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Influence of soil grading on the coefficient of permeability of hydraulic fills

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Abstract. Hydraulic filling is used for land reclamation work and/or to increase the ground level of low-lying areas. Changes in gradation properties of the hydraulic fill is to be expected during hydraulic filling process which comprises dredging, transportation, deposition, and compaction. These changes in gradation can influence the hydraulic conductivity (permeability coefficient) of the resulting hydraulic fill mass. This hydraulic conductivity is further exacerbated by potential ponding of the transient remnant sea water within the constructed fill mass and its extent in relation to location of points of discharge and the groundwater regime of the area. This paper examines the effect of change in gradation on the hydraulic fill mass coefficient of permeability, using the grading entropy framework to investigate changes in the coefficient of permeability of the hydraulic fill mass. The paper also examines the possibility of applying the gradation entropy framework to assess the liquefaction potential of sand fill mixtures 'after deposition' and the in-situ granular foundation strata due to seismic events.

Keywords: Hydraulic filling; Hydraulic fill mass; Grading entropy; Coefficient of permeability; Liquefaction.

1 INTRODUCTION

Hydraulic Filling (HF) is used for land reclamation work and/or to increase the elevation of low-lying areas by dredging, transport and deposition of the hydraulic fill material in the development area (e.g. van't Hoff and van der Kolff 2012, Kolman and van 't Hoff 2013). The sand fill material forming the hydraulic fill mass is classified as a young, newly deposited marine sediment whose density, gradation, particle segregation and drainage 'after deposition' have great influence on the performance of the constructed hydraulic fill mass (cf. Lee *et al.* 1999 and Lee 2001). Most hydraulic filling studies have focused on the geotechnical characterisation of the hydraulic fill in terms of settlement, bearing capacity and liquefaction with little attention to its hydraulic conductivity and the influence this has on design and construction considerations (cf. Boumendjel-Game *et al.* 2023, van Ginkel and Olsthoorn 2019).

Phoon and Kulhawy (1999a, b) presented a discussion of the use of transformation models to study geotechnical variability. The grading entropy framework (e.g. Lőrincz 1990, Lőrincz *et al.* 2005, McDougall *et al.* 2013a, McDougall *et al.* 2013b, Singh 2014) has been used to develop transformation models to allow for a-priori prediction of the coefficient of permeability for granular materials (Feng *et al.* 2019, O'Kelly and Nogal 2020, Arshad *et al.* 2020) and for asphalt concrete (Feng *et al.* 2021).

This paper presents a preliminary study on the use of the grading entropy coordinates to estimate the coefficient of permeability of the hydraulic fill mixture 'after deposition'. This study uses sand fill gradation data from published land reclamation case studies (Lee *et al*. 1999, Lee 2001, Chua *et al.* 2007, Vessies 2012, Lees *et al*. 2013). This paper also explores the possibility of applying the grading entropy framework to assess the liquefaction potential of the hydraulic fill mass 'after deposition' using the approach presented in Barreto *et al.* (2019).

2 LITERATURE REVIEW

2.1 Hydraulic Fill Deposition and Characterisation

Hydraulic sand fills are generally dredged marine sediments from selected offshore burrows. The quality and quantity of hydraulic sand fill are of paramount importance to hydraulic filling projects. The quality is determined by: (i) assessing the suitability of the sand as hydraulic fill 'at source' and (ii) the characterisation of the hydraulic fill mass performance 'after deposition'. For the latter, the evaluation is mainly targeted at the geotechnical criteria set for a specific project in terms of bearing capacity, settlement, and liquefaction potential: all of which are governed by the hydraulic fill mass geotechnical properties such as soil strength and stiffness. Various studies have demonstrated the influence of the methods of placement on the behaviour of the hydraulic fill mass (cf. Lee *et al.* 1999, Lee 2001, Chua *et al.* 2007, Lees *et al.* 2013, van Ginkel and Olsthoorn 2019). These studies demonstrate that the sand fill materials are loosened at source for easy extraction, transportation as soil-water mixture and placement at the designated site, using a combination of subaqueous and subaerial methods of deposition. The process shows that the resulting hydraulic sand fill mass may be formed from sand fill with variable gradation, variable density, and variable permeability (cf. Lee *et al.* 1999, Lee 2001, Chua *et al.* 2007, Lees *et al.* 2013, van Ginkel and Olsthoorn 2019).

