# Application of image processing in internal erosion investigation

# Application du traitement d'image dans l'investigation de l'érosion interne

Amirhassan Mehdizadeh
*Swinburne University of Technology, PhD Candidate, Australia, amehdizadeh@swin.edu.au*
Mahdi M. Disfani
*The University of Melbourne, Senior Lecturer, Australia*
Robert Evans
*Swinburne University of Technology, Senior Lecturer, Australia*
Arul Arulrajah
*Swinburne University of Technology, Professor, Australia*
D.E.L Ong
*Swinburne University of Technology, Director (Acting), Malaysia*

ABSTRACT: Internal erosion is a prime cause of dam failure. Despite studies over the years, there are still many ambiguities in the post erosion response of an internally unstable soil. In this study, a new combined erosion-triaxial apparatus was developed to investigate the post erosion behavior of a gap-graded soil (vulnerable to internal erosion). This new apparatus eliminated the need to remove the soil sample which thus prevented any loss in saturation and furthermore minimized testing disturbance. Photogrammetry and X-ray tomography techniques were effectively employed to assess deformations during the erosion phase. It was found that the primary soil structure became temporarily unstable after the initial erosion of some fine particles. However, this temporary instability was found to be reversed after rearrangement of the remaining coarse particles. This was detected by the measurement of sudden spikes in vertical deformations on the sample surface. This phenomenon was also visible in the 3-D Computed Tomography scans. Although dilation tendency during shearing was found to decrease after erosion, the measured increase in undrained shear strength at small strains was likely to be caused by enhanced mechanical interlock between the coarse particles.

RÉSUMÉ : L'érosion interne est la cause principale des ruptures des digues. Malgré les nombreuses études menées au fil des années, il reste toujours des zones d'ombre autours de la réponse des terrains instables en interne suivant une érosion. Dans cette étude, un nouvel appareil combiné érosion-triaxial a été développé pour examiner le comportement de terre échelonnée et vulnérable à l'érosion interne. Ce nouvel appareil vise à éliminer le prélèvement d'échantillon qui minimise la perte de saturation ainsi que toute déstabilisation due à l'analyse. La Photogrammétrie et la Tomographie par Rayons X ont été utilisées pour évaluer les déformations durant la phase d'érosion. Nous avons mis en évidence que la structure primaire du sol devient temporairement instable après la phase initiale de l'érosion des particules fines. Cette même instabilité temporaire peut être rétablie par réarrangement des grosses particules. Cela a pu être établie à travers la détection de pics brusques dans les déformations verticales sur la surface de l'échantillon. Ce même phénomène a pu être retrouve en Balayage de Tomodensitométrie 3D. Bien que la tendance à la dilatation au cours du cisaillement ait diminué après l'érosion, l'augmentation de la résistance au cisaillement observée ici sous faible tension était très probablement due à une augmentation de l'accrochage mécanique entre les grosses particules.

KEYWORDS: Internal erosion; Triaxial combined erosion apparatus; Photogrammetry

## 1 INTRODUCTION

The dislogment of soil particles caused by seepage flow was first investigated by Terzaghi (1925). Terzaghi found that there was a critical hydraulic gradient in an upward flow which initiates erosion of particles when the effective stress reduces to zero (due to hydraulic stresses of the seepage flow). Subsequently, researchers such as Skempton and Brogan (1994), Li and Fannin (2011) and Ke and Takahashi (2012) however showed that internal erosion can initiate under a much lower hydraulic gradient than that presented by Terzaghi (1925), if erodible particles are not fully involved in the force chains. Many reserachers have also investigated the suseptibility of soil gradations to internal erosion (Kezdi, 1969; Kenney and Lau, 1985; Wan and Fell, 2008; Moffat and Fannin, 2011; Chang and Zhang, 2013; Moraci et al., 2014; and Indraratna et al., 2015). However, these geometrical methods are only focused on assessing the susceptibility of soil to erosion and are unable to predict the impact of erosion on soil structure and consequently its post erosion behaviour. Chang and Zhang (2011), Xiao and Shwiyhat (2012) and Ke and Takahashi (2014) investigated the post erosion response of internally unstable soils using modified triaxial apparatuses and suggested that eroded specimens showed a higher undrained peak shear strength and a lower drained shear strength. One challenge in erosion testing is the measurement of strain as there is no control on the variation of pore water during the erosion phase, and the bottom of the soil specimen furthermore is open to drain water and collects eroded particles during erosion phase.

