Photometric analysis of the effect of substrates and obstacles on unconfined turbidity current flow propagation

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ABSTRACT: Experimental flows of turbidity currents are investigated using photometric analysis. The present work studies the interaction of turbidity currents with different obstacles and substrates, using a 25 mm square-bottomed cylinder obstacle, and a 0.8 mm rough surface for the entire base of the test basin. Notable differences are evident in the nature and characteristics of current flows. The rough substrate decreases current velocity and minimises the appearance of turbidity current phenomena, such as lobe and cleft formation and Kelvin-Helmholtz billows. Presence of an obstacle causes localised decreases in velocity, but otherwise has little effect on overall velocity of the flow. Lobe and cleft formations increase significantly after the current passes over an obstacle. It is concluded that these findings warrant the inclusion of rough substrates in further experimental testing. A generally used smooth laboratory substrate does not take into account substrates encountered in nature, and our preliminary study shows that there are significant flow characteristic differences. The presented work is based on limited tests, it is recommended to undertake a more comprehensive study to evaluate the substrate roughness effect.

1 INTRODUCTION

Turbidity currents are a type of gravity flow where sediment-laden fluid flows through deep ocean or lake environments, driven by a higher relative density of the fluid to the ambient water (Simpson, 1982). They can cause substantial damage to submarine structures (Ermanyuk & Gavrilov, 2005), including oil well caps and oil or gas pipelines (Gonzalez-Juez et al. 2009). Limited research exists into the nature of these flows in regard to their interactions with obstacles in an unconfined environment. Nogueira et al. (2012) did study the influence of bed roughness in a confined environment. Based on the previous studies, the hypothesis was developed that by using photometric analysis of experimental current flows and examining the characteristics of turbidity currents as they interact with obstacles and rough substrates, further insights into the dynamics of turbidity current flow can be obtained.

The study was thus structured as a preliminary comparison of current interactions with different configurations of rough substrates and obstacles. Three obstacle/ substrate setups are used:

a) Flow of an unconfined turbidity current over a smooth glass surface.

b) Flow of an unconfined turbidity current over a 25 mm square-bottomed cylinder running perpendicular to flow direction, on a smooth glass surface.

c) Flow of an unconfined turbidity current over a textured substrate of 0.8 mm roughness height.

2 METHODOLOGY

2.1 *Experimental methodology*

Testing of experimental lock-exchange flows was undertaken at the Fluid Mechanics Laboratory at the University of Auckland. The existing purpose-built apparatus for turbidity current testing consisted of a basin, length of 2420 mm, width of 2000 mm and height of 600 mm (Fig. 1a), and adjacent lockbox. The basin was constructed on the concrete floor of the laboratory, with 12 mm clear Perspex glass walls and plywood framing. Test flows travelled over a smooth glass false floor at 200 mm height above the concrete floor. A lockbox, situated at the proximal end of the basin, held the sediment-laden fluid before release.