2.2 Grading Entropy Theory

The grading entropy framework has been outlined in various publications (e.g. Lőrincz 1990, Lőrincz, *et al.* 2005, Lőrincz *et al.* 2015, McDougall *et al.* 2013b, Singh 2014). The gradation entropy framework is based on the application of the statistical entropy theory developed by Shannon (1948) to the particle size distribution (PSD) of a granular mixture used to depict a grading curve as a vector (McDougall *et al.* 2013b). The entropy coordinates *A* and *B* are given as Eqs. 1 and 2 (see e.g. Singh 2014 for a derivation):

$$A = \frac{\sum_{i=1}^{N} x_i (i-1)}{N-1} \qquad (1)$$

$$B = -\frac{\sum_{i=1}^{N} x_i \log_2 x_i}{\log N} \qquad (2)$$

where *A* is the relative base entropy, *B* is the normalised entropy increment, x_i is the relative frequency of the fraction, and *N* is the number of fractions.

Feng *et al.* (2019, 2020) proposed an empirical transformation model to estimate the coefficient of permeability of granular materials by means of the dimensionless grading entropy coordinates *A* and *B*. The transformation model was developed by regression analysis of laboratory test data from 30 grading curves, developed within a well-defined single grading envelope (Feng *et al.* 2019). The research detailed in Feng *et al.* (2019) was specifically aimed at evaluating performance of paving materials. The proposed transformation model was then modified by O'Kelly and Nogal (2020) to account for the density of the material by introducing the void ratio term (see also Feng *et al.* 2020).

The deposition of the hydraulic fill has considerable influence on the particle segregation and re-packing resulting in a heterogeneous hydraulic fill mass with variable densities and permeability over its full depth. This makes the prediction of void ratios after deposition very difficult, as it would need to also consider the hydraulically charged sub-layers of fill due to the subaqueous and subaerial methods of deposition, and the hydrogeological conditions of the site. This suggests, for this preliminary study, the statistically derived transformation models proposed by Feng *et al.* (2019) can be more readily adopted to test the applicability of the grading entropy approach to estimate the coefficient of permeability of the hydraulic fill mass. The transformation models developed in Feng *et al.* (2019, 2020) are given as Eqs. 3 to 5:

$$k_{20°C}\ (mm/s) = 509.13A^{11.78} \quad [R^2 = 0.83, n = 30, p < 0.0001] \tag{3}$$

$$k_{20°C}\ (mm/s) = 9.92B^{-5.38} \quad [R^2 = 0.63, n = 30, p < 0.0001] \tag{4}$$

$$k_{20°C}(mm/s) = 145.47A^{8.90}B^{-2.30} \quad [R^2 = 0.90, n = 30, p < 0.0001] \tag{5}$$

where: $k_{20°C}$ is the coefficient of permeability (mm/s) at a permeant test temperature of 20°C, A and B are the normalised grading coordinates (as defined in Eqs 1 and 2), R^2 is the coefficient of determination, n is the number of data points used to develop the transformation model and p is the p-value.

3 GRADING ENTROPY APPLICATION TO HYDRAULIC FILL MASS

3.1 Sand Fill Types

Five sand fill types have been selected for this study. These were obtained from published case study reclamation projects reported in the literature. These are reported in Table 1 alongside the source, description, and summary properties of each fill type. The gradation envelopes for each sand fill type as defined in the original publications are presented in Figure 1 and compared with the gradation range of the mixtures presented in Feng *et al.* (2019). The gradation envelope for some fill types depicts the sand fill ‘at source’ (Palm Jumeirah, Changi Airport, Chek Lap Kok) whilst for others, it was determined from classification tests on samples obtained from the reclaimed area (Maasvlakte II, West Kowloon). To simulate the possible change of gradation after deposition, two additional grading curves were drawn within the gradation envelopes. The additional gradings are described as ‘Mean’ and ‘Gap’, whilst the minimum and maximum grading envelopes are described as lower and upper bound, respectively. The ‘Mean’ grading curve has been determined as the median Particle Size Distribution (PSD) within the envelope, while the ‘Gap’ grading curve was a simulated curve transiting from the upper to the lower bound PSD at 50% passing. The resulting grading curves are presented in Figure 2.

