Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 17ecsmge-2019-Y-XXXX

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Influence of the momentum and the energy on the performance of dynamic compaction technologies – recent field and laboratory tests

Influence de l'impulsion et de l'énergie sur la performance du compactage dynamique - essais récents sur le terrain et en laboratoire

A. Knut
Leipzig UAS, Leipzig, Germany

R. E. Ocaña Atencio, F. Sandig, H. Pankrath, R. Thiele
Leipzig UAS, Leipzig, Germany

J. Kirstein
MENARD GmbH, Seevetal, Germany

ABSTRACT: This article presents recent field investigations with dynamic compaction technologies. Beside the area of the falling weight, the depth of the crater of dynamic compaction technologies can only be influenced by the technical parameters falling mass and falling height. Because both parameters influences the kinetic energy and the momentum of the falling weight a detached analysis of these two technical parameters is not possible. However a detached analysis of the influence of momentum and kinetic energy is possible and presented herein. Within the investigation the momentum or the kinetic energy was kept constant respectively and the other parameter was varied. Two different falling weights (3800 kg, 7100 kg) with the same geometry were used. Using these falling weights four combinations of falling mass and falling height were investigated. The momentum and the kinetic energy was controlled by measuring the impact velocity with two accelerometers attached on the falling weight. The depth of the crater was measured by precision levelling after 12 impacts. To reduce the influence of the soil the test site was especially build in layers by using approximately 2.500 m³ of well graded gravel. We found that the kinetic energy has no distinct influence on the depth of the crater. In other words: increasing the kinetic energy does not necessarily increase the depth of the crater while increasing the momentum does. The results of the field test proof the results of our 1g model tests evaluated with the PIV method.

RÉSUMÉ: Cet article présente des études récentes sur le terrain portant sur les technologies de compactage dynamique. Outre la zone de chute de poids, la profondeur d'amélioration des technologies de compactage dynamique ne peut être influencée que par les paramètres techniques de chute de masse et de hauteur de chute. Comme ces deux paramètres influencent l'énergie cinétique et l'impulsion de la chute de poids, une analyse séparée de ces deux paramètres techniques n'est pas possible. Cependant, une analyse détachée de l'influence de l'énergie impulsionnelle et cinétique est possible et présentée ici. Au cours de l'enquête, l'impulsion ou l'énergie cinétique a été maintenue constante et l'autre paramètre a été modifié. Deux poids de chute différents (3800 kg, 7100 kg) avec la même géométrie ont été utilisés. À l'aide de ces poids tombants, quatre combinaisons de chute de masse et de hauteur de chute ont été étudiées. L'impulsion et l'énergie cinétique ont été contrôlées en mesurant la vitesse d'impact à l'aide de deux accéléromètres fixés sur la masse tombante. La profondeur du cratère a été mesurée par nivellement de précission après 12 impacts. Pour réduire l'influence du sol, le site d'essai a été spécialement construit en couches en utilisant environ 2.500 m³ de gravier bien nivelé. Nous avons constaté que l'énergie cinétique n'a pas d'influence distincte sur la profondeur du cratère. En d'autres termes : augmenter l'énergie cinétique n'augmente pas nécessairement la profondeur du cratère tout en augmentant la dose d'impulsion. Les résultats de l'essai sur le terrain prouvent les résultats de nos essais sur modèle 1g évalués avec la méthode PIV.

Keywords: dynamic compaction, momentum, energy, performance, crater depth

1 INTRODUCTION

This article relates to the influence of the momentum and the kinetic energy on the performance of dynamic compaction technologies. Dynamic compaction induces high energy blows into the soil by heavy tampers which are dropped from heights longing from 10 to 40 m (Kirstein et al. 2016). Physically this kind of soil densification is an inelastic collision between the tamper and the soil. This inelastic process is described by the law of energy and momentum conservation:

$$p = p' \tag{1}$$

$$E = E' + \Delta U \tag{2}$$

The momentum of the system p (for example the tamper) before and during the impact is always the momentum of the system p' (for example the soil), whereas the energy E of the tamper splits to kinetic energy in the soil E' (e.g. elastic wave propagation) and plastic deformation or heat ΔU. The only conserved quantity in such an inelastic process is the momentum. Contrary to this the performance of this technology is described in terms of the potential energy of the falling weight lifted in a specific height. Which raises the question of whether the energy is the right quantity to describe the performance of soil densification of such processes.