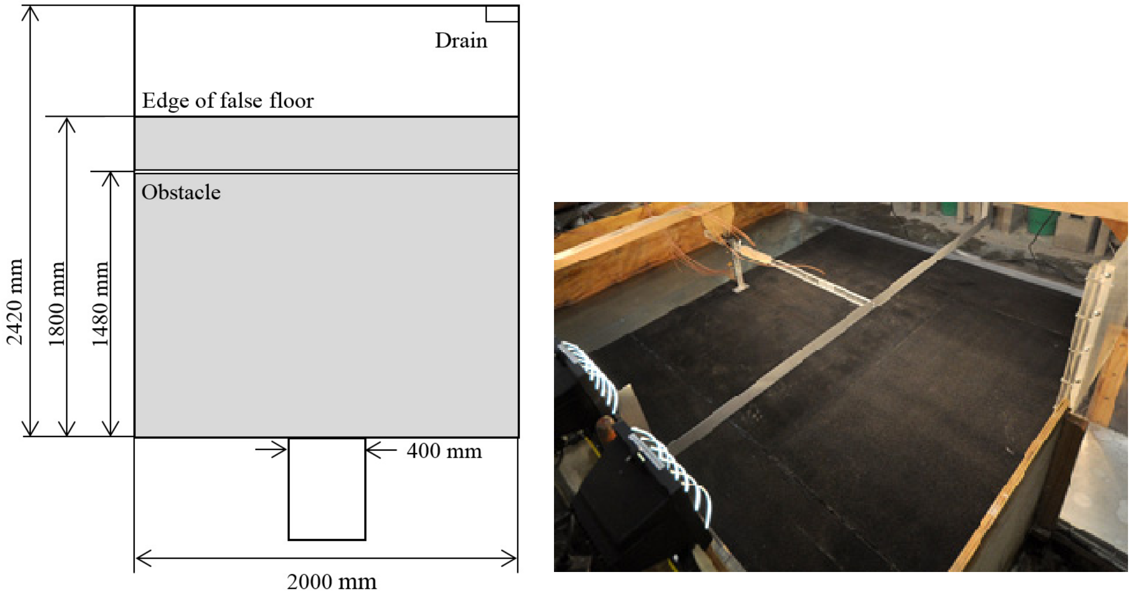

Figure 1. (a) Plan view diagram of basin setup. (b) Fixed rough substrate used for the third test scenario

Fluid for the sediment-laden flow was created as a slurry of powdered kaolinite clay and Ballotini (2 % each, by volume) in water, which resulted in a current density in the range of 1075-1082 kgm^{-3}. Use of this mixture was justified by previous research recommending the proportions as optimal for generating a sufficient density gradient for turbidity current flow in an experimental setting (Sangster, 2011).

The obstacle selected for the second test scenario was a 25 mm x 25 mm square-bottomed aluminium cylinder. The height of 25 mm was chosen to roughly approximate the size and shape of a submarine cable, as these are common obstacles that a turbidity current in nature may interact with.

The final test scenario incorporated the use of a fixed rough substrate, which was attached to the glass false floor (Fig. 1b). The substrate consisted of 0.8 mm diameter sand glued evenly over a 4 mm thick silicon plastic sheet.

Use of multiple recording instruments, including plan and elevation cameras and a digital video camera, meant that points of reference were required to synchronise the images captured, for correct analysis.

To provide this reference between the cameras, the video camera started recording first, and plan view camera was triggered using a remote switch, at the point when the lockbox gate lifted from the floor of the basin. Oral direction from the person operating the plan view camera was given to the person operating the elevation view camera to ensure synchronisation. As images were captured at 4.5 frames per second, a small margin of error was likely between the starting frames for each camera. To adjust for this, profiles created for the plan and elevation view were matched by finding the furthermost point on the plan profile (in the longitudinal direction) and matching it to the elevation profile that had progressed to the same point in the longitudinal direction.

The following steps were undertaken during the experimental testing:

a) Lighting setup rigged into place and switched on, all other lighting in Fluid Mechanics Laboratory switched off (Fig. 2a).

b) Cameras rigged into position, focused and set to appropriate zoom by connecting to laboratory computer and adjusting settings in Camera Pro 2.0.

c) Cameras disconnected from computer, remote switch attached to plan view camera.

d) Slurry of water, kaolinite and Ballotini mixed in large bucket.

e) Video camera started recording.

f) Slurry poured into lockbox and lockbox gate lifted slowly and evenly.

g) Plan and elevation view cameras begin capturing images at the point where lockbox gate lifts off basin floor.

h) Cameras continue to capture images at 4.5 frames per second until the flow reaches the end of the false floor.

2.2 *Digital camera setup and illumination*

Two Nikon D90 digital cameras captured images of the turbidity current flow in plan and elevation view (Fig. 2b). The plan view camera was attached to a rig, suspended from the ceiling of the laboratory, facing directly downwards. A second camera was set on a tripod at the side of the basin to capture elevation view images, equidistant from the basin wall as the plan view camera was from the water surface.

