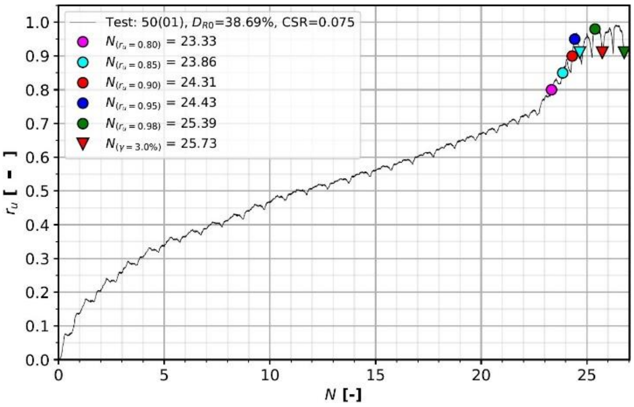

Figure 2: Moment of occurrence of r_u and γ markers in N-r_u space in a loose sample, sheared at a low σ'_{v0} and *CSR*.

The r_u thresholds at 95% and 98% were defined based on suggested values found in literature

(Armstrong, 2018; Idriss and Boulanger, 2008; Wu et al., 2004), whereas those at 80% and 85% were defined as control markers, although they have also been mentioned in Wu et al. (2004). A threshold at 90% (also present in Wu et al., 2004) was included due to the cyclic behaviour observed in some cyclic triaxial compression (CTXC) and CUDSS tests sheared at various conditions, where r_u did not reach magnitudes much greater than 0.90. No threshold at 100% was defined, as most of the analysed CUDSS tests did not reach the theoretical stress-based value of liquefaction. These r_u values were more commonly reached in a CTXC test setting, as observed in the test database of El Ghoraiby et al. (2017), El Ghoraiby and Manzari (2018), and Vasko et al. (2014).

As for the γ thresholds, 3% was selected due to its predominance in the presentation of cyclic resistance curves as shown in, e.g., Idriss and Boulanger (2008), whereas the ones at 1% and 5% were defined due to their use in test databases presented in Parra (2016), El Ghoraiby and Manzari (2018), as well as in Wu et al. (2004), and to have a decent tracking range for deformation. For more details, please refer to Portugal (2019).

Table 1: Liquefaction-triggering thresholds evaluated

Type of threshold	r_u-based (-)	γ-based (%)
Fixed (=)	0.80 and 0.85	1.0
Flexible (≈)	0.90, 0.95, and 0.98	3.0 and 5.0

3.3. Data processing and evaluation methodology

To properly assess the effects of σ'_{v0} and *CSR* on liquefaction onset in the tested sand samples, it was necessary to group the CUDSS tests in various combinations. In total, 9 groups were created to account for different effects on the overall cyclic and liquefaction behaviour as described in Portugal (2019). The effect of *CSR* was evaluated based on tests from groups 1 to 4, whereas the effect of confinement pressure used the tests from groups 5a to 6.

Values of *N* for both stress and strain markers were plotted together for joint evaluation, as shown in Fig. 3 for a loose sample sheared at a low σ'_{v0} and *CSR*. Tests belonging to the same analysis group were also plotted together for an easier visual comparison, all of which is shown in detail in Portugal (2019).

For ease of evaluation of the effects of *CSR* on loose and dense samples, magnitude ranges were created based on the overall behaviour exhibited in the CUDSS tests as shown in Table 2.

Table 2: Ranges of CSR defined for evaluation.

Range type of *CSR*	Magnitude range of *CSR* (-)
Low	$CSR \leq 0.09$
Intermediate	$0.09 < CSR \leq 0.12$
High	$0.12 < CSR \leq 0.19$
Very high	$CSR > 0.19$

The low-intermediate limit was set based on the exhibited strength reduction in both loose and dense samples when sheared at *CSRs* greater than 0.09. Next, the intermediate-high limit was defined based on the cyclic resistance shown by loose samples at all tested confinement pressures. Even though samples in Parra (2016) were only sheared up to a *CSR* of 0.114, the cyclic resistance evidenced in loose samples still showed considerable strength, giving reason to extend the limit to 0.12 so that all loose samples could fail. This may seem like an arbitrary approach, but it was deemed reasonable considering that the cyclic strength of loose sands to high *CSRs* was very low, which is why this limit was set at that magnitude. Lastly, the high-very high limit was defined based on the reduced cyclic resistance observed in dense samples presented in Parra (2016) when sheared at an approximate *CSR* of 0.19. No upper limit was defined for the very high *CSR* range.