There are a range of direct and indirect methods to measure local vertical/lateral and volumetric strains during triaxial testing. In an ordinary triaxial test on a fully saturated specimen, volumetric and general vertical strains are typically measured using pore water volume variation and a Linear Variable Differential Transformer (LVDT) mounted on the top of the specimen. When the soil specimen is unsaturated, pore water volume measurement is not reliable. Other techniques such as cell liquid measurement, air-water volume measurement, local displacement sensors, non-contacting laser and photogrammetry have been developed to overcome this issue. For the cell liquid measurement technique, the confining cell liquid is monitored to measure sample volume changes. However, this technique requires intensive calibration as ambient temperature, chamber creep, immediate cell expansion during cell pressurization, loading ram movement and sample loading/reloading can affect the result. This calibration needs to be conducted for each individual test. The prime advantage of this technique is its simplicity, however, Bishop and Donald (1961) further improved it by proposing a double cell chamber to minimize the cell liquid volume. The air-water volume measurement is another technique to record the volume changes of the soil sample, which can be performed by connecting two air-water pressure controllers to the soil specimen. However, undetectable air leakage and diffusion, small temperature and atmospheric pressure changes, and air compressibility need to be taken into account in this method (Adams et al., 1996; Geiser, 1999; Blatz and Graham, 2000; Laloui et al., 2006). Apart from indirect techniques such as cell liquid and air-water volume measurements, there are some direct measurement methods where the volume change of a specimen can be computed with superficial changes in the sample. The use of local displacement sensors is the most commonly used technique (e.g. 1989; Goto et al., 1991; Klotz and Coop, 2002). However, the reinforcing effect on the soil sample, discrete measurement of the local strains, delicate sensor installation and low accuracy when the sample deformation pattern is barrel shape are some noted drawbacks. The non-contacting long range laser system was proposed first by Romero et al. (1997). Non-uniformity and local deformations are also detected using this technique. However, it is costly and needs a sophisticated installation procedure. Photogrammetry including video imaging, particle image velocimetry (PIV) and digital image correlation (DIC) is a direct measurement method, easy to setup and cheap in comparison to other techniques. However, image processing might be time-consuming and complicated. Macari et al. (1997) were the first to report on the use of video imaging to measure volume changes of a triaxial soil specimen. Major challenges included considering the light refraction through water and cell chamber as well as curvature of the cell. This technique was further improved by others (Alshibli and Al-Hamdan, 2001; White et al., 2003; Gachet et al., 2007 and Zhang et al., 2015). Uchaipichat et al. (2011) showed that if the purpose of the test is to measure the sample volumetric strains, light retraction effect can be eliminated by considering relative deformation in image processing. This method was later investigated by Mehdizadeh et al. (2015) who demonstrated a high accuracy in local vertical/lateral strains measurement.

This paper aims to investigate the post erosion behavior of a soil that is susceptible to internal erosion under downward seepage flow using a modified triaxial apparatus. To erode the soil specimen, it is necessary to provide an outlet for discharging water and eroded particles. It was decided to employ photogrammetry technique in this research to investigate sample deformations during erosion and undrained shearing. This paper presents the internal erosion effects on the behavior of a gap-graded soil in terms of deformations during erosion progress and post erosion stress-strain relationship using a newly developed triaxial-erosion apparatus and photogrammetry technique. Results are further supported by 3-D images of samples obtained using a computed Tomography scans (CT scans).

## 2 TEST PROCEDURE AND MATERIAL PROPERTIES

An ordinary triaxial chamber was modified to perform erosion and shearing phases continuously, thus preventing sample disturbance or desaturation. This modification consisted of a new specimen top cap and a funnel shaped base plate with an outlet. In addition, a water supply system with flow controller and a pressurized collection tank were used to apply the required hydraulic flow and collect the washed particles and drained water from the bottom of the soil specimen during downward seepage while the back presure was kept constant. Figure 1 shows some details of chamber modification.

Two internally unstable gap-graded soil specimens (50 mm in diameter and 115 mm in height) with 25 per cent non-plastic fine fraction were prepared using the moist tamping technique according to the procedure provided by Ladd (1978) and Jiang et al. (2003). Soil gradation and properties of the specimens are shown in Figure 2. Susceptibility of the soil gradation to internal erosion was examined using available geometrical methods from the literature such as Kezdi (1969), Sherard (1979) and Burenkova (1993). All methods showed that the fine particles will be washed out if the applied hydraulic gradient overcomes the critical value. Specimens were consolidated to 150 kPa and subjected to two different seepage flow velocities of 52 mm/min (E1-V52) and 208 mm/min (E2-V208).