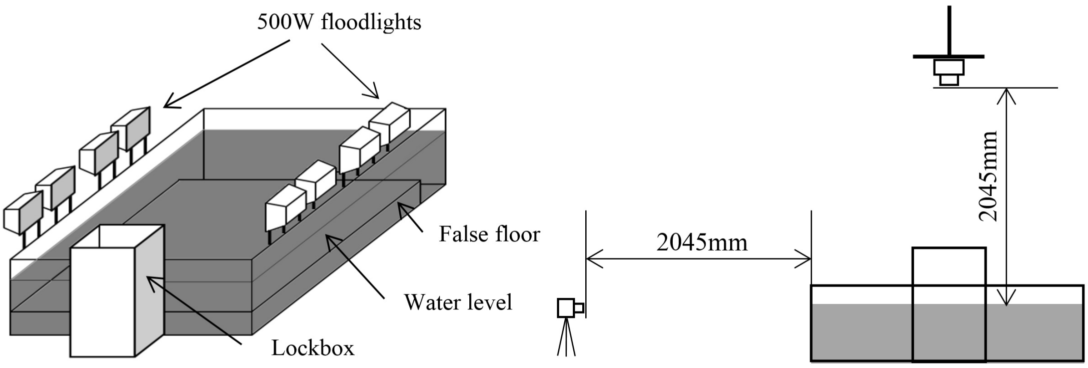

Figure 2. (a) Lighting configuration for optimal illumination of turbidity current flow. (b) Plan and elevation camera setup

Camera mode was set to manual so that all settings could be adjusted. Shutter speed was set to 1/200, and aperture 3.5 to obtain optimal image quality. Capture mode was set to ‘continuous high speed’, with a frame rate of 4.5 frames per second. A video of each test run was recorded using a Casio Lumix camera, mounted approximately 2m away from the basin walls at the side. Due to the relatively poor video resolution, video data collected was for observational purposes only and not used for analysis.

Eight 500W floodlights provided illumination to the testing basin (Fig. 2a). Photometric analysis measures the amount of light and dark in an image, thus it was a priority to arrange lights in the best configuration to obtain the best level of clarity and contrast in captured images. To find the best configuration, four different variations were trialed in preliminary tests, and images processed in MATLAB to evaluate their suitability.

2.3 *Photometric methodology*

Recently, photometric analysis of gravity current flow is becoming more popular (Nogueira et al. 2013). The photometric analysis processes each captured image, to obtain a profile of the current’s outer boundaries for each image, and use these to create flow progression contour plots (plan and side view), to examine the flow and compare the interactions with different substrates and obstacles. Images captured on the Nikon D90 digital camera were saved first on to the camera's memory, and later uploaded to a PC for analysis.

Pre-processing of images in Adobe Photoshop involved the removal of known lens distortion from the Nikon D90 camera, and adjustment of images to optimal contrast and brightness for processing. For each test run, the appropriate lens distortion and rotation correction was set to ensure basin sides were vertical and parallel. Brightness and contrast were also adjusted to improve image quality for processing. These modifications were recorded as an Action in Photoshop, and applied using Batch Process, to modify each image in a photo-series.

Corrected images were processed using photometric analysis in MATLAB to generate current profiles for each frame. Custom code was developed in MATLAB to generate the most accurate and clear results. For each experimental test, the image series contained between 80-110 frames. Steps carried out in MATLAB processing are detailed below; Figures 3 and 4 illustrate the transformations for plan and elevation views, respectively.

The processing code used the following steps to generate the required visualisations (Figs 5a, b, c):

a) Read jpeg image file into MATLAB.
b) Crop image to area of interest.
c) Convert to gray scale, black out UDVP rig.
d) Apply threshold to produce binary image.
e) Filter binary image to remove areas of light.
f) Generate profile of object in binary image.

In another study (Wilson & Friedrich, 2014), ultrasonic Doppler velocity profiler (UDVP) measurements were used to better quantify the turbulence characteristics of turbidity currents. Thus, a measurement rig is visible in the plan view contour plots, and head outlines are not available for the sections occupied by the UDVP measurement rig.