Table 1. Description, properties and source of sand fill materials for the five case studies reviewed in this paper

Case Study Ref.	Sand fill characteristics					Source
	Fill Description	Particle Shape	Fines Content (%)	Coeff. of Uniformity (C_u)	Coeff. of Curvature (C_z)	
Palm Jumeirah, Dubai, UAE	Very variable highly cemented shelly carbonate sand	Angular (with shell fragments)	10	4.8	0.74	Lees *et al.* (2013)
Maasvlakte II, the Netherlands	Quartz sand of marine origin	Sub-angular	8-10	2.2-2.5	--	Vessies (2012)
Changi Airport, Singapore	Poorly graded quartz sand of marine origin	--	10	2.063	0.976	Chua *et al.* (2007)
Chek Lap Kok, Hong Kong	Uniformly to well-graded quartz sand of marine origin	Rounded to sub-rounded	< 12	4.5	0.9	Lee (2001)
West Kowloon, Hong Kong	Quartz sand of marine origin	Sub-angular to sub-rounded	< 1	6.4	0.42	Lee *et al.* (1999)

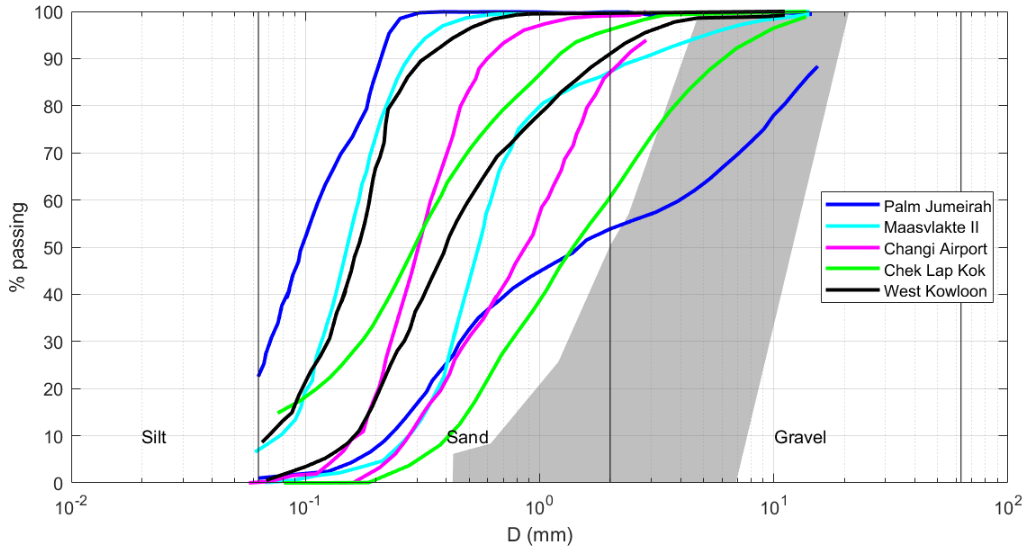

Figure 1. Selected sand fill gradation envelopes (data digitised and taken from Lee *et al.* 1999, Lee 2001, Chua *et al.* 2007, Vessies 2012 and Lees *et al.* 2013) (gradation bounds of the material tested in Feng *et al.* 2019 are shown as the shaded zone).

