A reliable PIV approach for measuring velocity profiles of highly sheared granular flows

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Abstract: This work reports a particle image velocimetry (PIV) approach for measuring flow velocities profiles in dry granular flows. An experimental research has been performed on steady-state dry granular flows, reproduced in a laboratory environment and under controlled conditions. Side wall images of the flowing pile have been acquired by a high-speed camera. An open-source code, PIVlab, is employed for the derivation of the velocities profiles from digital images. The reliability of the PIV code has been confirmed by comparing its numerical results with those obtained through using the widely used commercial code, proVISION-XS by IDT Corp. The PIVlab code is found to provide reliable results also in case of high sheared flows, typically observed in the presence of no-slip bottom boundary conditions, thanks to its multi-grid multi-step features, that enhance the dynamic range of velocity measurements and, at the same time, provide a higher spatial resolution.

Key-Words: PIV, multi-grid PIV algorithm, granular flows, rheology, avalanche, debris-flow, PIVlab

1 Introduction
Geophysical granular flows, such as debris flows and rock/snow avalanches, are dangerous phenomena for human activities and infrastructures in mountainous areas. These flows consist of the gravity-driven motion of granular particles, embedded in an ambient fluid. Because of the discrete nature of the flowing material, their rheological behavior is very complex and may exhibit at least three very distinct flow regimes (solid-like, dense-collisional, gas-like), which depend on the momentum exchange mechanisms and can be regarded as analogous to states of aggregation of matter. Unfortunately, a unified constitutive law for all these regimes is still to be found [3]. Recently, an increasing effort has been devoted to better describe the constitutive laws and propagation stages of granular flows and liquid-granular mixtures (e.g. [1,2,8,12,15,19]).

In this work, we present an experimental study on steady dry granular flows, where the side-wall velocity profiles have been obtained by employing a multi-grid multi-step particle image velocimetry (PIV) numerical code, PIVlab. The main purpose of this approach is to setup and validate a low-cost PIV system to estimate flow velocity profiles. In the first part of the work, the numerical results obtained with PIVlab code are compared with those obtained through using the commercial software proVISION-XS by IDT Corp, which has been successfully employed in [18]. Digital images of granular flow motion, used for these tests, result from two
experimental activities performed at the Dept. of Hydraulic and Ocean Engineering of the National Cheng Kung University (Taiwan) and at the Environmental and Maritime Hydraulics Laboratory (University of Salerno). A short discussion about the measured velocity profiles is provided.

2 Particle image velocimetry

In the last decades, PIV techniques have been increasingly employed to get reliable measurements of flow velocity fields in fluid dynamics contexts (e.g. [20]). A PIV algorithm basically works by calculating the cross-correlation function of the image intensity field between two consecutive images, taken in a short time interval \( \Delta t \). Each image is partitioned in rectangular shaped regions, called interrogation windows. The study of the cross-correlation function allows to determine the most likely displacement of each of these regions. With reference to a generic interrogation window, \( W \), and by assuming that image deformations are negligible with respect to the rigid displacement, the cross-correlation analysis can be interpreted as the following optimization problem [17]

\[
\max_d \int_W f(r) g(r + d) \, dA,
\]

where \( r \) represents the position vector, \( d \) denotes the displacement vector to be varied in the optimization task, \( f \) and \( g \) are the image intensity fields (i.e. brightness distributions) of the first and second frame, respectively. The integral in Eq. (1) represents the correlation function, \( \phi_{fg} \), between \( f \) and \( g \). Today, PIV usually employs digital images, composed of a discrete number of pixels [22]. The cross correlation function, \( \phi_{fg} \), can be rewritten in the following discrete form

\[
\phi_{fg}(m,n) = \sum_{i,j=-M}^{M} f(i,j) g(i+m,j+n),
\]

