Review of Doctoral Dissertation of **Arianna Varrani**
Thesis title: **Onset of motion of compact-shaped microplastics in open-channel flows**

General comments on thesis:

Overall, the structure and form of the thesis are very good, and it is formatted to an excellent standard throughout. It is, however, a very concise thesis, totalling 88 pages (+ references and appendices), which is far shorter than any PhD theses (UK and international) that I have examined in the past (which have typically ranged from 150-250 pages). In terms of the quality of the work itself, the experimental studies that are reported in the thesis are performed to a high standard and yield interesting and potentially valuable results, looking both at the initiation of particle motion from homogeneous beds of microplastics, and the remobilisation of microplastics from the surface of static beds of sand and gravel. This topic clearly has considerable topical interest at present time, given the levels of microplastics being encountered in all aquatic systems, including rivers.

My main concern, which is associated with the thesis length, relates to the lack of detail provided within some of the results chapters, particularly around some of the data processing and analysis techniques that were employed to analyse microplastic movements and hence determine appropriate threshold conditions. Also, many of the results themselves have been presented very much in a summary or ensemble format, meaning that it is not straightforward to ascertain individual differences between the multiple runs and experimental conditions that have been explored within the study. There may also be an (over?) reliance on characterising thresholds for particle motion in terms of the tried and tested Shields' parameterisations, which in many respects is entirely understandable. This, however, precludes any real physical analysis of the individual fluid-particle interactions associated with instantaneous and local effects of near-bed flow turbulence (e.g. turbulent bursts and sweeps) that can initiate particle motions, which will ultimately be the main cause of microplastic particle entrainment and remobilisation of microplastics from the bed surface (rather than spatially and temporally averaged shear velocity conditions). That said, clearly from a numerical modelling point of view, specifying this initiation of microplastic particle motion as an average threshold criterion has its advantages in terms of modifying existing sediment transport models (that are typically based on excess critical shear stress) to account for the transport of microplastics when these are less dense than traditional clastic bed sediments (i.e. sands and gravels).

It would also have been desirable to see more detailed information provided on the different measurement techniques (e.g. ultrasonic velocity profiling, sediment bed visualisation for particle motion) and data analysis methodologies (visual assessment of particle detachments, limit state/semi-probabilistic approach to determining threshold bed shear velocity) in order to better understand how the processed data that is largely presented in ensemble-form within the results chapters is derived for individual experimental runs and conditions. As it stands, some of the sections that provide relatively concise descriptions of these methods are not easy to follow and interpret. This aspect could be significantly improved by giving more examples of the kinds of manipulations and calculations performed on the raw datasets from individual runs, and in the case of the assessment of particle detachments, better visual representation of the different steps in image manipulation and analysis involved.

Finally, the candidate demonstrates that, in general, both her threshold data on (i) the initiation of motion for microplastic particles within homogeneous beds of the same microplastics, and (ii) the remobilisation of microplastics from the surface of static beds of sands and gravels, show good agreement with past studies. I therefore think what is currently missing is a more definitive statement on what new knowledge has been derived specifically from these experiments that builds on, and advances, the findings from previous similar studies.

Overall, the candidate has clearly demonstrated a comprehensive knowledge of the subject under investigation, firstly, on the incipient motion of microplastic particles from a homogeneous bed of the same particles and then on the remobilisation of microplastic particles from the surface of a clastic (sand or gravel) sediment bed. In this regard, the candidate has recognised and addressed some of the outstanding research questions in the field, particularly around how the transport of microplastics differs from that of other clastic sediments. They have carried out a competent, comprehensive piece of research that will be of great interest to sediment transport and microplastics research community. I therefore support the candidate's admission to public defence.

Alan Cuthbertson

Dr Alan Cuthbertson, 06 May 2025.

For records, individual, more detailed, comments on each of the chapters of the thesis are also provided below.

Chapter 1 Outline

Specific comment:

P1 – the problem statement does not actually provide a definitive statement on what the problem being addressed actually is, certainly not in an explicit manner. I would also suggest that the research questions are a bit vague.