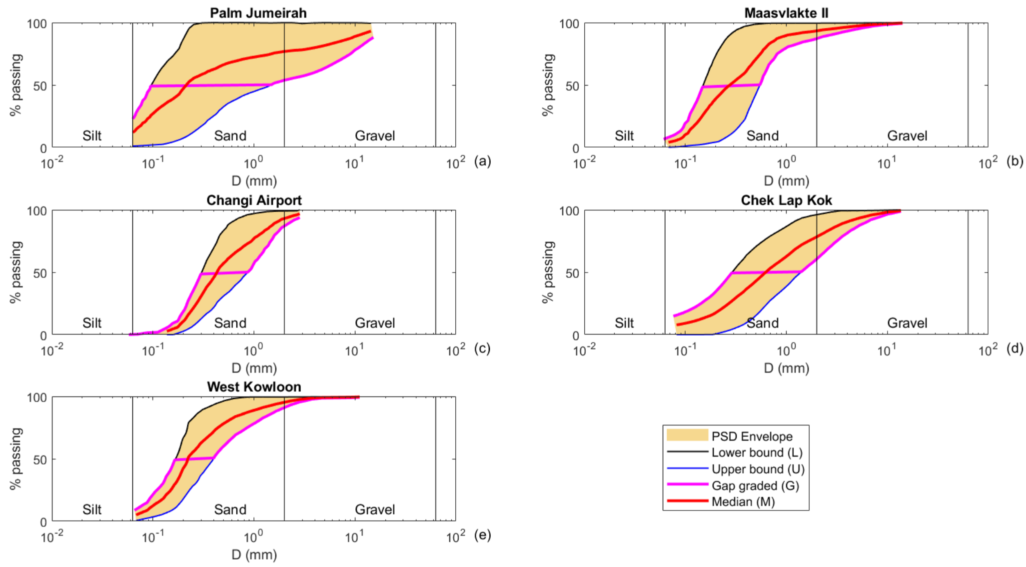

Figure 2. Grading mixes for each sand fill type.

3.2 Entropy Coordinates for Selected Sand Fill Types

By considering four gradings for each sand fill type, a total of twenty gradings were available for the analysis. Figure 3 shows each of the twenty PSDs represented as a point on the normalised grading entropy diagram. The points representing the PSDs for each sand fill type are illustrated in the same colour as given in the legend. Most of the points are concentrated within the central region around A = 0.5 with a few points extending beyond the A = 2/3 boundary. Concentration around A = 0.5 generally points to the general uniformity of grain size distribution, with those extending beyond the A = 2/3 boundary reflecting the coarser materials. A limited number of points are located to the left of $A \approx 0.4$, potentially reflecting fine materials, notably most of the West Kowloon sand fill grading curves.

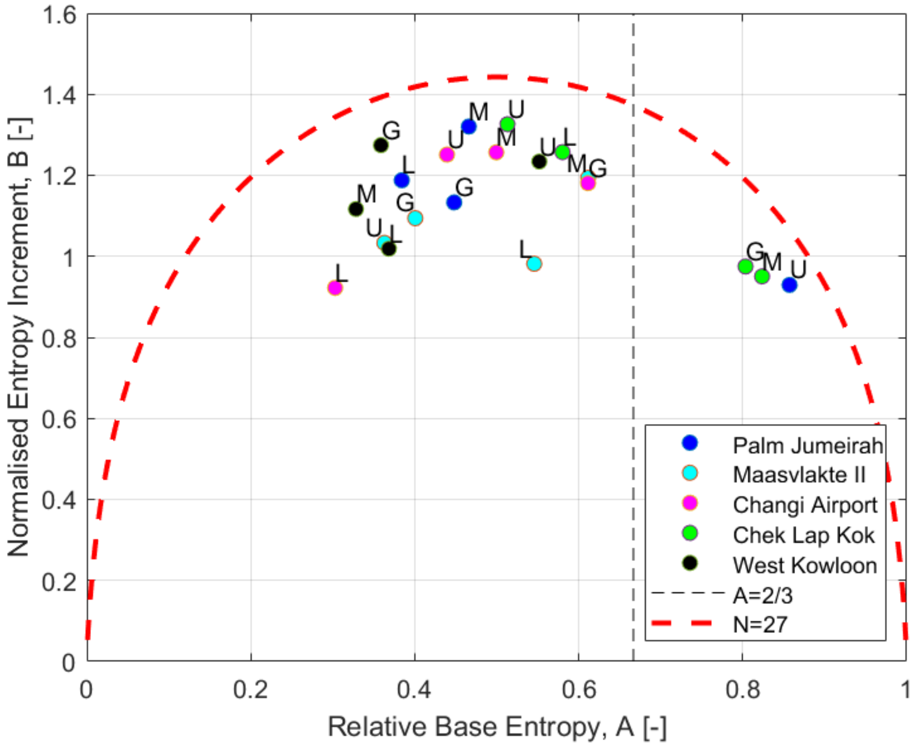

Figure 3. Gradation of sand fill mixes plotted as individual points on the normalised grading entropy diagram (L = lower bound, U = upper bound, G = gap graded and M = median).