Poran investigated the depth of soil densification in scaled model tests and postulates a relationship between the sum of the normalized potential energy and the normalized depth of improvement. (Poran et al. 1992)

Lukas evaluates field data and postulates a relationship between the empirical formula presented in (Menard et al. 1975) for the estimation of the depth of improvement $DI = \alpha\sqrt{WH}$ and the potential energy of the falling weight. (Lukas 1986), (Lukas 1995)

Hajialilue-Bonab evaluates the field of deformation of a fine dry sand with the PIV/DIC-method (Particle Image Velocimetry / Digital Image Correlation). Beside the depth of improvement, also the depth of the crater is investigated. It was suggested, that the depth of the crater can be fitted according to a logarithmic law. Also the depth of the crater is in a linear relationship with the measured depth of improvement. Furthermore he postulates that the depth of the crater increases with an increase in the energy applied to the soil. However, this assumption must be critically scrutinised because the momentum of the compared impacts was not constant. (Hajialilue-Bonab et al. 2009)

Furthermore several filed surveys investigated possible parameters describing soil densification (Kopf and Paulmichl 2005), (Adam et al. 2011). Other field surveys are focused on the validation of numerical models (Kirstein et al. 2016).

An experimental study focused on the influence of the momentum and the energy of the tamper with respect to the depth of the crater is not done yet.

Within this article we present results of scaled laboratory investigations using the PIV/DIC-method in the field of gravity. Furthermore an attending field investigation concerning this question is presented.

2 METHOD

2.1 Laboratory Investigation

The setup of the laboratory investigation is shown in Figure 1 schematically. The soil specimen was made of regional dry sand and is prepared by air raining. The used raining method is presented more into detail in (Trudeep et.al. 2012). The used Material is described properly in (Knut et al. 2017). The dimensions of the specimen were 880 x 620 x 400 mm (length x height x width). With this method of sample preparation the initial density of the specimen was ϱ_0 = 1.62 g/cm^3.

A sheet made of PMMA (Poly(methyl methacrylate) or acrylic glass) on one side of the container allows an insight into the soil during compaction. The sheet has a thickness of 20 mm to reduce its deflection. The impacts are applied by a guided, half-round tamper falling close to the PMMA. The mass, diameter and falling height of the tamper can be varied within our experimental setup.

A high speed camera (PCO.dimax HS4) recording at 1600 fps (frames per second) captures the deformation of the soil during the process of compaction. The camera is calibrated prior to the experiment to calculate the intrinsic and extrinsic camera parameters. The images are processed with the PIV/DIC-method using the commercial software ISTRA4D. The PIV/DIC-method calculates the field of displacement by a cross-correlation algorithm which compares discrete regions of the picture pair-by-pair. The method is well established in physical modelling of geotechnical applications and described into detail in (White et al. 2003) or (Take 2015).

A uniaxial acceleration transducer gather the kinematic behaviour of the tamper prior and during the impact. The acceleration is measured with a sampling rate of 10 kHz and low-pass filtered with a cut off frequency of 100 Hz. Thus the behaviour of the soil and the tamper are captured synchronously, it is possible to investigate its interdependency. Because the momentum and the kinetic energy relates to the velocity it is necessary to calculate the velocity from the unfiltered signal of the acceleration transductors according to equation (3)

$$\boldsymbol{v_i}(t) = \int \boldsymbol{a_i}(t)dt + \boldsymbol{v_0} \tag{3}$$

The resulting parameter of the laboratory investigation presented in this article is the depth of the crater z_c^i (mm). The depth of the crater with respect to the soil surface is the lowest point of the falling weight before the falling weight is lifted for the next drop. The depth of the crater is measured with the described PIV/DIC-method and validated with the calculated translation of the tamper measured with the acceleration transductor.

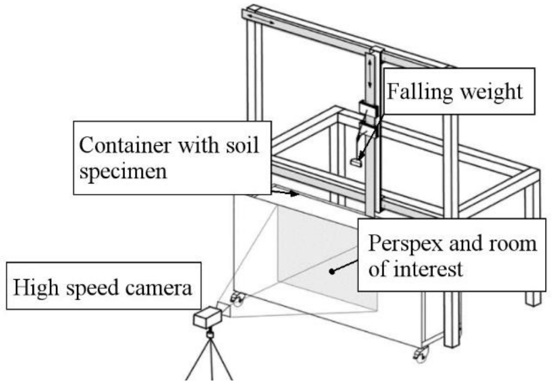

Figure 1. Schematically setup of the laboratory investigation.