where \( M \) is the total number of pixels in \( W \), while \( m \) and \( n \) denote the generic row and column, respectively. The cross-correlation process is usually speeded up by employing a fast Fourier transform (FFT), instead of algebraically calculating Eq. (2) [22]. If the fluid under investigation is transparent, it needs to be seeded by small reflective particles so as to be able to recognize moving brightness patterns. A laser sheet is typically used to illuminate the area under investigation in the flowing domain. The seeding density and the size of seeding particles are important factors for reliable PIV calculations and also influence the spatial resolution of measurements. Moreover, the accuracy of a PIV analysis is strongly related to the size of the interrogation window. As a general rule, the size of the interrogation window should not be less than 4 times the maximum displacement to have a high-confidence measurements [6]. If it is smaller, the displacement estimation will be inaccurate, because some seeding particles may leave the interrogation window in the second image (loss-of-pairs issue). On the other hand, the finite size of the interrogation window yields a slight systematic underestimation of the displacements [20]. The size of the interrogation window limits the effective spatial resolution of PIV output, since the estimated displacement is an average of the displacements of all seed particles inside the interrogation window. Moreover, owing to Nyquist sampling theorem, the spatial wavelength response exhibits an upper cutoff at half the size of the interrogation window (e.g. [22]).

More recently, PIV techniques have been employed to granular flows (e.g. [4,7]). This application is often referred to as granular-PIV (G-PIV). In this case, seeding particles are unnecessary, because the moving grains usually have good optical properties for brightness pattern identification. Thanks to natural grain patterns, the equivalent seeding density is very high with obvious advantages. However, some new issues arise. Measurements inside the flowing mass are impossible since the granular material is non-transparent, so that the use of laser sheets to illuminate the grain particles is inadequate. Alternative lighting systems have been proposed, such as flash lights [4,10] or flickering-free LED lights [14,18]. The outlined issues, related to the finite size of the interrogation window, become more important in case of highly sheared flows, which is common in granular flows with no-slip bottom boundary condition. The reliability of PIV algorithms in this context is still matter of debate.

In order to improve the dynamic range of velocity measurements and the spatial resolution of PIV outputs, some more sophisticated algorithms, using window displacement, multi-grid or multi-step approaches (e.g. [17]), have been proposed. The basic idea of window displacement methods [6,21] consists of applying a relative shift of the interrogation window in the second image, by using a predictor displacement. Such a technique is found to yield an extension of the lower end of the dynamic range due to the increase of signal to noise ratio [21]. A multi-grid iterative refinement of the interrogation window is proposed in [16], which permits an increase of spatial resolution.

Here, we use the freely available Matlab package, PIVlab, written by W. Thielicke and E. J. Stamhuis (http://pivlab.blogspot.it/). This package has been recently used in different applications (e.g. [5,11]).
The code performs PIV analyses, by using a FFT correlation with multiple passes and deforming windows. The displacement information of each pass is used to shift the interrogation window in the subsequent pass. Thanks to these features, this algorithm yields a high spatial resolution, high signal-to-noise ratios and high dynamic ranges. The sub-pixel estimation is based on a Gauss interpolation.

3 Experimental tests

2.1 Experiments on Ottawa sand

An experimental campaign on free surface steady state flows of Ottawa sand was carried out at the Dept. of Hydraulic and Ocean Engineering of the National Cheng Kung University (Taiwan). The experimental apparatus is composed of a straight Plexiglas laboratory channel, 140cm-long and 4cm-wide. The upper part of the channel, 28cm-long, is used as reservoir for the granular material. The reservoir is separated from the lower part of the chute by a thin baffle with a 5cm-high opening, close to the bottom. The granular material used was Ottawa sand (ASTM C-778 20/30), which is a well-sorted round shaped silica sand with a mean diameter of 0.725 mm. Although the seeding is usually unnecessary in G-PIV applications, in order to improve the quality of PIV analysis, a small amount of sand (about 10% of the total weight) has been colored black by using alcohol-based ink. In each experiment, around 6.7 kg of Ottawa sand, was loaded into the upper reservoir and let flow down. The image recording was performed by using a high-speed camera (IDT XStream3-Plus), that was placed at the side of the inclined channel, 20cm downstream the release gate. The camera is equipped with a flickering-free LED light, placed aside the channel. A second light source of fluorescent type was placed above the channel with the purpose to reduce incidental shades by increasing the environmental illumination. The camera frame rate was set equal to 2000 frames per second (fps), with a spatial resolution of 648x312 pixels. The shutter time was 100 μs to avoid motion blur. A picture of the experimental apparatus is reported in Fig. 1 and a sample of captured image is shown in Fig. 2.