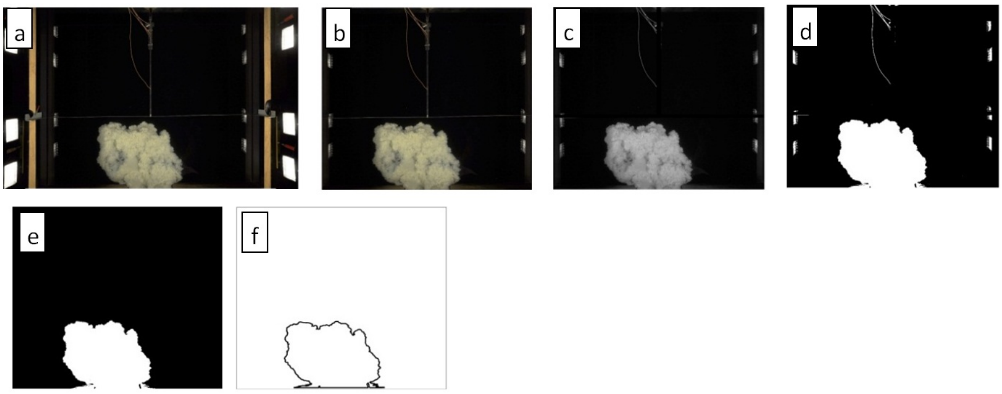

Figure 3. Plan view image processing

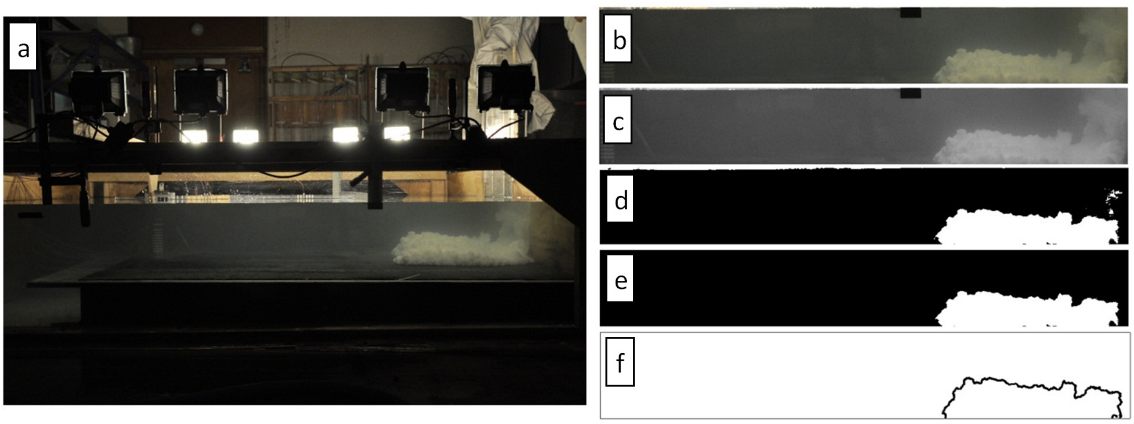

Figure 4. Side view image processing

3 RESULTS AND DISCUSSIONS

Profiles for each image in a series were plotted to create a contour plot, mapping the progression of the current and using a graduated colour scale to indicate current progression (Figs 5a, b, c).

3.1 *Comparison to previous research*

Initial research into turbidity current flow found several conclusions that could be compared with results for this study. Experimental tests over a rough substrate with a variety of heights (0.7 mm - 3.0 mm) showed minimal effects in the initial phase of motion, but in the latter phase the velocity reduction is significant (La Rocca et al. 2008). Velocity was measured by the extent of the current head over a set of continuous-capture images from above. Our results, using contour line spacing as an approximation for relative velocities, confirmed La Rocca's et al. (2008) observation. Other research indicated that gravity currents showed a raised current head and decreased velocity leading up to an obstacle (Lane-Serff et al. 1995); this was not evident in testing, however the differences in experimental setup may account for this. Lane-Serff et al. (1995) tested a gravity current over a triangular prism-shaped obstacle, approximately half the height of the current, whereas our study examined a square-bottomed cylinder of a height around 1/10th of the current height. The difference in proportions meant that in our study the obstacle had less impact on the flow.

