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REPLY TO THE DISCUSSION BY WHITE AND TAKE ON "APPLICATION OF PARTICLE IMAGE VELOCIMETRY (PIV) IN CENTRIFUGE TESTING OF UNIFORM CLAY"

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The authors would like to thank the discussers for their interest in our work and for sharing their views on the application of the PIV technique. The discussers raised four interesting points and these are now addressed.

NON-DIMENSIONAL PERFORMANCE

The authors agree that the use of pixel unit to define and compare the performance of PIV technique provides a non-dimensional and thus more general picture. However, in geotechnical engineering, most people are more at ease with the precision of measuring displacement in terms of a length unit, in this case millimeters *(mm)* as it provides a direct feel of the adequacy of the precision. It is for this reason the authors choose to present the precision in terms of *mm* as most of the other measurements are also expressed in a length unit within a spatial domain rather than in pixels in an image domain. This expression also allows a direct comparison with other modes of measuring displacement directly such as using a LVDT. In the paper, both the precision in spatial domain and the calibration factor between length and pixel is provided. The pixel value in image domain could be obtained from the corresponding expression in terms of *mm*.

ARTIFICIAL MARKERS

In this paper, the authors have emphasized the application of the PIV technique on a uniform clay which on its own does not have enough natural texture to apply the PIV technique as demonstrated in Fig.1 of the paper. To apply the PIV technique, it is necessary to provide a texture. The paper compares two different methods of generating the texture. The first was created by painting black dots and the second was done by spraying very small black plastic beads on the surface. There are two important criteria of choosing a suitable marker material to measure soil deformation during an experiment. The first is that the color of the marker material should make good contrast to the background which is also emphasized by the discussers. The second is that the makers must be able to follow the flow of the soil and that they are not obscured or covered by soil during the experiment so that the

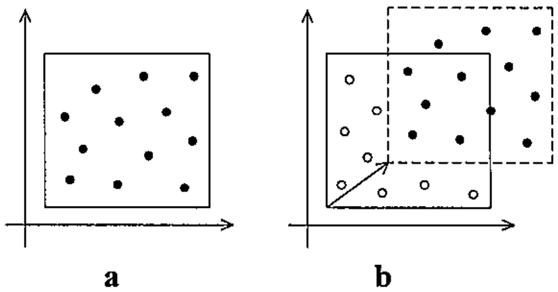


Fig. 1 Application of the window offset: a. Interrogation window in the first image; b. Interrogation window in the second image (after Scarano and Riethmuller, 1999)

correlation peak will represent truly the soil movement. In our paper, we showed that both methods of generating textures are suitable for centrifuge experiment. Further, because the texture needs not be ordered, the creation of this artificial texture is a rather easy process, taking not more than 30 minutes in experiments conducted by the authors. The discussers (2003) reported that the texture in kaolin clay could be formed by dusting colored powder or dyed sand. This is another approach.

PATCH DESCRIPTOR

The authors agree that for the effective implementation of the PIV technique, the lighting condition should be bright and steady; artificial texture should be chosen to maximize the brightness contrast between markers and background materials and the focus should be sharp to distinguish the light and dark regions. These guidelines are also adopted in the works described in the paper to ensure the image quality for reliable PIV analysis.

In our opinion, the most important criterion of imprinting artificial texture is that each patch should have adequate unique information to distinguish the monitored patch from other surrounding patches. In the paper, it was demonstrated that a texture with 6~8 particles within each patch has enough unique information, and therefore enough brightness variation and spatial frequency to perform a successful cross correlation analysis. For this same reason, the

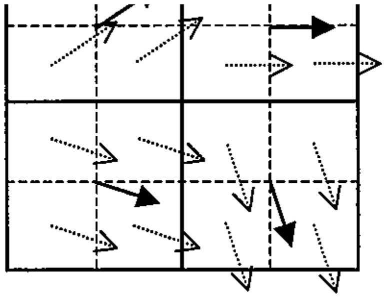


Fig. 2 Application of window size refinement (after Scarano and Riethmuller, 1999)

performance of patches with number of particles higher than the threshold of 6~8 provides similar results. Philosophically, this is not dissimilar to the observations by White et al. (2003) that when the patch size is beyond a certain value, the standard error is almost constant. The rationale behind this is that when the patch size is beyond certain value, the patch contains enough unique information to assure accurate cross correlation analysis. Another factor that is important to assure accurate tracking is a robust and efficient algorithm - in the works reported, a hybrid algorithm was used to improve the performance of PIV analysis, without sacrificing too much computational efficiency.

IMPROVED ALGORITHMS

To improve the accuracy and increase the maximum detectable movement, a hybrid algorithm was adopted to perform cross correlation analysis to measure the movement (Zhang, 2004). Conventionally, cross correlation, based on Fast Fourier Transform (FFT), is computed only once to measure movement and the cross correlation is performed without window offset. One outcome of these features of a conventional algorithm is that error increased with displacement due to information loss and further, the maximum detectable movement is limited to 20%-30% of the interrogation window size.