Figure 2. Test site and used crawler crane in the field investigation.

2.2 Field Investigation

The test site and the used crawler crane are shown in Figure 2. The test site was made of well graded gravel with a water content of 5% and a thickness of 4 m on a more than 6 m thick layer of pre compacted loess. The necessary thickness of the layer of gravel was estimated with a numerical simulation. It is believed, that the influence of this sublayer is negligible small. The test site was built with approximately 2.500 m³ of material in as possibly loose conditions especially for this investigation. During the earthwork the density and the water content of the gravel was monitored in each layer to ensure the quality of the investigation. Also a lot of material and data was gathered to investigate all necessary soil mechanical properties for further numerical simulations. The mean initial dry density of the prepared test site was ϱ_0 = 1.58 g/cm³.

Two rectangular tampers made of concrete with a mass of 3.800 kg and 7.100 kg were used for the investigation. The edge length of both tamper was 1.5 m. We observed 12 impacts with different falling heights.

Two acceleration transductors, each measuring in three axes were attached on the tamper. The signal of the acceleration transductor, measuring at 10 kHz, was low-pass filtered with a cut off frequency of 100 Hz. The impact velocity, was calculated from the signals of the acceleration transductors according to equation (3). As presented in section 2.3.2 the height of fall was adjusted to ensure that the momentum and the kinetic energy was constant for each configuration.

The depth of the crater z_c^i was measured with a high precision levelling instrument after the sixth and twelfth impact.

2.3 Experimental Setup

2.3.1 Influence of the falling height

The detached examination of the mass *m* (kg) of the tamper and the falling height *h* (m) is not possible, because according to equations (4) and (5) both are part of the momentum *p* (Ns) and the kinetic energy *E* (J).

$$\boldsymbol{p} = m\,\boldsymbol{v} \tag{4}$$

$$\boldsymbol{E} = \frac{1}{2} m\,\boldsymbol{v}^2 = \frac{\boldsymbol{p}^2}{2\,m} \tag{5}$$

However, the falling height can be reduced by applying an artificial acceleration a on the tamper as shown in figure 3. The artificial acceleration is applied by a loaded spring which increases the velocity of the tamper. To investigate the tamper without effects of inertia the artificial acceleration must be removed before impact happens.

The variations of the drop height are shown in table 1. In the table, *m* (kg) corresponds to the mass of the tamper, *h* (m) to the falling height and *v* (m/s) to the impact velocity according eq. (3).

With this method it is possible to vary the falling height with otherwise constant momentum and kinetic energy. The impact velocity is therefore constant despite the lower drop height. Thus it is possible to investigate a technical parameter with otherwise constant kinematic boundary conditions.

Table 1. Variation in the falling height by the application of an artificial acceleration.

m (kg)	h (m)	v (m/s)	p (Ns)	E (J)
4.80	0.50	3.23	**15.50**	**25.03**
4.96	0.30	3,13	**15.50**	**24.30**
4.96	0.00	3.13	**15.50**	**24.30**

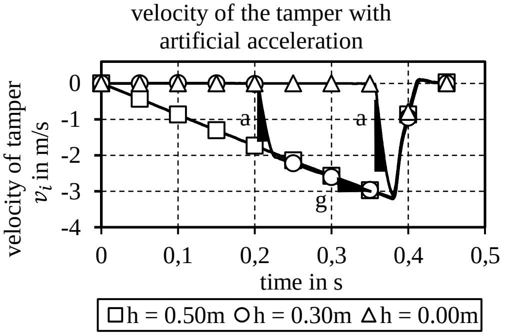

Figure 3. The velocity of the tested configurations.

2.3.2 Influence of the momentum and the kinetic energy

The detached influence of the momentum and the kinetic energy is investigated in a laboratory study and a field survey.

The corresponding variations of the mass of the tamper and the falling height are shown in table 2 for the laboratory studies and the field test respectively. The impact velocity was calculated using equation (3) presented in section 2.1. Due to friction (either on the guide in the laboratory or on the rope in the field), the measured impact velocity is lower than that which would result from the potential energy.

In table 2 the kinematic parameter (momentum or energy) which is kept constant is marked bold.