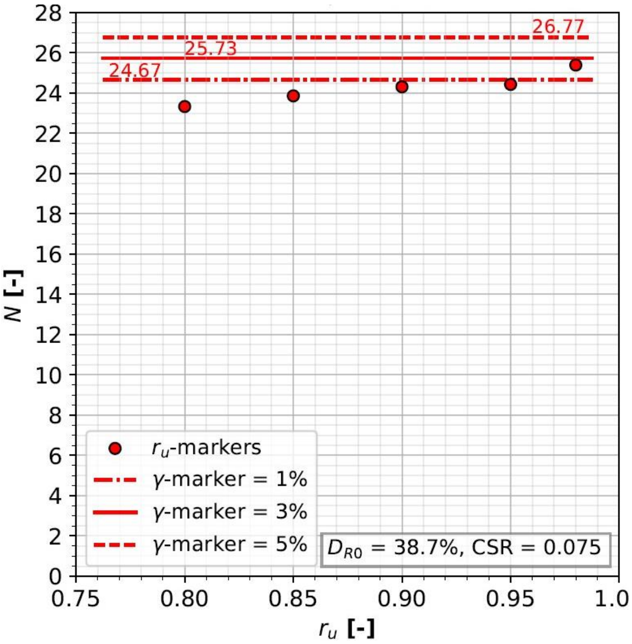

Figure 3: Comparison of number of uniform shearing cycles (*N*) at the moment of occurrence of r_u and γ markers in a loose sample, sheared at a low σ'_{v0} and *CSR*.

3.4. Observed cyclic undrained behaviour

This section provides a summarised overview of the observed cyclic undrained behaviour of loose and dense Ottawa F-65 sand subjected to various initial state and shearing conditions.

In general, dense samples sheared at most levels of *CSR* showed a slower accumulation of shear strains, as the more densely packed soils needed more shearing cycles to reach higher levels of deformation. Dense samples that were sheared at high to very high *CSR* levels were able to quickly reach the γ = 1% due to the initial shift of densely packed particles but then progressed slowly to the 3% and 5% strain markers. In the case of loose sands, the accumulation of shear strains happened very fast after certain degradation occurred both in terms of stress and strain. All marker types were activated very closely after each other, signifying a rapid deterioration of soil integrity in loose samples during liquefaction onset.

The effect of *CSR* could be seen in both loose and dense samples confined at low to high overburden pressure, as cyclic resistance steadily reduced with increasing *CSR*. This was more evident in loose and dense samples when sheared up to high levels of *CSR*, beyond which (high to very high *CSR*s) the latter's effect was not too visible due to the very high magnitude of cyclic stress. In the case of dense samples confined at low overburden pressures, the cyclic resistance degradation was not too evident in terms of r_u compared to γ, where the degradation was observed. This discrepancy could be due to the high variability in tests when sheared at higher *CSR*s and at low σ'_{v0}.

On the other side, the effect of σ'_{v0} was observed in evaluated samples from PB2016, as cyclic resistance in loose and dense samples increased with increasing overburden pressure, which was also observed in other researcher's findings (Tziolas 2019). However, the opposite trend was observed in samples from EG2018 when comparing the results at all *CSR* levels (see Figure 3.13 in Portugal, 2019). This could have been the product of abnormal behaviour as described in Portugal (2019), or that, due to variability in testing, changes observed between samples sheared at low and intermediate overburden pressure were not large enough to show a clear trend.

3.5. Observed liquefaction onset behaviour

A thorough analysis of loose and dense samples from the two before-mentioned databases sheared at diverse ranges of *CSR* and σ'_{v0} allowed for the determination of physically consistent liquefaction-triggering criteria that would be able to best represent a liquefied state in sands sheared at various conditions. A summary of the determined thresholds is presented in Table 3.