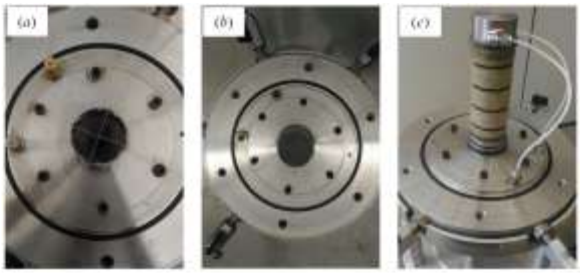


Figure 1. Modified Triaxial Cell (a) Netted plate, (b) Bottom mesh and (c) Sample Setup

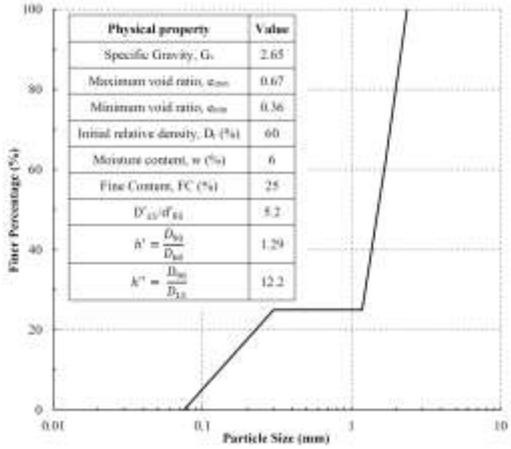


Figure 2. Gradation and properties of the soil specimens

## 3 TEST RESULTS

The 25 per cent initial fines content dropped to 10.2 and 6.9 per cent after two hours of erosion with a decreasing trend for E1-V52 and E2-V208, respectively. This difference was attributed to the much higher flow velocity experienced for specimen E2-V208. It seems that the survived fine particles were sandwiched between the coarse particles and contributed directly to stress transfer as the seepage flow in the second test was unable to wash them entirely. Figure 3 shows the measured total vertical strains during erosion for the two specimens.

It is evident that the vertical strains showed different trends during erosion. However, the final vertical strains were similar for both specimens. In addition, both specimens experienced a considerable deformation at the beginning of the erosion when the inflow velocity was very low. The observed different patterns in vertical strains during erosion might be due to various preferred erosion paths. It is believed that in a granular gap-graded soil, fine particles may only act as a void filler and provide no contribution to stress transfer (Case-i), provide lateral support for force chains (Case-ii) or be in full contact with coarse particles in the primary soil structure (Case-iii) depending on particle shape, fine fraction, confining pressure, soil gradation, sample preparation method and relative density. The erosion of fine particles in each case leads to different consequences in terms of settlement during erosion and post erosion mechanical behavior. The erosion of free fines (Case-i) does not affect soil response during erosion but may change the post erosion mechanical response considering particle angularity. However, the loss of semi-active fine particles (Case-ii) forms a metastable structure as the lateral support of force chains disappeared. Local coarse particle rearrangement occurred to reach a new stable stress state that led to local vertical settlements. These rearranged particles can be identified in Figure 3 where the vertical strains suddenly spiked. Furthermore, Figure 4 shows a CT-scan image 10 mm below the top of a soil specimen pre and post erosion.