4 ANALYSIS AND DISCUSSION

4.1 Coefficient of permeability

Table 2 shows the predicted permeability coefficients obtained by means of entropy coordinates, using Eqs. 3 to 5. The published measured coefficients of permeability available in the literature for some of the sand fill types considered in this analysis are also included in Table 2. It should be acknowledged that these values of the permeability must be treated with caution and taken as indicative only, since details of the testing procedures (testing method and sample conditions) were not explicitly provided in the original sources. If further information becomes available regarding the reported values of the coefficient of permeability from the reviewed case studies, then some of the observations outlined in this paper may change.

A key observation is that the predicted permeability coefficients by means of the relative base entropy only (Eq. 3) and by means of both entropy coordinates A and B (Eq. 5) generally fall within the measured permeability coefficients for Palm Jumeirah, except for the upper bound gradation curve where the predicted coefficients of permeability fall outside the measured range and appear much higher than the reported upper limit of coefficient of permeability values. This may be attributed to both the high coarse sand and gravel percentage content for the upper bound PSD curve and to the high initial void ratio reported for this carbonate sand fill type (Lees *et al.* 2013). The latter may, in turn, have been manifested in the measured low coefficient of permeability, because of the high shell fragments contents known to be susceptible to crushing. Interestingly, however, is that the opposite is observed between the reported measured and predicted coefficient of permeability values for the West Kowloon sand fill; whilst for Chek Lap Kok the predicted permeability values are broadly the same or higher.

Although the predicted values of the coefficient of permeability by Eqs. 3 and 5 broadly agree with those measured for some gradation curves, the distinct variation observed for other gradations may be attributed to the fact that the relationships proposed by Feng *et al.* (2019): (i) were based on a sand mixture within a single grading envelope, (ii) were developed for evaluation of road paving materials; and (iii) were based on laboratory prepared samples subjected to laboratory testing. Nonetheless, the results of the predicted coefficient of permeability demonstrate the potential change of the coefficient of permeability for each gradation curve when correlated with the entropy coordinates, thus, highlighting the potential influence of the evolution of gradation after deposition and re-packing on the coefficient of permeability of the hydraulic fill mass.

Table 2. Predicted permeability coefficient compared with reported values for the selected sand fill types

Case Study Ref.	Grading Curve	Relative Base Entropy	Normalised Entropy Increment	Predicted Coefficient of Permeability, k_p			Reported Coefficient of Permeability, k_r
		A [-]	B [-]	k_p (Eq. 3) [mm/s]	k_p (Eq. 4) [mm/s]	k_p (Eq. 5) [mm/s]	k_r [mm/s]
Palm Jumeirah	Lower	0.38416	1.18775	6.5×10^{-3}	3.9	2.0×10^{-2}	4×10^{-4} to 5×10^{-2} (Lees *et al.* 2013)
	Upper	0.85715	0.92943	83	15	44	
	Median	0.46590	1.32038	6.3×10^{-2}	2.2	8.6×10^{-2}	
	Gap	0.44810	1.13315	4.0×10^{-2}	5.1	8.6×10^{-2}	
Chek Lap Kok	Lower	0.58024	1.25734	8.4×10^{-1}	2.9	6.8×10^{-1}	0.9×10^{-1} to 2.3×10^{-1} (Lee 2001)
	Upper	0.51307	1.32613	2.0×10^{-1}	2.2	2.0×10^{-1}	
	Median	0.82362	0.95059	52	13	29	
	Gap	0.80345	0.97503	39	11	22	
West Kowloon	Lower	0.36846	1.01886	4.0×10^{-3}	9.0	1.9×10^{-2}	5.6×10^{-2} to 1.4×10^{-2} (Lee *et al.* 1999)
	Upper	0.55195	1.23396	4.6×10^{-1}	3.2	4.5×10^{-1}	
	Median	0.32832	1.11677	1.0×10^{-3}	5.5	5.6×10^{-3}	
	Gap	0.35878	1.27436	2.9×10^{-3}	2.7	9.1×10^{-3}	

4.2 Liquefaction Potential

According to Barreto *et al.* (2019), the internal stability criterion of sand mixtures in terms of the grading entropy coordinates can be defined in the partly normalised grading entropy diagram as shown in Figure 4, where the region left of the $A = 2/3$ boundary is classified as 'unstable' whilst the region to the right of the same line is classified as stable (or transitionally stable). Barreto *et al.* (2019) presented their database of liquefied soils on the normalised grading entropy diagram. The grading entropy points for the fill types suggest that generally most of the sand fill types fall in the unstable conditions with only the PSDs with larger grain size such as the upper bound for Palm Jumeirah and the Median and Gap for Chek Lap Kok fall in the stable quadrant. This suggests the influence of change of gradation on the liquefaction potential of the hydraulic fill mass and the potential need for ground improvement to counter potential liquefaction of both the bearing strata and the hydraulic fill mass after deposition. The results also show that the grading entropy framework has the potential to assist with understanding the liquefaction potential of the sand fill at source and after deposition due to potential change in gradation during the placement process.