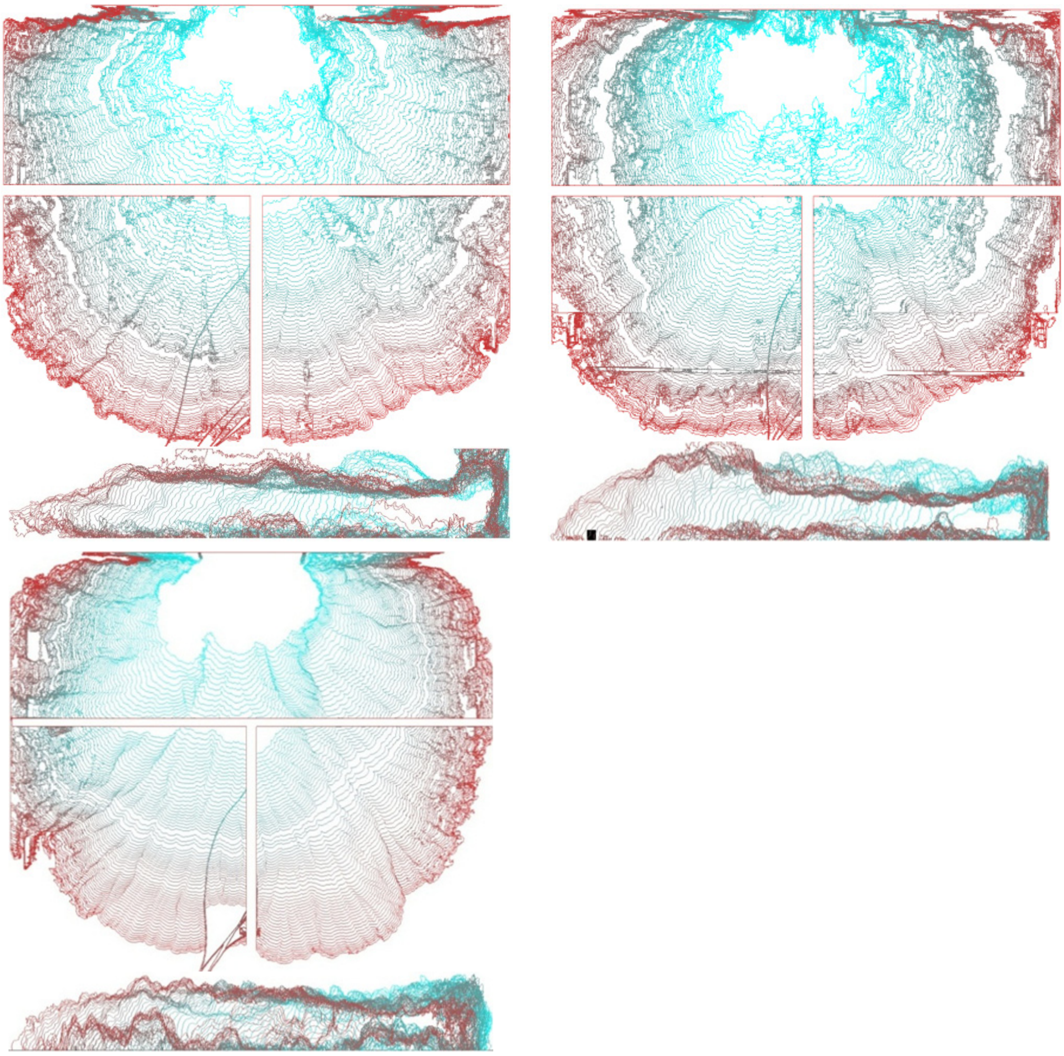

Figure 5. Plan and elevation velocity contour plots: (a) Control scenario. (b) Obstacle scenario. (c) Rough substrate scenario

3.2 *Significance of results*

Several key insights gained from the analysis have implications for the behaviour of turbidity currents in nature, and important considerations for experimental testing. It needs to be noted that those considerations are based on limited tests, and a more comprehensive study is needed to validate the presented initial observations.