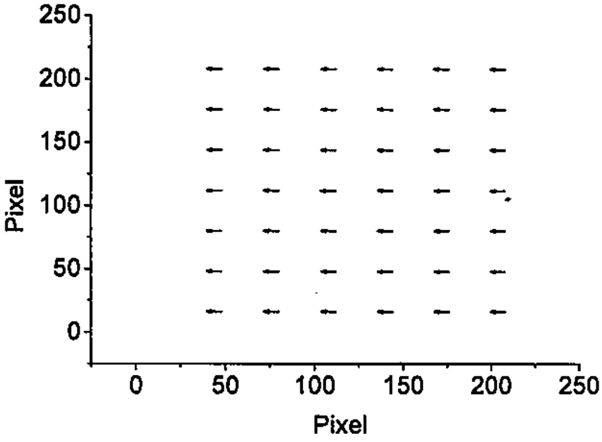
The cross correlation function can be computed either directly in the special domain with normalization or in the frequency domain via FFT. The direct implementation of the cross correlation function has the advantage of accuracy. On the other hand, FFT based cross correlation is computationally efficient. The hybrid algorithm combines advantages of both methods to ensure accuracy and speed. The process of hybrid algorithm is described briefly.

The hybrid algorithm first implements a FFT-based iterative multi-grid approach which combines the discrete window offset and a reduction of the size of the interrogation windows (Scarano and Riethmuller, 1999). A larger interrogation window is used first to obtain the movement. Using this information, a second interrogation window is Meanwhile, the size of the interrogation window can be reduced to half of previous one, as shown in Fig. 2. This process can be repeated until a desired interrogation window size is achieved.

Second, a technique which makes use of normalized cross correlation Huang et al. (1997) is then applied. They recognized that direct implementation of normalized cross correlation performs better than the above FFT based process. The sharp correlation peak of the FFT based correlation function cannot allow a reliable sub-pixel estimation of the displacement. To overcome this problem without losing the advantage of fast processing for FFT, Huang et al. (1997) proposed to normalize five correlation values used to determine the sub-pixel location of the correlation peak. The center point is found using the above FFT based iterative multi-grid procedures. Then this point and its four neighboring points are normalized. These five normalized correlation points are finally used to evaluate displacement between images. It is clear that the normalization on only five values takes little additional computation time.

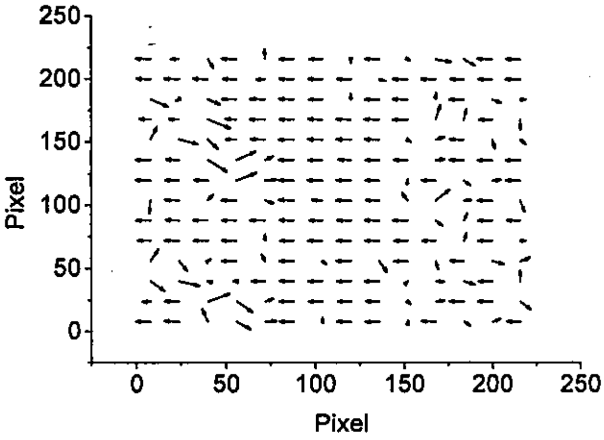
To illustrate the improvement for the hybrid algorithm, Fig. 3 shows the displacement field obtained by different schemes to measure a uniform displacement field of about 8.35 pixels between two successive images. It is clear from Fig. 3(c) that if the basic correlation algorithm is incorporated with the window offset and window size refinement, even though the interrogation was reduced to 16×16 pixels, the measured displacement vectors were quite consistent. Furthermore, now there are four times as many vectors as in Fig. 3(a), which means that the window refinement can increase the spatial resolution. Therefore, the iterative multi-grid algorithm with window offset and window size refinement not only increase the maximum measurable displacement but also the spatial resolution.

The better performance of the improved algorithms could be observed in Figs. 4 and 5. The measured displacements from the basic algorithm are obviously biased towards a smaller value compared to the readings from the dial gauge. These differences range from 0.1~0.15 pixel and agrees well with Huang et al. (1997) finding that the measurement error is of the order of 0.1 pixel for the basic interrogation algorithm. The results from the other two improved algorithms are quite similar, which are also biased towards a smaller value, but most of the differences are less than 0.05 pixel. This finding also confirms that the measurement error for the improved algorithm is of the order of 0.04 pixel (Westerweel et al., 1997; Scarano and Riethmuller, 1999). The results show the effectiveness of the improved algorithm. The best algorithm is the one with normalization, which gives the most accurate results, with errors less than 0.03 pixel.