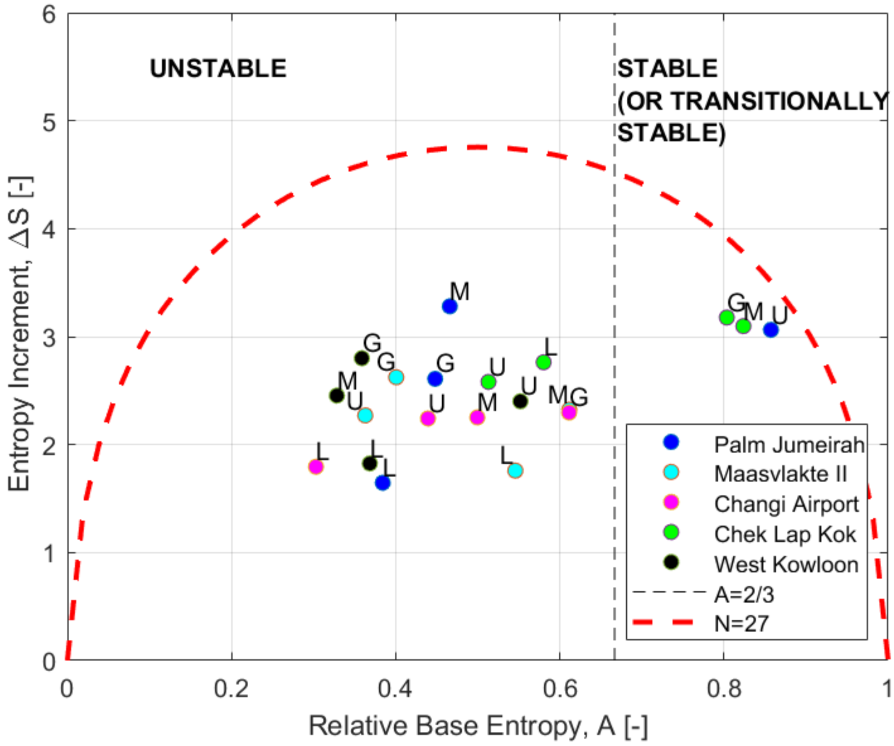

Figure 4. Stability of the sand fill types against liquefaction plotted on the (partly) normalised grading entropy diagram (L = lower bound, U = upper bound, G = gap graded and M = median) (plot design based on Barreto *et al.* 2019).

5 CONCLUDING REMARKS

This preliminary study has shown that the grading entropy framework can be used along with the transformation models from Feng *et al.* (2019) to make reasonable predictions of the coefficient of permeability of the hydraulic fills reviewed in this paper. Further research is recommended to support this finding using a wider range of hydraulic sand fill gradation, taking in consideration the influence of method of placement on potential particle segregation, erosion, and volume change of the hydraulic fill mass. Liquefaction potential of hydraulic fills may also be potentially assessed using the grading entropy framework as suggested by Barreto *et al.* (2019).

DATA AVAILABILITY STATEMENT

This study has not generated new experimental data.

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REFERENCES

Arshad, M., Nazir, M.S. and O'Kelly, B.C. (2020). Evolution of hydraulic conductivity models for sandy soils. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **173(2):** 97-114.

Barreto, D., Leak, J., Dimitriadi, V., McDougall, J., Imre, E. and Lőrincz, J. (2019). Grading entropy coordinates and criteria for evaluation of liquefaction potential. In: Silvestri, F. and Moraci, N. (eds.), *Earthquake*

Geotechnical Engineering for Protection and Development of Environment and Constructions: Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering, (ICEGE 2019), June 17-20, 2019, Rome, Italy. Leiden, The Netherlands: CRC Press/Balkema*,* pp. 1346-1353.

Boumendjel-Game, O., Diambra, A. and Vardanega, P.J. (2023). Commentary on the art & science of hydraulic filling. *17th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, accepted for publication.