The rough substrate minimised Kelvin-Helmholtz billows, maintaining the shape of lobes formed early in the flow. In minimising the billows, it absorbed kinetic energy in the current and caused the overall current velocity to decrease relative to the control setup. As most turbidity currents in nature flow over an ocean or lake floor, it is realistic to assume that a 0.8 mm rough substrate is more representative of actual conditions than a smooth glass substrate. Based on the marked difference in the current flow over the rough element, the inclusion of rough substrates in experimental testing could be considered as a requirement for results relevant to real-life circumstances. To validate this claim, further testing using a range of roughness heights should be undertaken to fully understand the relationship between substrate roughness and current flow characteristics.

Furthermore, the reduction in development of lobe and cleft formations as the current progressed over a rough substrate also holds implications relating to the real-life occurrence of currents. The formation, growth, and subdivision of lobes in the current form are the predominant method by which the flow progresses forwards and breaks down. As the rough surface slows down this process, there are likely implications for the magnitude of the forces in the flow, and local velocities in the different flow regions.

Results obtained in this study illustrate the importance of the topography a current is traversing in determining the nature and characteristics of the flow. Thus, the importance of incorporating obstacles and roughness in substrates is highlighted for further research, to better mimic the behaviour of turbidity currents as they are found in nature.

3.3 *Statistical relevance and limitations to testing*

Attaining statistical relevance for qualitative analysis of this nature is difficult; as results are non-numerical and turbidity currents display a large degree of random variation in the flow progression. A large number of samples would be required to eliminate all variability and reach definite and irrevocable conclusions. Testing methods were perfected to find the best setup and procedures for accurate data collection. The lighting configuration in particular required an iterative procedure of setting up four different configurations, capturing photos from a test run and processing these images in MATLAB to find the configuration that gave the best clarity in profiles obtained.

Limitations to experimental accuracy were found in capturing images from both a plan and elevation view. The relatively small depth of 265 mm relative to the basin width of 2000 mm meant that the plan view showed very clear outlines of the turbidity current as it progressed, whereas the elevation view contained some cloudiness, especially in the rear sections of the flow. However, this was a trade-off between the plan and elevation views, as the wide basin allowed the accurate observation of unconfined flows, which would otherwise be prevented in a narrower testing structure.

3.4 *Recommendations for future work*

Further research in this area of turbidity current interactions with obstacles is supported by the findings of this study. In particular, the rough substrate used is more representative of the ocean or lake bed that turbidity currents would encounter in nature, compared to the smooth glass base. Given the strong influence of the rough substrate in inhibiting certain characteristics of the current flow, further research would benefit by including the roughness in order to gain results that are relevant to turbidity currents in nature. Additionally, including the effect of sediment entrainment in turbidity current flow further adds to the relevance of results as the entrainment of sediment into a current, from the bed it is travelling over, can play a strong role in the nature and evolution of the turbidity current.

4 CONCLUSION

a) The presence of a rough substrate of 0.8 mm height caused unconfined turbidity current flow to slow during the latter phase of flow, relative to the control setup.

b) Flow over a rough substrate of 0.8 mm height showed diminished Kelvin-Helmholtz billows and the absence of a hydraulic jump between the flow head and the rear of the flow.

c) Findings of significant influences of the rough substrate on flow velocity and characteristics indicate the need for inclusion of a rough or textured substrate in further experimental testing, to ensure results are relevant to turbidity currents as they occur in nature.

d) Flow over a 25 mm square-bottomed cylinder obstacle showed localised changes in velocity both preceding the obstacle and after traversing it, however the overall current velocity remained the same as that for the control setup

e) The presence of a 25 mm square-bottomed cylinder caused the number of lobe and cleft formations at the current's leading edge to increase up to a factor of two

f) Inclusion of sediment entrainment as an experimental variable is recommended for further research.

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