After opening the release gate, an initial transient motion, lasting a few seconds, was observed. Then, a statistically steady state took place. A final transient flow took place as the reservoir continued to empty. The present study is only focused on the intermediate stage in steady state. Different runs were carried out by changing the chute inclination between 28° and 40° and bottom roughness. Each experiment was repeated at least three times. It has been found that a time-averaging on 1000ms is sufficient to obtain reliable and stable time-averaged velocity profiles. For more details refer to [14]. Before the PIV analysis, all the frames were subjected to a pre-processing contrast limited adaptive histogram equalization (CLAHE) to enhance the image contrast.

Preliminary PIV measurements were obtained through using the commercial code proVISION-XS by IDT Corp. Since the maximum grain displacement was found to be less than 10 pixels in all experiments, the interrogation window was chosen equal to 32x32 pixels (corresponding to 2mmx2mm in real scale) with a mesh overlap of 50%. Considering the image scale, the particle-image diameter is around 11 pixels.

The same images were processed by PIVlab code with two different setups. Firstly, a single step cross-correlation analysis with an interrogation
window of 32x32 was performed. Then, a two-step setup was chosen, where an interrogation window of 32x32 was set in the first step and a refinement of 16x16 was chosen in the second one. For sake of brevity, here we only show the PIV analyses of runs reported in Table 1, where the chute bottom surface was of smooth type (Plexiglas).

Table 1

<table>
<thead>
<tr>
<th>Run</th>
<th>Chute incl.</th>
<th>Material</th>
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<tbody>
<tr>
<td>R-31s</td>
<td>31°</td>
<td>Ottawa sand</td>
</tr>
<tr>
<td>R-40s</td>
<td>40°</td>
<td>Ottawa sand</td>
</tr>
</tbody>
</table>

PIV calculations were performed on non-overlapping image pairs (e.g. 1-2, 3-4 and so on). The velocity profiles are averaged over a time-window of 1 second (i.e. over 1000 measurements). With \( x \) denoting the down-flow direction, \( x \)-component velocity profiles of runs R-31s and R-40s and related standard deviations are reported in Figs. 3 and 4. As one can easily see from Figs. 3-4, all time-averaged velocity profiles are very similar, regardless the PIV algorithm used. As regards the run R-31s, the average relative discrepancy, \( \left| \frac{u_{x}^{\text{PIVlab}} - u_{x}^{\text{pro-VISION}}}{u_{x, \text{max}}^{\text{pro-VISION}}} \right| \), between PIVlab (single-pass) and pro-VISION-XS results is 1.40%, while it is 2.95% between PIVlab (two-pass) and pro-VISION-XS results. By considering the scale and the time interval of frame pairs, the displacement disagreement is of order of 0.1 pixels.

In R-40s, the average relative discrepancy is 1.62% between PIVlab (single-pass) and pro-VISION-XS and 2.92% between PIVlab (two-pass) and pro-VISION-XS results. It is interesting to note that proVISION-XS algorithm yields a systematic underestimation of flow velocities, especially near the free surface, compared to the two-pass PIVlab algorithm. This behaviour is congruent with the expected increased accuracy of the two-pass algorithm, due to a wider dynamic range and bigger wavelength bandwidth [17]. The velocity profile is almost linear with a non-null bottom slip velocity in run R-40s (Fig. 4a). Differently, a no-slip bottom boundary condition arises in run R-31s (Fig. 3a). Because the bottom surface roughness is kept constant in both experiments, such a different behaviour is only due to the additional resistance exerted by the side walls [14]. In this case, the velocity profile can be regarded as composed of a lower exponential tail, smoothly connected to an almost linear profile, close to the free surface. Such a behaviour is congruent with other experimental studies on different granular materials (e.g. [9]).

