DISCUSSION ON “APPLICATION OF PARTICLE IMAGE VELOCIMETRY (PIV) IN CENTRIFUGE TESTING OF UNIFORM CLAY”ⁱ⁾

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The Authors present a validation of the use of particle image velocimetry (PIV) to analyse the movement of uniform clay on which texture has been created by painting black dots, and the movement of an artificial target on which black dots have been printed. For the centrifuge test arrangement shown, a texture of 6-8 marker particles per PIV patch (or ‘window’) is found to be sufficient for PIV to operate, and a precision of 0.01 mm is quoted.

These two conclusions are of limited value without further clarification, which we offer in this discussion. Firstly, the performance of an image processing procedure is determined in image space (i.e. pixels) not object space (e.g. mm) and should be quoted in this way in order to be applicable to situations with different geometry. Secondly, as we report in our earlier use of PIV on textured clay (White et al., 2001), a key benefit of PIV in geotechnical modelling is that there is no need to add marker particles to the model since PIV operates on any form of texture (i.e. spatial variation in brightness). Hence, the Authors’ texture criterion based on the required number of marker particles is of limited use, except for cases where the modeller wishes to painstakingly apply markers rather than scatter random texture, as we suggest.

In this discussion, we firstly compare the image-space performance of the Authors’ system with other PIV applications. Secondly, we introduce two more useful descriptors of image texture, which in our view are a) more widely applicable than the authors’ approach and b) provide more practical guidance for the use of artificial texture with PIV.

NON-DIMENSIONAL PERFORMANCE

In order for the Authors’ conclusions to be applied in other modelling situations, it is useful to generalise the results non-dimensionally, but first we highlight the different definitions of performance. The performance of a measurement system is quantified by accuracy, precision, and resolution, each of which has a strict definition. Accuracy is defined as the systematic difference between a measured quantity and the true value. Precision is defined as the random difference between multiple measurements of the

same quantity. Resolution is defined as the smallest interval that can be present in a reading.

The accuracy of a PIV system can be tested by comparing the ‘true’ movement of an object (measured using a technique that is assumed to be perfectly accurate) with a systematic error found from calculations using PIV- as reported by the Authors in Figs. 4-11. The precision of PIV can be quantified by the apparent random movement of a stationary object calculated using PIV- as reported by the Authors in Fig. 3. However, since there is noise in the data of Figs. 4-11 due to random precision errors, no systematic error can be seen and so the accuracy is too good to be quantified. The performance is instead limited by precision.

In order to be applicable to other experimental arrangements, the precision of a PIV system should be quoted in units of pixels rather than mm since the random errors that govern the precision of PIV do not depend on the dimensions of the experiment. The Authors’ precision of 0.01 mm for the quoted image scale of 0.22 mm/pixel is slightly better than $1/20^{\text{th}}$ of a pixel, and is comparable to our experience when testing sand and textured clay (White et al., 2003a).

The precision observed in other applications of PIV in geotechnical engineering is given in Table 3. Values in the range $1/10^{\text{th}}$ - $1/50^{\text{th}}$ of a pixel are reported, independent of the image scale (mm/pixel). This range is in agreement with experience in experimental fluid mechanics (e.g. Raffel et al., 1998). The consistency demonstrates that performance is better compared in units of pixels than in mm, and that any object-space influences on precision (such as vibration of the camera) are small.

A precision defined in terms of pixels rather than mm is more useful when planning the use of PIV. When designing an experiment, the required object-space performance (which might be 0.02 mm for a centrifuge model as quoted by the Authors, but as large as 2 mm for field monitoring) can be combined with the achievable system performance (in pixels) to select an appropriate image scale (mm/pixel) and hence camera position and field of view. By dividing the precision by the number

Application description	Precision (object-space)	Precision (image-space)	Precision (fraction of FOV)	Reference
Bench-top experiments (rigid body movement of soil, camera located 280 mm away)	0.001-0.01 mm	0.01-0.1 pixels ¹	1/17680- 1/176800	White et al. (2003a)
Field monitoring (camera located 239 metres from target)	0.6 mm	0.04 pixels	1/40000	White et al. (2003b)
Field monitoring (camera located 20.5 metres from target)	0.17 mm	0.045 pixels	1/57000	Take et al. (2005)
Centrifuge validation experiment	0.01 mm	0.05 pixels	1/25920	Zhang et al. (2005)
Biaxial testing of sand	0.005 mm	0.03 pixels	1/34100	Rechenmacher & Finno (2004)

¹Dependent on patch size and image texture

of pixels across the image, the precision can be expressed as a fraction of the field of view. This quantity allows image-based methods to be compared with other measurement techniques, since the width of the field of view is approximately equal to the maximum displacement, or ‘full scale deflection’ that can be detected. As the resolution of camera CCDs increases, the precision as a fraction of the FOV will increase for a given image-space precision.

Whilst the Authors’ object-space precision of 0.01 mm is adequate for most centrifuge modelling applications, this does not represent an upper limit on performance. If necessary, smaller movements could be detected by moving the camera closer to the object or increasing the zoom setting and CCD resolution. Similarly, the authors would not achieve a precision of 0.01 mm if they moved their camera back or zoomed the image outwards. It is therefore better to define performance in image-space (pixel) units, since this is consistent across applications and independent of camera settings.