P2 – I also found the section on “the terms incipient motion and remobilisation” difficult to follow and interpret. This is explained much clearer later in the thesis. Basically, from my understanding, incipient motion refers to microplastic particle motion from a homogenous bed of the same microplastics, while remobilisation is the movement of microplastic particles from the surface layer of stable, immobile clastic sediments (e.g. sands and gravels).

Chapter 2 Introduction

General comment:

This chapter is generally very well written and gives a comprehensive review of initiation of motion studies and the different methodologies and approaches utilised. It would be good if there was a more definitive statement at the end of the chapter reinforcing the current gaps in knowledge that motivate the current study and help identify the research questions. There also needs to be a clearer rationale as to why the candidate has focused on defining Shields’ type threshold criteria for microplastic incipient motion and remobilisation, particularly after the wide range of different approaches have been introduced within Chapter 2.

Specific comments:

P6 – the main thesis aim seems to be limited to defining average mobility thresholds for microplastics that could be used in existing sediment transport formulae. However, does the measurement techniques employed in the experimental study not potentially permit a closer look at the physics of fluid-particle interactions that specifically result in particle motions?

P8 – the equation for the Froude number (2.1) is incorrect. This should be $Fr = U/\sqrt{gL}$.

P10 – third line in section 2.2.1, should this be (Bagnold, 1966…) rather than just (1966…)?

Chapter 3 Methodology

General comment:

On the whole, this chapter is also well-written and provides a good level of detailed information on the experimental design and set-up. Again, however, this could have been clearer with more images or schematics provided for the set-up and methodologies applied in the experiments. At times, the largely text-based descriptions of these methods and apparatus are not entirely clear. An example of this is the description of the ultrasonic velocity profiler (UVP) used in determining the near-bed hydrodynamic conditions for the different experimental set-ups. There is very little information provided on the operation of these systems, what raw data is provided and how this is processed to provide time-averaged and spatially averaged streamwise velocity profiles to determine the shear velocity for each experimental condition tested. I think this is one of the issues with such a concise thesis, some of the important detail that would normally be included on experimental measurement techniques and data analysis methodologies is not there.

Specific comments:

P34 – there is very little description provided for the two UVP devices used in the experiments, why the same device was not used throughout and why the configuration of near-bed velocity measurements was altered between different experimental set-ups. Were both systems tested together at any point to gauge consistency in measurements?

P34 – what is meant by “ad-hoc image analysis algorithms”?

P34 – clearer zoomed images showing the geometric nature of the two types of microplastic particles used would have been really helpful, particularly since geometric shape is described later as potentially being important in the threshold of motion.

P39 – it was not clear from the description of the experimental set-up in Fig. 3.2 how the UVP transducers were mounted, a schematic diagram might have helped here. In terms of the contour lines for the UVP measurements in Fig. 3.3, it would also have been interesting to see these for more than one experimental condition. It might also have been interesting to visualise the similar isolines for the lateral velocity component across the channel. I presume that with all UVP measurements, the flow velocity component is measured along the beam axis (i.e. 70 deg. to streamwise direction) and therefore the candidate had to derive the streamwise and lateral velocity components, while assuming vertical velocity components were negligible. A description on how this was done from the raw UVP data would have been helpful.

P42 – I did not really follow in the preparation of the gravel bed condition, what the purpose of the plastic film was, and how this was folded on the gravel base layer – again an image would have helped here.

P45 – the collection of the UVP data is not clear in terms of the array of different sampling rates that were used for the different experimental groups. A clearer description of the purpose of sampling (and resampling) at different rates for different microplastics and microplastic-clastic sediment bed set-ups would have been useful. As would more examples of the processing procedure by which the raw datasets from UVP measurements resulted in time-averaged and spatially averaged streamwise velocity profiles from which the shear velocities were obtained. Could the fluctuations in UVP velocity measurement not been used as a proxy for near-bed turbulence to see if there was any correlation with individual particle motions?

P47-50 – similarly, the description of the analysis of videos for particle detachments could have been clearer by including processed images associated with the different pre-processing steps (p.i) – (p.v) and image analysis steps (a.i) – (a.iv). In this regard, Fig. 3.6 is not particularly clear in defining this procedure. It could also be clearer how the first-order moments are utilised to detect bed changes associated with particle movements – again this is difficult to interpret for text alone.