The geometric boundary conditions (diameter or edge length respectively) were constant. Thus this experimental setup investigates just the influence of the momentum and the kinetic energy of the falling weight.

Table 2. Variation in the mass of the tamper and the falling height used in the laboratory with the aim of a constant energy and momentum.

Laboratory investigation

m (kg)	**h (m)**	**v (m/s)**	**p (Ns)**	**E (J)**
7.09	0.85	3.60	26.15	**48.22**
4.96	1.20	4.40	21.87	**48.21**
7.09	1.00	3.77	**26.73**	50.38
6.12	1.35	4.38	**26.81**	58.70
4.96	2.00	5.40	**26.78**	72.32

Field investigation

m (t)	**h (m)**	**v (m/s)**	**p (kNs)**	**E (kJ)**
3.80	3.80	5.33	20.27	**54.00**
7.10	3.00	3.75	26.63	**49.92**
7.10	3.80	4.47	**31.74**	70.95
3.80	9.50	8.09	**30.72**	124.20

3 RESULTS

3.1 Influence of the falling height

The results of the investigation of the influence of the falling height at the same momentum and kinetic energy of the tamper are shown in figure 4. The depth of the crater z_c^i was related to the diameter of the drop weight according to the statements presented in (Poran 1992) in order to reduce scaling effects. Despite the reduction of the drop height, the depth of the crater does not change significantly. The range of variation of ±1.75% is in the range of the measurement error of the used method (Knut et al. 2017).

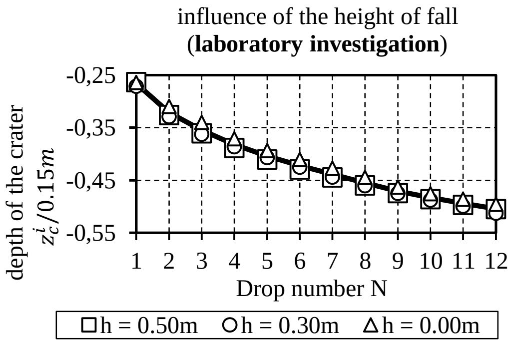

Figure 4. The depth of the crater according to the experimental setup presented in table 1

3.2 Influence of the momentum and the kinetic energy

The results of the laboratory investigation and field survey according to table 2 are shown in figure 5. The relative change of the depth of the crater after 12 impacts was chosen as the result variable:

$$rz_c^i = \frac{z_c^i}{z_c^{min}} \tag{5}$$

Wherein rz_c^i (%) is the relative change of the depth of the crater z_c^i (m) related to the smallest crater of the configuration z_c^{min} (m). The normalization was done to discuss the qualitative influence of momentum and energy and not absolute depths of the crater.

The diagrams show the curves for a constant energy and momentum level respectively. The solid lines are showing the influence of the momentum on the relative depth of the crater with a constant kinetic energy for the laboratory investigation and the filed survey respectively. The dashed lines are showing the influence of the kinetic energy on the relative depth of the crater with a constant momentum applied in the field survey and in the laboratory.

In the laboratory, as well as in the field, it can be observed that the depth of the crater increases with increasing momentum. The relative increase of the relative depth of the crater in the laboratory is 125%, with an increase of the momentum by 4.3 Ns. In the field survey, a 165% greater depth of the crater was found with a 6.35 kNs magnification of the momentum.

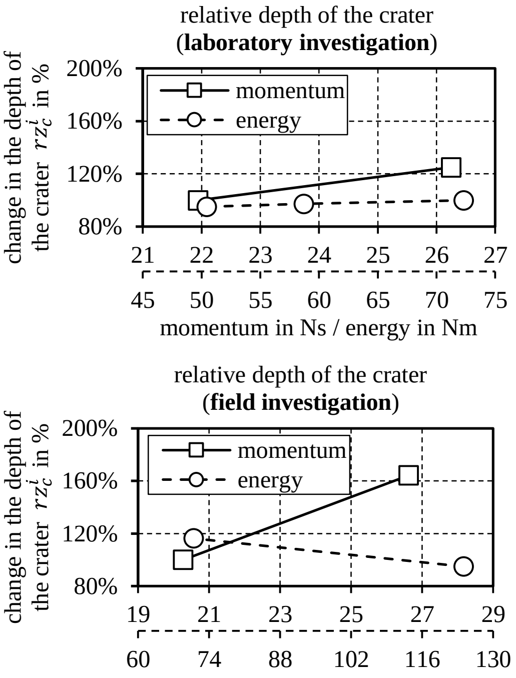

Figure 5. The relative depth of the crater measured in the laboratory (top) and in the field (bottom) according to the experimental setup of table 2.