THE INFLUENCE OF IMAGE TEXTURE ON PIV PRECISION

The authors’ descriptor for image texture is the number of marker particles within a PIV patch. They state that 6-7 marker particles per image patch are sufficient for PIV to operate, and find ‘*no distinguishing trend among the results for three different densities*’ of marker particle. This descriptor is irrelevant in cases where the image texture is not created by marker particles. When monitoring sand, the texture arises from the different colours of grains, and the light and dark regions formed when they are lit. When monitoring objects, the texture simply arises from the variation in brightness across the object. Also, since no trend of precision was identified for different numbers of particles within a PIV patch, the authors have not identified any link between their texture descriptor and PIV precision.

In our previous work (White et al., 2003a, Take, 2003), we show that texture has a significant influence on the precision of PIV by comparing the results of validation exercises conducted using materials of varying texture. This discussion is enlarged below, and we suggest two better descriptors than that used by the authors.

Before introducing these descriptors of texture, it is useful to summarise how PIV operates. Figure 16 illustrates one PIV implementation, in which the normalised correlation between a test patch (I_{test}) and a larger search patch (I_{search}) is evaluated (White & Take, 2002). The highest peak in the normalised correlation plane (R_n) is used to identify the displaced position of I_{test} . This peak is interpolated to sub-pixel precision. Further details of this PIV implementation are given by White et al. (2005), and a wider description of the subject is provided by Raffel et al. (1998). The precision of PIV depends on the random error between the actual displacement of the test patch and the calculated location of the correlation peak.

TWO DESCRIPTORS OF IMAGE TEXTURE

Since the image texture within a PIV patch arises from the spatial variation in brightness, two simple descriptors are (1) the standard deviation in pixel brightness, and (2) the spatial frequency in pixel brightness. The effect of these two descriptors on the precision of PIV is now qualitatively explained, and the practical implications described. A quantitative study is the subject of a forthcoming paper.

In the case of descriptor (1), if the patch is of uniform brightness (i.e. the standard deviation in pixel brightness is zero), no peak is generated in the correlation plane, so no movement can be identified. If this brightness variation is only slight, it can be overshadowed (literally) by random variations in brightness between pairs of images caused by the camera CCD, or by the lighting of the experiment (this effect is particularly relevant for centrifuge experi-

Fig. 16 PIV procedure used by GeoPIV software (White & Take, 2002; White et al., 2003a)

ments where external lighting may cause flickering with each rotation). A greater standard deviation in pixel brightness gives a stronger correlation peak, which can be better located within the correlation plane.

The practical implication of this first descriptor is that

be chosen to maximise the contrast with the underlying material. The focus should be sharp in order that light and dark regions are not blurred together.

Descriptor (2) is the frequency at which brightness varies across the PIV patch. The images shown as Figs. 17a and 17b contain the same values of pixel brightness and

Fig. 17 PIV patches with varying spatial brightness frequency (a, b after White et al., 2003a)

since the correlation peak will be rounded, and shifted by any uniform change in brightness across the whole image. Instead, it is desirable for neighbouring pixels to have unrelated brightnesses, so that the correlation peak is sharp, and no correlation exists one pixel away from the exact match. The sharp peak resulting from the random image of Fig. 17a can be located to a precision better than $1/100^{\text{th}}$ of a pixel (White et al., 2003a).

However, real images of textured soil are not random since neighbouring pixels depict parts of the same grain (or piece of artificial texture), so are similarly coloured, and the correlation peak is less sharp. We previously demonstrated this effect by enlarging the random image of Fig. 17a so that 2×2 pixel blocks had the same brightness (Fig. 17b) (White et al., 2003a). This resampled coarse image, which has a lower spatial brightness frequency, can be located with approximately one third of the precision of the finer parent image. This exercise shows that a higher spatial brightness frequency gives a sharper correlation peak, which can be better located within the correlation plane.

The practical implication of this second descriptor is that artificial texture should be fine enough to give a high spatial brightness frequency, but not so fine that the contrast between the texture and the soil is lost, giving a uniform brightness across the image. The focus should be sharp in order that high frequency texture is not lost by blurring.

DISCUSSION SUMMARY

In summary, the Authors' validation exercise confirms the high measurement detail that can be revealed by PIV in geotechnical applications, but their conclusions are expressed in a manner that has limited value as it is specific to their testing setup. The performance of a PIV application should be defined in image space units, which we show

gives consistency across applications. The Authors' quoted precision of 0.01 mm should therefore be recast as $\sim 1/20^{\text{th}}$ pixel, which is in agreement with previous similar validation exercises.

The Authors show tests on kaolin clay that has been textured by the manual painting of black dots. This time-consuming procedure is not as simple as our previously-reported techniques of adding coloured powder or dyed sand (White et al., 2001, 2003a). The Authors quantify their texture by the number of marker particles within a PIV patch, but are unable to identify how this quantity affects precision. In contrast, we have shown previously that texture has a significant influence on PIV precision (White et al., 2003a). In this discussion we offer two descriptors of texture- the variation in brightness and its spatial frequency- and discuss why these influence precision. These definitions are a) suitable for automatic analysis b) lead to practical guidance when applying artificial texture, and c) apply to all types of texture, not only where it is formed by discrete markers.

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