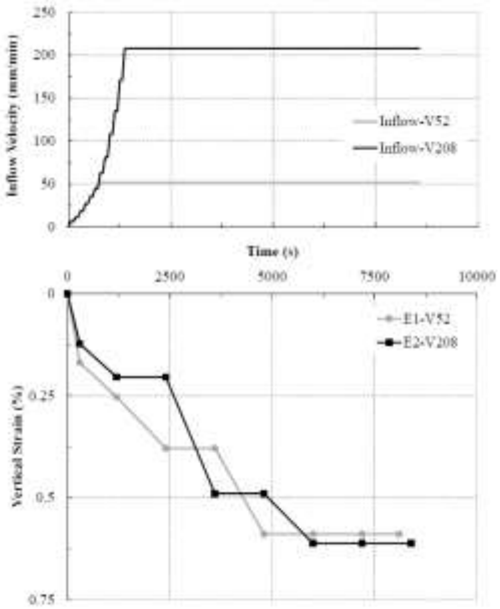


Figure 3. Measured vertical strains using photogrammetry during erosion

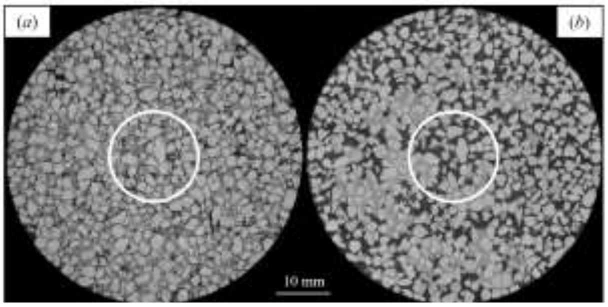


Figure 4. X-ray tomography image at 10 mm from the top of specimen E2-V208 (a) Pre-erosion and (b) Post-erosion

From Figure 4, it can be observed that a percentage of fine particles did survive the internal erosion process. These surviving fine particles were wedged between coarse particles and were definitely involved in transferring load. In addition, focusing on the center of the specimen, rearrangement of the coarse particles is recognizable as some coarse particles have clearly rotated or moved to reach a new stable state.

The change of global and inter-granular void ratios (Mitchell, 1993) for the tested specimens are shown in Figure 5. The global void ratio increased with the loss of fine particles as expected. However, the inter-granular void ratio dropped for E1-V52 with no further change for E2-V208. This suggested that the extra 3.3 per cent erosion of fine particles in specimen E2-V208 which experienced a much higher seepage flow velocity, did not affect the soil structure. These particles can be categorized in Case-i and were clogged somewhere inside the soil specimen in the first test when the applied seepage flow was not strong enough to wash them out. However, under a flow with a velocity four times greater, they were washed out of the specimen with no consequences on the inter-granular void ratio and soil structure. A decrease in the inter-granular void ratio can be explained by local particle rearrangement which was detected using photogrammetry during erosion and has been presented in Figure 3.

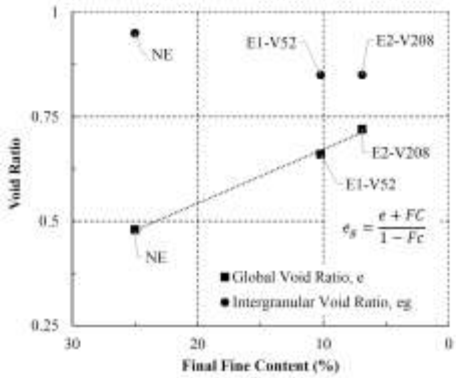


Figure 5. Change in global and inter-granular void ratios with final fine content

The influence of erosion of the fine particles on undrained mechanical behavior of the soil specimens was also investigated. A new undrained shearing stage was defined at the end of erosion phase and results were compared with the undrained behavior of a non-eroded specimen (Figure 6).

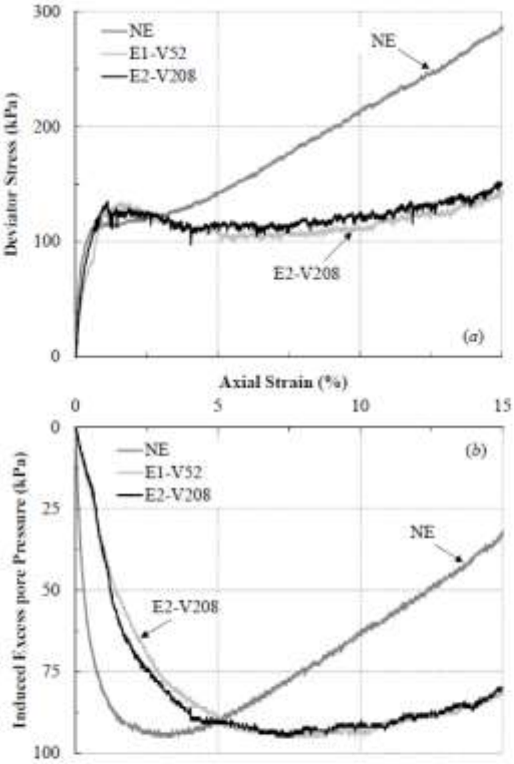


Figure 6. Pre and post erosion undrained mechanical behavior (a) Stress-strain relationship, (b) Induced excess pore water pressure and