If the momentum is kept constant and the energy is increased, the result is contrary. Concerning the laboratory investigation, an increase of the kinetic energy before the impact occurs does not significantly increase of the depth of the crater. Despite an magnification of 21.86 J in the impact energy, the relative depth of the crater only increases by 103% of the minimum value and is therefore within the range of the measurement error of the method used (Knut et.al. 2017).

The results of the field investigation shows similarity. An increase of 53.25 kJ causes an apparent change of 114% in the depth of the crater. However, the momentum of the comparison variants (see table 2) was not exactly the same. The difference was 1.02 kNs. Due to the high sensitivity of the depth of the crater to the momentum, it can be assumed that the higher depth of the crater is due to this slight difference in the momentum.

4 DISCUSSION

4.1 Influence of the falling height

The experimental study on the influence of the falling height on the depth of the crater shows two results. Firstly, it is obvious that the falling height has no influence on the depth of the crater as long as the momentum and the kinetic energy between the variants are the same just before the impact occurs. This leads to the second conclusion, that all conceivable methods to achieve a certain momentum and energy level before the impact will lead to the same depth of the crater after the impact. Which means neither the falling height nor the mass of the tamper characterizes the efficiency of dynamic compaction correctly because both relate to the momentum and the kinetic energy. The following section discusses whether the momentum or the kinetic energy has greater influence on the depth of the crater.

4.2 Influence of the momentum and the kinetic energy

It could be shown in the laboratory as well as in a field survey that the depth of the crater depends significantly on the momentum. The introductory thesis that the efficiency of dynamic compaction should be describe with respect to the momentum is supported by the results presented in section 3.2. A variation of the kinetic energy with a constant momentum shows no relevant increase of the depth of the crater neither in the laboratory nor in the field.

The assumption that the depth of the crater is influenced by the kinetic energy made in (Hajialilue-Bonab et al. 2009) could not be reproduced. Because the momentum within the investigation presented in (Hajialilue-Bonab et al. 2009) was not constant the authors suggest that not the energy but the momentum causes the increase in the depth of the crater. This suggestion is supported by the results presented in this article.

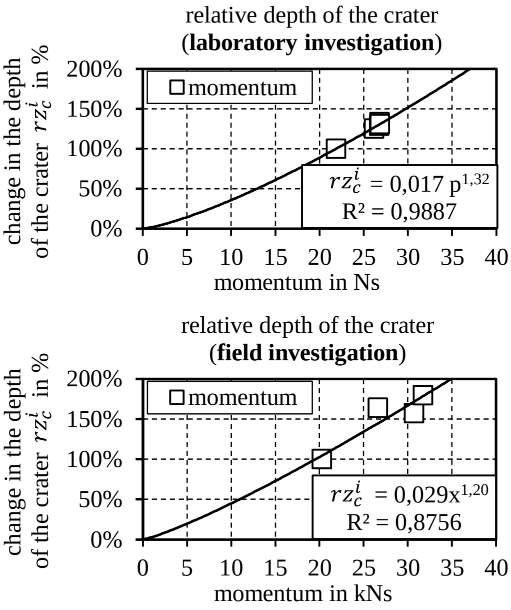

Figure 6. The relative depth of the crater according to the experimental setup presented in table 2 and fitted with the function (6)

As determined in the field and in the laboratory, the depth of the crater depends on the momentum. Therefore, the depth of the crater can be fitted regarding the momentum. On the basis of the data, a polynomial with the boundary condition $rz_c^i(p = 0) = 0$ and the form:

$$rz_c^i(\mathrm{p}) = m\, p^n \tag{6}$$

could be used. The result of this attempt is presented in figure 6. The coefficient of determination of the fit for the laboratory investigation as well as for the field survey is high. In spite of the fact that the measuring points partly showing significantly different energy levels, the depth of the crater can be estimated with the simple polynomial function depending on the momentum. This underpins the assumption that the depth of the crater is more sensitive to the momentum then on the kinetic energy of the tamper.