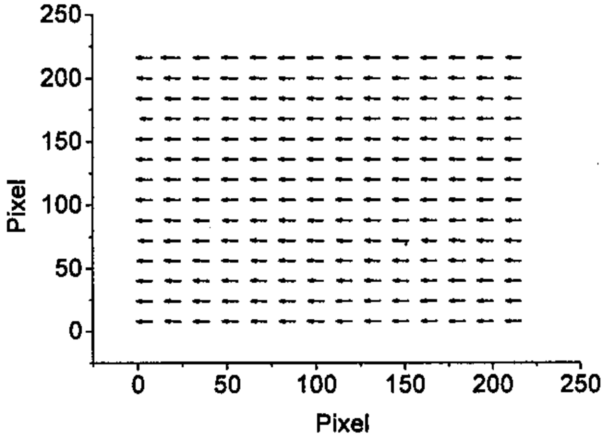
I. Interrogation window size: 32×32 pixels
II. Without window offset
III. Without window size refinement

(a)



I. Interrogation window size: 16×16 pixels
II. Without window offset
III. Without window size refinement

(b)



I. Original Interrogation window size: 32×32 pixels
II. With window offset
III. With window size refinement from 32×32 pixels to 16×16 pixels

(c)

Fig. 3 DPIV measurements of a uniform movement field with about 8.35 pixels

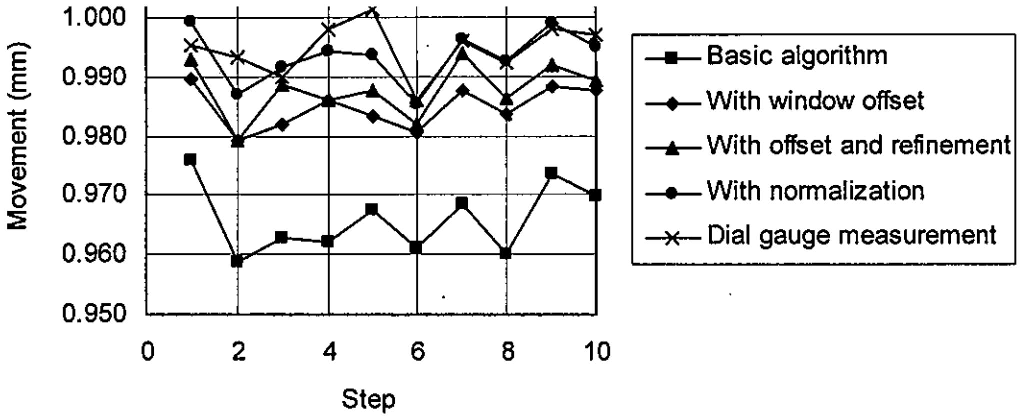


Fig. 4 Measured movement from the four algorithms and dial gauge

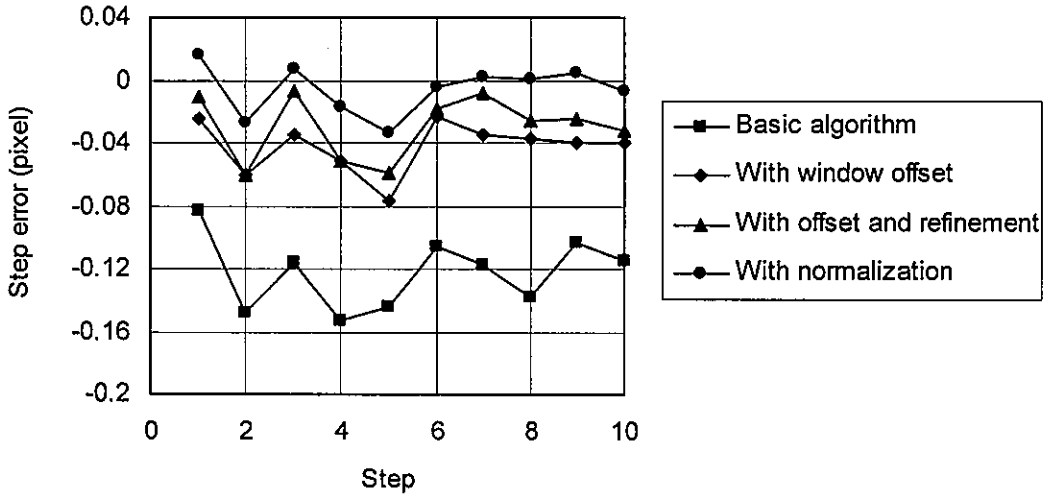


Fig. 5 Measurement differences for the four algorithms

CONCLUSIONS

To successfully apply the PIV technique, the images need enough unique information to perform the cross-correlation analysis. Uniform clay, on its own, does not have enough texture to supply such information and therefore an artificial texture is needed. The authors and discussers have shown different ways of imprinting on the surface of a uniform clay such a texture. As the texture needs not to be uniform or ordered, the imprinting is easy using any of these methods. While there are many different factors to consider in such an application, an important point is the minimum number of particles to ensure enough unique information. The paper has shown that 6-8 particles are enough. Part of the reason for the good accuracy achieved is the adoption of a hybrid algorithm which not only increases the maximum measurable movement but also improves the accuracy. This hybrid algorithm is elaborated.

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