Low overburden pressure (≈ 40 kPa to 50 kPa): Groups 1 and 2 included all loose and dense samples confined at low overburden pressure and sheared at low to very high *CSR*s belonging to both EG2018 and PB2016. The liquefied state in both loose and dense samples sheared at low to very high *CSR*s was adequately represented by thresholds $r_u \approx 0.95$ and $\gamma = 3\%$ and $r_u \approx 0.90$ to 0.95 and $\gamma = 3\%$, respectively, considering samples from both EG2018 and PB2016. Given that the activation of r_u markers in loose sands happened extremely quickly, it was deemed sufficiently conservative to define the r_u threshold at 0.95.

Intermediate overburden pressure (≈ 100 kPa): Groups 3a to 3c included all loose and dense samples confined at intermediate overburden pressure and sheared at low to very high *CSR*s belonging to both EG2018 and PB2016. In loose samples, the activation of all r_u and γ markers occurred consecutively in a very rapid manner after reaching a certain number of shearing cycles. For these samples, sheared at low to intermediate *CSR*s, thresholds $r_u \approx 0.95$ and $\gamma = 3\%$ were sufficient to describe a liquefied state. As for dense samples, some variation in terms of activation of strain thresholds was experienced between samples tested belonging to PB2016 and EG2018. Therefore, to allow for variability in testing, thresholds $r_u \approx 0.90$ to 0.95 and $\gamma = 3\%$ were deemed adequate to describe a liquefied state in dense sands sheared at high to very high *CSR*s.

High overburden pressure (≈ 400 kPa): Group 4 included all loose and dense samples confined at high overburden pressure and sheared at low to very high *CSR*s belonging to both EG2018 and PB2016. Based on the observed cyclic behaviour in loose sands, thresholds $r_u \approx 0.95$ and $\gamma = 3\%$ were able to represent a liquefied state in loose sands sheared at low to intermediate *CSR*s. In contrast, $r_u \approx 0.80$ and $\gamma = 3\%$ thresholds were able to adequately describe a state of liquefaction in dense samples sheared at high to very high *CSR*s. This combination was most likely a consequence of the very large deformations experienced at this range of *CSR*.

Table 3: Liquefaction-triggering criteria for all evaluated scenarios in Ottawa F-65 sand

σ'_{v0}	D_{R0}	*CSR*	r_u and γ thresholds
Low (~ 40 kPa to 50 kPa)	Loose (~ 40%)	Low to intermediate	$r_u = 0.95$ $\gamma = 3\%$
	Dense (~ 70%)	High to very high	$r_u = 0.90$ to 0.95 $\gamma = 3\%$
Intermediate (~ 100 kPa)	Loose (~ 40%)	Low to intermediate	$r_u = 0.95$ $\gamma = 3\%$
	Dense (~ 72% to 80%)	High to very high	$r_u = 0.90$ to .95 $\gamma = 3\%$
High (~ 400 kPa)	Loose (~ 44%)	Low to intermediate	$r_u = 0.95$ $\gamma = 3\%$
	Dense (~ 85%)	High to very high	$r_u = 0.80$ $\gamma = 3\%$

3.6. Remarks regarding testing and interpretation

It is worth noting that the results presented in the above sections are, so far, representative of cyclic undrained behaviour in clean and uniform sands. These results are limited to materials similar in nature and would need to be further validated against other databases to increase the robustness of the conclusions presented here. Additional validation would need to be performed to extrapolate these results to types of sandy and silty deposits which are more commonly present in nature and in engineering practice.

Dense samples from EG2018 sheared at low confinement pressure (40 kPa) had difficulties reaching r_u values ≥ 0.90, or even ≥ 0.85 in some cases. This could mean several things: that the testing setup was not adequate to ensure fully undrained boundary conditions during shearing, transducers located in the centre of the sample were not able to adequately capture the full extent of excess pore water pressure development, or that dense samples confined at very low pressures do allow liquefaction at those levels of r_u. The latter statement would need to be validated with additional testing, as the available data was not sufficient to draw a definitive conclusion on this potential type of behaviour.