Standard deviations of instantaneous velocities are reported in Figs. 3(b)-4(b). In the ideal case of infinite PIV accuracy, these deviations are uniquely due to velocity fluctuations. In real cases, PIV
delivers an error, related to the cross-correlation procedure itself (e.g. noise, loss-of-pairs) and to the sub-pixel interpolation, which usually provides an accuracy of order of 0.1 pixels in case of single pass PIV algorithms and Gaussian-type sub-pixel interpolation [17]. Despite these unavoidable uncertainties, from Figs. 3(b) and 4(b) it is clear that the standard deviations, predicted by different PIV algorithms, exhibit a very similar behaviour, where the mean fluctuation velocity increases with the distance from the bottom surface. This agreement among different PIV algorithms supports the feasibility to measure granular temperature profiles from a PIV analysis. Nevertheless, in all PIV analyses standard deviations close to the free surface are noticeably influenced by saltating particles and, thus, cannot be regarded as reliable estimates of granular temperature.

An important advantage of the increased spatial resolution of PIVlab two-pass analysis is the improved identification of the free surface position. As well, owing to the different spatial resolution, the distance from the bottom surface of the closest velocity vector is only 8 pixels (half the interrogation window) in PIVlab two-pass analysis, while it is 16 pixels in the other two analyses.

### 2.2 Experiments on POM artificial beads

A second experimental campaign was carried out at the Laboratory of Hydraulic Engineering (University of Salerno). The main purposes of this additional study are to investigate the PIVlab performances on a granular material with different optical properties and to test the multi-step capabilities of the code. The experimental apparatus, consisting of a 2m-long 8cm-wide Plexiglas chute, is very similar to the previous one.

The upper part of the channel is used as reservoir and is connected to the lower part through a sluice gate with an 8cm-high opening, close to the channel bottom. Different from the previous experiments, the granular material, here employed, consists of artificial plastic beads, made of acetal copolymer (POM), with mean diameter of 3.3mm [13]. The smooth and shining optical surface of the artificial granular material (Fig. 5) is expected to be more challenging for a PIV analysis than natural Ottawa sand, previously employed.

The channel bottom was made of Plexiglass and two different inclination angles, 30° and 40°, were investigated. The experimental procedure was the same as the previous campaign. Before each run, the granular material was loaded in the upper tank. Then, the shutter was manually removed and side-wall recordings of the intermediate steady-state motion were obtained. In order to do so, the experimental apparatus was equipped with an high-speed camera (AOS S-PR1), capable to record at 1000fps and placed aside the channel together with a flickering-free LED lamp. The shutter time was chosen equal to 50μs in order to avoid motion blur.

![Granular material (POM beads).](image)

All the PIV analyses were performed on partially overlapping image pairs (e.g. 1-2, 2-3 and so on), so as to have 1000 PIV measurements in a time interval of 1s. Considering the image scale, the particle-image diameter is around 22 pixels. The experiments, here reported, are listed in Table 2.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>R2-30s</td>
<td>30°</td>
<td>POM beads</td>
</tr>
<tr>
<td>R2-40s</td>
<td>40°</td>
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</table>

In Fig. 6, PIV analyses related to run R2-30s are reported. Three different PIV setups were used:

1. single-pass algorithm with 32x32 (approximately corresponding to 4.8mmx4.8mm in real scale) interrogation window;  
2. two-pass algorithm with 32x32 and 16x16 interrogation windows for each pass;  
3. three-pass algorithm with 64x64, 32x32, 16x16 interrogation windows for each pass.