Chua, L.H.C., Lo, E.Y.M., Freyberg, D.L., Shuy, E.B., Lim, T.T., Tan, S.K. and Ngonidzashe, M. (2007). Hydrostratigraphy and geochemistry at coastal sandfill in Singapore. *Hydrogeology Journal* **15(8):** 1591-1604.

Feng, S., Vardanega, P.J., Ibraim, E., Widyatmoko, I. and Ojum, C. (2019). Permeability assessment of some granular mixtures. *Géotechnique* **69(7):** 646-654.

Feng, S., Vardanega, P.J., Ibraim, E., Widyatmoko, I., Ojum, C., O'Kelly, B.C. and Nogal, M. (2020). Discussion: Permeability assessment of some granular mixtures. *Géotechnique* **70(9):** 845-847.

Feng, S., Vardanega, P.J., James, M. and Ibraim, E. (2021). Studying hydraulic conductivity of asphalt concrete using a database. *Transportation Engineering*, **3:** [100040].

Kolman, R. & van 't Hoff, J. (2013). Port Expansion through land reclamation. *Port Technology International* **58:** 26-28.

Lee, K.M. (2001). Influence of placement method on the cone penetration resistance of hydraulically placed sand fill. *Canadian Geotechnical Journal* **38(3):** 592-607.

Lee, K.M., Shen, C.K., Leung, H.K. and Mitchell, J.K. (1999). Effects of placement method on geotechnical behavior of hydraulic fill sands. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* **125(10):** 832-846.

Lees, A., King, D.A. and Mimms, S. (2013). Palm Jumeirah, Dubai: cone penetrometer testing data from carbonate sand fill. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **166(3):** 253-267.

Lőrincz, J. (1990). Relationship between grading entropy and dry bulk density of granular materials. *Periodica Polytechnica Civil Engineering* **34(3):** 255-265.

Lőrincz, J., Imre, E., Gálos, M., Trang, Q.P., Rajkai, K., Fityus, S. and Telekes, G. (2005). Grading entropy variation due to soil crushing. *International Journal of Geomechanics (ASCE)* **5(4):** 311-319.

Lőrincz, J., Imre, E., Trang, Q.P. and Fityus, S. (2015). Grading entropy and degradation of sands and rocks. In: *Proceedings of the 2nd International Electronic Conference on Entropy and Its Applications, 15–30 November 2015.* Basel, Switzerland: Multidisciplinary Digital Publishing Institute*.* 9pp.

McDougall, J.R., Kelly, D. and Barreto, D. (2013a). Particle loss and volume change on dissolution: experimental results and analysis of particle size and amount effects. *Acta Geotechnica* **8(6):** 619-627.

McDougall, J.R., Imre, E., Barreto, D. and Kelly, D. (2013b). Volumetric consequences of particle loss by grading entropy. *Géotechnique* **63(3)**: 262-266.

O'Kelly, B.C. and Nogal, M. (2020). Determination of soil permeability coefficient following an updated grading entropy method*. Geotechnical Research* **7(1):** 58-70.

Phoon, K-K. and Kulhawy, F.H. (1999a). Characterization of geotechnical variability. *Canadian Geotechnical Journal* **36(4):** 612–624.

Phoon, K-K. and Kulhawy, F.H. (1999b). Evaluation of geotechnical property variability. *Canadian Geotechnical Journal* **36(4):** 625–639.

Shannon, C.E. (1948). A mathematical theory of communication. *Bell System Technical Journal* **27(3):** 379-423.

Singh, V.P. (2014). *Entropy Theory in Hydraulic Engineering: An Introduction*. Reston, VA, USA: American Society of Civil Engineers.

van Ginkel, M. and Olsthoorn, T.N. (2019). Distribution of grain size and resulting hydraulic conductivity in land reclamations constructed by bottom dumping, rainbowing and pipeline discharge. *Water Resources Management* **33(3):** 993-1012.

van 't Hoff, J. and van der Kolff, A.N. (eds.) (2012). *Hydraulic Fill Manual: For Dredging and Reclamation Works*. Leiden, The Netherlands: CRC Press/Balkema.

Vessies, W.C.N. (2012). Relative density differences of a sand fill. *M.Sc. thesis*, Delft: The Netherlands: Delft University of Technology.