Chapter 4 Plastic grains over a plastic bed

General comment:

This chapter is designed to provide an assessment of the incipient motion of the two microplastic particle types (PA6 and POM) utilised in the study from a homogeneous bed layer consisting of the same microplastic types. This is based on identifying the critical threshold of motion through video analysis of changes to the microplastic particle arrangements at the bed surface. This results chapter is only 11 pages long and, although it is presenting results from 18 individual runs (i.e. 2 particle types x 3 flow conditions x 3 repetitions), there is data presented from only a very limited number of cases and very little discussion on the observed differences between these individual runs (for example, only two examples of bed changes are presented for the PA6 particle bed in Fig. 4.3 and very little information provided on consistency between repetitions). Instead, much of the information from these runs is presented as ensemble-data plotted on Shields' θ-Re* plots against other previously published data collected for lightweight sediments. It is also not particularly clear on how the "limit state" methodology is applied to analyse the bed changes frequency versus shear velocity data in section 4.3.3.

Specific comments:

P53 – within the experimental conditions, it suggests that the turbulent boundary layer is not fully developed – does this affect the analysis of the bed shear velocities? Does the law-of-the-wall not assume fully developed turbulent flow conditions?

P53 – there is a reference to an unspecified Appendix ?? in terms of the UVP settings. This appendix does not seem to exist.

P53 – In terms of the reduction in raw image resolution to 1/5 of the original, again showing what effect this has on the microplastic particle bed images would have been useful – are microplastic particles in this reduced resolution covered by 6x6 pixels rather than 30x30 pixels?

P55 – in the estimation of the bed shear velocities, it suggests that dense space-resolved estimations of local shear velocity were obtained (i.e. 1 data point every 1.1 mm in the transverse direction). It would have been good to see examples of these plots in the results to see how much variability there was in shear velocity measurements across the channel and between different runs. It is not clear how exactly this information is used to represent the probabilistic (spatial) distribution in U* values across the channel? Does the temporal variation in estimated shear velocities follow a Gaussian profile (i.e. probability density function) for each experimental condition, as suggested in the text?

P56 – as suggested previously (Ch. 4 general comment), it would have been good to see more of the time-averaged bed shear velocity distributions and cumulative bed change maps for different experimental conditions (+ repetitions) to see whether there were any distinct trends in the data. The variability observed of the two plots shown in Fig. 4.3 is ascribed to near-bed turbulence, rather than temporally averages bed shear velocity. Unfortunately, this near-bed turbulence is not measured or reported.

P57 – Again, it is stated that the local values of U* across the flume result in Shields' number that range from $O(10^{-9}\text{-}10^{-2})$. It would have been interesting to see a more in-depth analysis of these to determine whether locations where Shields' numbers were higher corresponded to bed regions showing the most changes.

P58 – it is not clear to me what data is shown in Fig. 4.5 and what this plot tells us, apart from larger u* values are required for the homogeneous bed of denser POM particles to initiate the same magnitude of bed changes frequency as occur in beds of less dense PA6 particles at lower shear velocities. I am not clear, however, what all the individual data points for both PA6 and POM beds actually represent. Why does the bed change frequency not generally increase with increasing u* values for both types of particles?

P59 – As indicated in the general comment, more information on the adoption of a limit state approach and how this informs the semi-probabilistic method would have been appropriate to get a better understanding of what the candidate is trying to do here. For example, what was the rational for the threshold bed changes frequency to be set specifically at 10^{-4} s^{-1}? What would happen if a larger or smaller frequency was set? I am also not clear how the threshold shear velocities, critical shear stresses and Shield' parameters, and particle Reynolds numbers are calculated using this semi-probabilistic approach – could this be shown as an example process?

P60 – the POM data plotted in the Fig. 4.6 shows good overall agreement with Graf and Pazis (1977) data. Again, what specific new knowledge does the POM data provide over previous studies with lightweight plastic sediments? It is also not specifically clear to me what effect the depth of flow will have on threshold for motion, particularly if the near-bed velocity profile follows a log profile (for calculation of shear velocity).