Figure 6 shows the initial hardening behavior of the soil specimen changed to flow type with limited deformation and a temporary collapse was observed in both eroded specimens over the medium strain range. The initial peak undrained strength increased after erosion of the fine particles (Figure 6(a)), which might have been due to enhanced mechanical interlock between the coarse particles (coarse particles were classified as sub-rounded to sub-angular in shape). However, the contractive behavior was found to be dominant after internal erosion. An increase in the global void ratio (due to removal of fine particles) might have increased the chance of slip-down movement of particles and contraction tendency. This was in agreement with the variation of induced excess pore water pressure during shearing (Figure 6(b)). All specimens developed similar maximum excess pore pressure. However, it was induced and dropped at a much slower rate in the eroded specimens. In addition, although the eroded specimens showed contractive behavior, the specimens ended up on the same steady state as the non-eroded specimen. Interestingly, regardless of the inflow velocity, both eroded specimens showed very similar behaviors although they had different final fine content. It is evident from Figure 4 that the inter-granular void ratio was the same for the eroded specimens. The similar post erosion behaviors can be attributed to the similar stress matrixes that led to the same inter-granular void ratios and final vertical strains during erosion.

## 3 CONCLUSION

The influence of internal erosion on the soil structure and mechanical behaviour of a gap-graded soil was investigated using a newly developed triaxial-erosion apparatus, photogrammetry technique and 3-D CT scans. Results indicate that photogrammetry was capable of detecting particle rearrangement during erosion. It was also found that erosion of fine particles that provided lateral (secondary) support for the force chains resulted in the formation of a metastable soil structure. This temporary instability was restored due to rearrangement of the coarse particles, which led to vertical settements and a decrease in the inter-granular void ratio while the global void ratio increased due to removal of the fine particles. Regardless of seepage properties and the final fine content, the eroded specimens showed similar undrained behaviour. The inter-granular void ratio was the same for both specimens, which explains the similar post erosion response. In fact, it is the stress matrix (made by coarse and non-erodible fine particles) that controls soil behaviour after internal erosion. In general, the strain hardening behaviour changed to the flow type with limited deformation after internal erosion. An increase in contraction tendency was attributed to the increase in global void ratio. However, the initial peak undrained shear strength increase might have been due to better interlocking of the coasre particles. In addtion, it was understood that the steady state line is independent of fine particles as all specimens ended up on the same line at large strains.

## 4 ACKNOWLEDGEMENTS

The authors would like to thank the support provided through "Melbourne-Sarawak Research Collaboration Scheme", funded by Swinburne University of Technology, Australia.

## 5 REFERENCES


Adams B.A., Wulfsohn D. and Fredlund D.G. 1996. Air volume change measurement in unsaturated soil testing using a digital pressure-volume-controller. *Geotech. Test J.* 19(1), 12-21.

Alshibli, K.A., and Al-Hamdan, M.Z. 2001. Estimating volume change of triaxial soil specimens from planar images. *Computer-Aided Civil and Infrastructure Engineering* 16(6), 415-421.

Blatz, J. and Graham, J. 2000. A system for controlled suction in triaxial tests. *Géotechnique* 50(4), 465-470.

Bishop, A.W. and Donald, I.B. 1961. The experimental study of partly saturated soil in the triaxial apparatus. *Proc. 5th Int. Conf. on soil mechanics and foundation engineering*, Paris, 1, 13-21.

Burenkova, V.V. 1993. Assessment of Suffusion in Non- Cohesive and Graded Soils. Filters in Geotechnical and Hydraulic Engineering, Balkema, Rotterdam, The Netherlands, 357-360.

Chang, D.S. and Zhang, L.M. 2011. A stress-controlled erosion apparatus for studying internal erosion in soils. *Geotech. Test. J.* 34(6), 579-589.

Gachet, P., Geiser, F. and Laloui, L. 2007. Automated digital image processing for volume change measurement in triaxial cells. *Geotech Test. J.* 30 (2), 98-103.

Geiser, F. 1999. Comportement mécanique d'un limon non saturé: Étude expérimentale et modélisation constitutive. *PhD thesis*, Swiss Federal Institute of Technology, Lausanne, Switzerland.

Goto, S., Tatsuoka, F., Shibuya, S., Kim, Y.S. and Sato, T. 1991. A simple gauge for local small strain measurements in the laboratory. *Soils Found.* 31(1), 169-180.