When evaluating loose samples, the usefulness of defining liquefaction based on two parameters was evident, as r_u might reach values close to 1.0 quickly, but shear strains, one of the best indicators of seismic performance, have not had time to sufficiently develop to adequately represent a liquefied state.

3.7. Remarks regarding the use of laboratory-based liquefaction-triggering criteria in a practical setting

In contrast with what we see in a laboratory test setting, research, and practical experience in site response analysis, considering various limit states, have shown that large accumulations of shear strains, as defined in the above sections, can be hard to achieve even if high enough levels of r_u are reached. This poses a challenge in the correct identification of liquefaction in soil response in a practical setting through both γ and r_u criteria. Potential sources of this difference could be the effects on shear strain development caused by the constraints present when modelling a wider domain, or the strategy used to calibrate the constitutive models. This condition should be further investigated.

Furthermore, the applicability of the above-presented liquefaction-triggering criteria should be validated when assessing the cyclic undrained behaviour of non-clean sands and silts more commonly found in the field.

Lastly, it is worth emphasising that significant uncertainties in the overall cyclic undrained behaviour can stem from the testing device setup and method of execution themselves. The method of sedimentation, consolidation, and shearing (such as height control) can have a large impact on, e.g., initial stiffness and correct measurement of excess pore water pressure within the sample.

4. CONCLUSIONS

The main objective of this research was to characterise liquefaction onset behaviour in clean sands sheared under various initial state and loading conditions to provide a good understanding of liquefaction behaviour for use in the evaluation of liquefaction hazard in geotechnical earthquake engineering practice. The benchmark characterisation study was performed using 2 cyclic undrained direct simple shear test databases, where relevant r_u- and γ-based liquefaction-triggering criteria were evaluated in terms of the moment of occurrence and relationship to each other when observing cyclic undrained behaviour under different initial states and loading scenarios.

Loose Ottawa sands exhibited increases and decreases in cyclic resistance with increasing overburden pressure and *CSR*, respectively. In general, loose sands sheared at intermediate *CSR*s tended to exhibit net-contractive behaviour, with a very stiff behaviour before liquefaction onset. Dense Ottawa sands exhibited degradation in cyclic resistance with both increasing overburden pressure and *CSR* magnitude. In terms of the overall behaviour of dense sands when sheared at various ranges of *CSR*, samples confined at high overburden pressure tended to show a net-contractive behaviour, whereas a net-dilative behaviour was observed in dense samples confined at low to intermediate overburden pressure.

After evaluating all available data, a general set of liquefaction-triggering criteria for both loose and dense sands, sheared under various conditions, was defined at $r_u \approx 0.95$ and $\gamma = 3\%$. These criteria could adequately describe a liquefied state in most loose and dense scenarios, within a cycle tolerance of approximately ± 2.5 cycles, and would be suitable as the basis for calibration of cyclic undrained behaviour of clean sands in general.

Lastly, it is known that the development of large shear strain magnitudes is hard to achieve when modelling a larger domain, even when effective stresses have reduced significantly. This poses a challenge to the correct identification of liquefaction triggering based on the recommended liquefaction-triggering criteria defined in previous sections with the use of extensive laboratory data. The potential causes may come from modelling constraints or an inadequate constitutive model calibration strategy.

It is the opinion of the authors that a larger range of initial state and shearing conditions should be investigated, as well as the effect of different grain size distributions, fines contents and material types, to provide a better understanding of what constitutes a liquefied state under other, and more varied, testing scenarios in a laboratory setting. This would provide the means to validate the application of the above-presented triggering markers in sand and silt mixtures which are more common in the field.

Furthermore, modelling and calibration strategies should be validated through 1D and 2D seismic site response analyses to provide greater insights into how the triggering of liquefaction can be correctly identified in the modelled soil regions. Additional research would also be needed to determine whether the use of these liquefaction-triggering criteria in the calibration procedure of constitutive models would provide an improvement of the post-liquefaction triggering cyclic undrained behaviour of soils in numerical modelling.