Chapter 5 Remobilisation of plastic particles from a clastic bed

General comment:

A considerable number of experimental tests are conducted to investigate the remobilisation of microplastic particles (PA6 and POM) from two different clastic bed types (gravel and sand), three flow conditions, five microplastic concentrations, and 2 repetitions per case (i.e. 2 x 2 x 3 x 5 x 2 = 120 experimental tests). This is a considerable amount of work for which the candidate should be commended. In all the experimental runs, the clastic sediments remain immobile, and it is only the remobilisation of the microplastics from the static bed surface that is of interest. What is also interesting is the relative size of the microplastics in relation to the clastic sediments (i.e. $d_{MP} > d_s$), meaning that the microplastics are always exposed (to an extent) at the free surface to the near bed flow (as shown in Fig. 5.1). However, none of the experimental conditions tested appear to offer genuine hiding opportunities for the microplastics (i.e. which would occur when surface bed pores are larger than the microplastic particles, requiring $d_s > d_{MP}$). This is largely confirmed by the finding that the threshold conditions for microplastic particle remobilisation from the clastic sediment beds are actually lower (sometimes considerably so) than their equivalent incipient motion from a homogeneous bed made up of the same microplastic particles (Chapter 4). What might have been interesting would have been to consider a coarser gravel bed (with $d_s > d_{MP}$) to investigate potential hiding effects from clastic sediments on microplastics.

Specific comments:

P71 – it is not clear why the candidate chose to use the particle Reynolds number based on the microplastic particle size (Eq. 5.2) rather than the median bed grain size (Eq. 5.3), considering this is normally a measure of the bed roughness condition (smooth, transitionally rough, rough).

P72 – Fig. 5.2 shows that microplastic particles sitting on the clastic sediment beds have considerably lower Shields' parameters (through lower mean shear velocities) than those in homogeneous beds made up solely of the microplastics. This indicates that they are remobilised at much lower shear velocities than their incipient motion from the homogeneous bed of microplastics. Is this, in some respect, associated with the surface packing arrangement of MPs in the homogeneous bed that add resistance to bed shear, compared to the more exposed MPs at the surface of the clastic bed sediments?

P72 – again it would be good to see how the individual data points on the Shields' plot (Fig. 5.2) for MPs over the clastic bed were actually calculated (both through calculations of time-width-averaged bed shear velocities and the image analysis process used to determine MP mobility). There is very limited information provided on these processes.

P73 – what trends, if any, are observed in Fig. 5.4? How do these plots vary between different experiment conditions?

P74 – in defining the threshold conditions for MP remobilisation over clastic beds, it is again not explained why a specific threshold bed changes frequency (10^{-2} s^{-1}) was chosen, why this is different from the homogeneous MP bed cases, and what sensitivity does the threshold shear velocity have to changing this value?

P74 – the POM MPs on the sand bed are described as only having only rare (in time) and weak (in space) movements under the conditions tested. However, their threshold Shields' parameter is lower than either incipient motion from the homogeneous POM bed or remobilisation from the gravel bed surface. This seems counterintuitive. Did these other two bed conditions show greater movements of POM particles? The very low threshold for motion of PA6 particles over the sand bed suggests they are very unstable when exposed to even low magnitude shear flows.

P75 – it is not really very clear what Fig. 5.6 shows. On the x-axis the spread of data suggests a range of different concentration values, not just c_1 – c_5 as stated, therefore this axis should be specified by numbers rather than just labels. It is also not stated anywhere what the different horizontal dashed lines indicate (different levels of $\dot{n}$). Again, the lack of motions observed for POM over sand, compared to POM over gravel, is strange considering the threshold for motion of POM over sand is much lower than over gravel (Fig. 5.5). This point should be clarified.

P76 – again there is a lack of detail on the application of Buckingham theorem in dimensional analysis and how the non-dimensional parameter groups are defined. It is also not clear what the dimensionless degree of motion χ_B is and how this is derived.