Indraratna B., Israr J. and Rujikiatkamjorn C. 2015. Geometrical Method for Evaluating the Internal Instability of Granular Filters Based on Constriction Size Distribution. *J. Geotech. Geoenviron. Eng.* 141(10), 04015045.

Jiang, M.J., Konrad, J.M. and Leroueil, S. 2003. An Efficient Technique for Generating Homogeneous Specimens for DEM Studies. *Comput. Geotech.* 30(7), 579-597.

Ke L. and Takahashi A. 2012. Strength reduction of cohesionless soil due to internal erosion induced by one-dimensional upward seepage flow. *Soils Found.* 52 (4), 698-711.

Ke L. and Takahashi A. 2014. Triaxial erosion test for evaluation of mechanical consequences of internal erosion. *Geotech. Test. J.* 37(2), 1-18.

Kenney T.C. and Lau D. 1985. Internal Stability of Granular Filters. *Can. Geotech. J.* 22(2), 215-225.

Kezdi A. 1969. Increase of protective capacity of flood control dikes. Department of Geotechnique, Technical University, Budapest. Report No. 1.

Klotz, E.U. and Coop, M.R. 2002. On the identification of critical state lines for sands. *Geotech. Test J.* 25(3), 289-302.

Ladd, R.S. 1978 Preparing Test Specimens Using Undercompaction. *Geotech. Test J.* 1(1), 16-23.

Laloui, L., Peron, H., Geiser, F., RIFA'I, A. and Vulliet, L. 2006. Advances in volume measurement in unsaturated soil triaxial tests. *Soils Found.* 46(3), 341-349.

Li M. and Fannin R.J. 2011. A theoretical envelope for internal instability of cohesionless soil. *Géotechnique* 62 (1), 77-80.

Macari, E.J., Parker, J.K. and Costes, N.C. 1997. Measurement of volume changes in triaxial tests using digital imaging techniques. *Geotech. Test J.* 20(1),103-109.

Mehdizadeh, A., Disfani, M.M., Evans, R.P., Arulrajah, A. and Ong, D.E.L. 2015. Discussion of 'Development of an Internal Camera-Based Volume Determination System for triaxial Testing' by S. E. Salazar, A. Barnes and R. A. Coffman." *Geotech. Test J.* 39(1), 165-168.

Mitchell, JK. 1993. Fundamentals of soil behavior. John Wiley & Sons, Inc., New York, N.Y., 1–210.

Moffat R. and Fannin R.J. 2011. A hydromechanical relation governing internal stability of cohesionless soil. *Can. Geotech. J.* 48(3), 413-424.

Moraci N., Mandaglio M.C. and Ielo D. 2014. Analysis of the internal stability of granular soils using different methods. *Can. Geotech. J.* 51(9), 1063-1072.

Romero, E., Facio, J.A., Lloret, A., Gens, A. and Alonso, E.E. 1997. A new suction and temperature controlled triaxial apparatus. *Proc. 14th ICSMFE*, Hamburg, 185-188.

Sherard, J. L., 1979, "Sinkholes in dams of coarse, broadly graded soils," *In Transactions, 13th International Congress on Large Dams*, New Delhi, India. Vol. 2, pp. 25–35.

Skempton A.W. and Brogan J.M. 1994. Experiments on piping in sandy gravels. *Geotechnique* 44 (3), 449-460.

Terzaghi K. 1925. Erdbaumechanik. *Franz Deuticke*, Vienna.

Uchaipichat, A., Khalili, N. and Zargarbashi, S. 2011. A Temperature Controlled Triaxial Apparatus for Testing Unsaturated Soils. *Geotech. Test J.* 34(5), 424-432.

Wan C.F. and Fell R. 2008. Assessing the potential of internal instability and suffusion in embankment dams and their foundations. *J. Geotech. Geoenviron. Eng.* 134(3), 401-407.

White, D.J., Take, W.A. and Bolton, M.D. 2003. Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Geotechnique* 53(7), 619-632.

Xiao M. and Shwiyhat N. 2012. Experimental investigation of the effects of suffusion on physical and geomechanic characteristics of sandy soils. *Geotech. Test. J.* 35(6), 890-900.

Zhang, X., Li, L., Chen, G. and Lytton, R. 2015. A photogrammetry-based method to measure total and local volume changes of unsaturated soils during triaxial testing. *Acta Geotechnica* 10(1), 55-82.