In all PIV calculations a 50% mesh overlap was employed. As one can see from Fig. 6(a), the flow velocity profiles are almost linear, similarly to run R-40s, but exhibit a slightly sigmoid shape and an higher slip bottom velocity, depending on the smaller angle of friction of the granular material. In this experiment, the single-pass calculation noticeably underestimates the flow velocity profile, especially near the bottom surface, compared to the three-pass calculation. This discrepancy seems to be due to the more challenging optical properties of the granular material and might also depend on the higher slip velocity. However, it is interesting to note that the two-pass and three-pass calculations provide very
similar velocity profiles, except some residual disagreement near the bottom surface. This behavior is congruent with the fact that higher is the number of passes, the higher will be signal to noise ratio in the cross-correlation procedure [16,21]. It is difficult to know a priori how many passes are necessary to get a given accuracy. An heuristic approach could be finding the limiting velocity profile, by simply increasing the number of passes until the velocity differences can be considered negligible for the particular purpose.

As regards the standard deviation (Fig. 6b), it is remarkable that the behavior is extremely different from that observed in Figs. 3(b)-4(b). In fact, the mean fluctuation velocity exhibits a maximum value (approx. 0.06 m/s) at the bottom and decreases up to 0.015m. Then it increases up to the free surface. Such a behavior could depend on the mechanical properties of the granular material (e.g. stiffness, coefficient of restitution etc.) and on the higher slip velocity at the bottom surface. A further investigation about it is advisable.

The PIV analyses, related to run R2-40s, are reported in Fig. 7. Because of a very high maximum velocity, which is greater than 8 pixels/frame, also a four-pass calculation was carried out, featuring 128x128, 64x64, 32x32, 16x16 interrogation windows at each pass and a 50% mesh overlap. The other calculations were performed with the same parameters as run R2-30s.

From Fig. 7 it is interesting to note that three-pass and four-pass calculations deliver almost identical velocity profiles. Thus, in this case no real advantage exists in using the more time-consuming four-pass algorithm. In other words, a three-pass calculation with a first interrogation window of 64x64 pixels is sufficient to reconstruct reliably the entire velocity field. Similarly to run R2-30s, single-pass noticeably underestimates the velocity profile with a mean relative error of 5.5% with respect to the four-pass velocity profile. Differently, two-pass calculation yields reasonable results with less computation time and a mean relative discrepancy of 2.55%, compared to the four-pass velocity profile. As regards the standard deviation profiles (Fig. 7(b)), similar results as the ones of run R2-30s are found.

4 Conclusion
In this work the open-source code, PIVlab, has been used to estimate side wall velocity profiles in channelized free surface granular flows. A validation of the algorithm, by comparison with the commercial code proVISION-XS, has been provided with excellent results. The PIVlab code
yields very similar velocity profiles to the commercial PIV code with the advantage of being freely available. Moreover, PIVlab gives the opportunity of reliably increasing the spatial resolution by means of the multi-pass multi-grid capabilities. Secondly, PIVlab has been employed in another experimental campaign with the purpose of investigating its multi-pass multi-grid features on a artificial granular material with different optical properties. It has been found that the velocity profiles converge toward a limiting distribution, by increasing the number of passes. It cannot be known a priori the right number of passes to obtain a given accuracy but there is clear evidence that a straightforward heuristic approach, consisting of progressively increasing the number of passes, is capable to provide reliable results.

This work also suggests that a PIV approach can be reliably used to measure fluctuation flow velocities in granular flows. From a physical viewpoint, this short research reports that the fluctuation velocity may increase or decrease with the distance from the bottom surface, depending on the nature of the granular material and the kinematic bottom boundary condition. A further research about this interesting topic is advisable.

The proposed approach can be fruitfully used to better understand some features of the granular flow dynamics, and, thus, to shed light also on the propagation stages of real-scale geophysical granular flows, such as avalanches and debris flows.

Acknowledgements
The authors wish to thank Dr. Chih-Yu Kuo for his generous support of the high-speed camera IDT XStream3-Plus and the commercial software ProVISION-XS. The authors also thank Ing. Nicola Immediata for his useful support in designing the experiments performed at the Environmental and Maritime Hydraulics Laboratory of the University of Salerno.

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