4.3 Practical relevance

The relevance of this thesis will be conclusively substantiated by a practical example. A heavy tamper with a mass $m_0 = 10t$ is dropped from a height $h_0 = 20.4m$. The energy required to lift the drop weight is approximately 2000 kJ. The momentum at the impact of the tamper is 200 kNs assuming no friction. According to the assumption that the depth of the crater is dominated by the momentum other tampers with the mass m must reach the same depth of the crater when they are lifted to the height h

$$h = \left(\frac{m_0}{m}\right)^2 h_0 \tag{7}$$

To reach the same depth of the crater a tamper with the mass of 20t must be lifted only 5.1m. The effort for lifting the tamper is reduced to 1000 kJ. The fact that the heavy drop weight has to be lifted 15m less increases the efficiency even further.

5 CONCLUSION

It could be shown that all conceivable methods for the achievement of a certain energy and momentum rivet must lead to the same depth of the crater on granular dry material. With a simple polynomial fit it could be shown that the momentum of the tamper is the dominating parameter for the characterization of the depth of the crater.

The energy is a suitable parameter to describe the mechanical process of lifting the tamper and thus allows an estimation of the mechanical effort for the crawler crane (e.g. fuel consumption, lifting time). As soon as the drop weight touches the ground, however, the momentum is the more suitable descriptor.

This finding should give an impetus to the design of any compaction process that can be described as an inelastic impact process. Not the energy, but the momentum determines the depth of the crater.

Ongoing research must be made on the relation of the depth of the crater and the depth of improvement, because depending on soil conditions small craters can be linked to deep improvements.. Also the theory presented herein should be underpinned by more field investigations.

6 ACKNOWLEDGEMENT

The research reported in the paper was funded by the BMWi (MF150157) and by the authors doctoral studies grant funded by the ESF.

7 REFERENCES

Adam, D., Paulmichl, I., Kopf, F., Erdmann, P. 2011. Integrierte Verdichtungskontrollen bei dynamischen Verdichtungsverfahren. *Baugrundverbesserung in der Geotechnik* (Eds. Adam D., Herrmann R. A.). 135–159 Eigenverl. des Inst. für Geotechnik, Siegen.

Hajialilue-Bonab, M., Rezai, A.H. 2009. Physical Modelling of Low-Energy Dynamic Compaction. *Journal of Physical Modelling in Geotechnics* **3**: 21–32.

Kirstein, J., Grabe, J., Chmelnizkij, A. 2016. Numerische Berechnung und messtechnische Begleitung zur Dynamischen Intensivverdichtung. *34. Baugrundtagung*, 297–394.

Knut, A., Pankrath H., Ocaña Atencio R. E., Thiele, R. 2017. Modellversuche zur Eingrenzung von Verdichtungsindikatoren bei impulsartig wirkenden Bodenverdichtungstechnologien. *11. Österreichische Geotechniktagung: Baugrund Risiko & Chance* (Eds. ÖIAV). 251–260

Kopf, F. Paulmichl, I. 2005. Die dynamische Intensivverdichtung (DYNIV) - Verdichtungskontrolle mittels dynamischer Messungen. *Österreichische Ingenieur- und Architekten-Zeitschrift (ÖIAZ)* **150,** 149–159.

Lukas, R. G. 1986 Dynamic Compaction for Highway Construction: Volume 1: Design & Construction Guidelines. FHWA Report, FHWA/RD-86/133

Lukas, R. G. 1995. Geotechnical Engineering Circular No. 1: Dynamic Compaction. FHWA Report, FHWA-SA-95-037

Ménard L., Broise, Y. 1975. Theoretical and practical aspect of dynamic consolidation. *Géotechnique* **25,** 3–18

Poran, C. J., Heh, K-S., Rodriguez, J.A. 1992. Impact Behaviour of Sand. *Soils and Foundations* **32,** 81–92.

Take, W. A. 2015. Thirty-Sixth Canadian Geotechnical Colloquium: Advances in visualization of geotechnical processes through digital image correlation. *Canadian Geotechnical Journal* **52,** 1199–1220.

Trudeep, N. D., Dasaka, S. M. 2012. Assessment of portable traveling pluviator to prepare reconstituted sand specimens. *Geomechanics and Engineering* **4,** 79–90.

White, D. J., Take, W. A., Bolton, M.D. 2003. Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique* **53,** 619–631.