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REFERENCES

1) Armstrong, R.J. (2018): Numerical analysis of LEAP centrifuge tests using a practice-based approach. In: Soil Dynamics and Earthquake Engineering, vol 133, 793-803. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.06.025
2) Beaty, M.H. and Byrne, P.M. (2011): UBCSAND constitutive model (Version 904aR). University of British Columbia.
3) Boulanger, R.W. and Ziotopoulou, K. (2017): PM4Sand, a sand plasticity model for earthquake engineering applications (Version 3.1). University of California, Davis.
4) Carey, T. et al. (2018): LEAP-GWU-2015 centrifuge test at UC Davis. In: Soil Dynamics and Earthquake Engineering, vol 113, pp 663-670. DOI: https://doi.org/10.1016/j.soildyn.2017.01.030
5) Cooper Lab (2013): Dry densities Ottawa F-65 sand.
6) El Ghoraiby, M. et al. (2017): LEAP 2017: Soil characterisation and element tests for Ottawa F-65 sand. George Washington University.
7) El Ghoraiby, M. and Manzari, M. (2018): Liquefaction Experiments and Analysis Projects (LEAP): Stress-strain response of Ottawa F-65 sand in cyclic direct simple shear tests. George Washington University.
8) Idriss, I.M. and Boulanger, R.W. (2008): Soil liquefaction during earthquakes. In: EERI Publications. ISBN: 9781932884364.
9) Kokkali, P. et al. (2018): Physical modelling of soil liquefaction: Overview of LEAP production test 1 at Rensselaer Polytechnic Institute. In: Soil Dynamics and Earthquake Engineering, vol 113, 629-649. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.01.036
10) Kutter, B. et al. (2015): LEAP-GWU-2015 experiment specifications, results, and comparisons. University of California, Davis.
11) Kutter, B. et al. (2018): Twenty-four centrifuge tests to quantify sensitivity of lateral spreading to DR and PGA. Proceedings of the Geotechnical Earthquake Engineering and Soil Dynamics V, Austin, USA, 383-393. DOI: https://doi.org/10.1061/9780784481486.040
12) Manzari, M. et al. (2018): Liquefaction experiment and analysis projects (LEAP): Summary of observations from the planning phase. In: Soil Dynamics and Earthquake Engineering, vol 113, 714-743. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.05.015
13) Obermeier, S.F. et al. (2001): Paleoliquefaction studies in continental settings: Geology and geotechnical factors in interpretations and back-analysis.
14) Parra, A.M. (2016): Ottawa F-65 Sand characterization. PhD thesis, University of California Davis.
15) Portugal, H. (2019): Seismic liquefaction analysis of a critical facility with PM4Sand in Plaxis, MSc thesis, Delft University of Technology, Delft. DOI: http://dx.doi.org/10.13140/RG.2.2.34718.89925
16) Ruffatto, M. (2013): Recommendation for a new standard sand for use at the UC Davis Geotechnical Modeling Center., MSc thesis, University of California at Davis.
17) Sriskandakumar, S. (2004): Cyclic loading response of Fraser River sand for validation of numerical model centrifuge tests, MSc thesis, University of British Columbia.
18) Tobita, T. et al. (2018): Kyoto University LEAP-GWU-2015 tests and the importance of curving the ground surface in centrifuge modelling. In: Soil Dynamics and Earthquake Engineering, vol 113, 650-662. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.10.012
19) Tziolas, A. (2019): Evaluation of the PM4Sand constitutive model for the prediction of earthquake-induced and static liquefaction in hydraulic fills, MSc thesis, Delft University of Technology, Delft.
20) Vasko, A. et al. (2014): An Investigation into the behaviour of Ottawa F-65 sand under monotonic and cyclic shear tests. George Washing University.
21) Wu, J. et al. (2004): Laboratory study of liquefaction triggering criteria. In: Proceedings of the 13th world conference on earthquake engineering. Vancouver, Canada.
22) Zhou, Y. and Chen, Y. (2018): Zhejiang University benchmark centrifuge test for LEAP-GWU-2015 and liquefaction responses of a sloping ground. In: Soil Dynamics and Earthquake Engineering, vol 113, 698-713. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.03.010