P77 – along a similar vein, the description of the principal component analysis (PCA) is very brief, while the actual application of the methodology to the data is not clear (what does Fig. 5.7 actually show?). The outcomes from this analysis are also not clearly defined and I am not clear on how the values in Fig. 5.8 are derived or what it tells us. This analysis needs far more description and detail.

P79 – Why is the difference in submergence depth y/d_{MP} from previous studies likely to be the reason for the considerably lower threshold condition for PA6 particles over sand, when the other conditions tested (PA6 over gravel & homogeneous bed and POM over all beds) show good agreement with these previous studies – as shown in Fig. 5.9 (even though their submergence depths were also considerably lower than previous studies)?

P80 – It is not really clear what specifically is deduced from the ensemble plot of bad changes frequency against mobility parameter in Fig. 5.10. It also seems obvious that plastic particles that are less dense than gravel particles have a lower mobility threshold. Higher Shields' parameters are also achieved, in general, for lighter PA6 microplastics compared to denser POM particles. The candidate suggests that this could be down to shape, but no quantitative evidence for this is provided. The mobility parameter for PA6 and POM particles is also lower over smoother beds (i.e. sand) than coarser beds (i.e. gravel) due to increased exposure, which does make sense.

P81 – A key finding from the study seems to be that the remobilisation of microplastic particles with densities closer to that of the fluid cannot be well defined by "averaged" bed shear velocity thresholds (i.e. Shields' approach) in the same way as has been used to describe the initiation of motion for clastic sediments (i.e. sands and gravels) with much higher densities for many decades. Instead, it is suggested that MPs are more responsive to individual turbulent fluctuations in the flow conditions (i.e. near-bed turbulence). This suggests that a better approach might be to consider the nature of individual fluid-particle interactions (e.g. through quadrant analysis) that lead to MP remobilisation, rather than the spatial and temporal averaging of flow conditions that has been undertaken and relied on here.

P82 – The conclusions drawn on the derived thresholds based on the semi-probabilistic approach, and analysis of key parameterisations based on PCA approach, need a fuller discussion to fully understand the significance of these approaches to the results and their interpretation.

Chapter 6 Conclusions and Furter Developments

General comment:

This is a relatively short chapter summarising the main findings from the studies. It seems to capture the main points from the two distinct experimental studies: MP incipient motion from homogeneous beds and MP remobilisation from clastic sediment beds. However, in the interpretation of microplastic transport characterisation in terms of the so-called sediment analogy framework, it suggests that MP particle shape (and, hence, orientation) is a defining parameter in terms of the incipient motion threshold from the homogenous bed and remobilisation of MPs from the surface of clastic beds. However, no firm evidence (as far as I can see) has been provided on justifying this point, with only very basic descriptions provided on the different shapes of the PA6 and POM microplastics used in the study. As such, it is not clear what role particle shape actually plays in defining the thresholds for incipient motion and remobilisation, certainly in a quantitative sense. This also needs to be taken in the context that it is difficult to separate the influences of particle shape and density when both actually vary between PA6 and POM particles. There is possibly some observational evidence (e.g. from Fig. 5.10) that PA6 particles have a larger "spread" in mobility parameters than observed for POM particles, particularly over the clastic beds, but this has not been defined in any statistical sense.

Specific comments:

P87 – in section 6.4, there does not seem to be any mention of the possibility of microplastic and clastic transport occurring concurrently and what effect that might have on the potential for MP burial within, and/or exposure from, mobilised clastic sediment beds. There also does not appear to be any real mention of future studies looking into more local and instantaneous fluid-particle interactions that are predominantly responsible for microplastic remobilisation.

Appendices

The limited appendices that are included in the thesis are well laid out. However, as stated throughout, the lack of any real detail provided for many of the raw data processing techniques (i.e. UVP and bed image analysis) and the subsequent data analysis techniques (i.e. derivation of thresholds via semi-probabilistic approach, bed changes frequency analysis, dimensional analysis, principal component analysis) would lend itself, at least, to the inclusion of further appendices showing how each of these different processes and analytical techniques are developed and applied to the data collected from the flume experiments. This would greatly enhance understanding of the approaches adopted, their novelty (where this exists), and the potential limitations within the current study.