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An Experimental Investigation of Underwater Dispersion of a Granular Material: Effect of Particle Size

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Abstract

Granular material being released into a large body of water occurs in many industrial processes, for instance during land reclamation and the underwater release of sediment tailings as part of the nodule harvesting process. The dispersion and settling process is of great interest, whether it is regarding the rate of land reclamation or as a concern to environmentalists due to clouding of the water. In this paper, we present the results of a series of simple table-top experiments. A small volume of granular material is released from a fixed distance above the surface of a tank of quiescent water and allowed to settle. From video recordings of the process, we obtain qualitative observations, as well as measurements of the average bulk velocities and the final dispersed area. Four different sizes of sediment are used, varying from 0.1 mm to 6 mm. We observe that there is a significant difference in the dispersion process between the smaller and larger particle sizes, which is reflected in both the evolution of average bulk velocity as well as the final dispersion spread. When the granular material is non-homogeneous, i.e. a mixture of sizes is used, the dispersion process shows a combination of the different characteristics previously observed for the homogeneous cases. This initial transient behaviour differs depending on the pre-release arrangement of the granular material, which implies that both the size composition as well as the general homogeneity of the granular mixture have significant effect on the dispersion process.

Introduction

Granular materials are used in many construction applications today, from pavement foundations to land reclamation [7]. In Singapore, for instance, land is limited and thus land reclamation, use of underwater space [3] as well as the offshore industry are very important. All these areas involve granular material (usually sand) being dispersed underwater, either as a direct process or as a by-product (e.g. in nodule harvesting). Thus understanding how granular material disperses underwater, as a function of the granular material's micro-scale and macro-scale characteristics as well as external factors such as water depth, temperature, relative density are important.

Generally, granular materials are non-homogeneous. This usually manifests as the individual particles being non-uniform in size (and hence a sand sample usually has a size range), although other areas of non-homogeneity can include shape, chemical composition, surface roughness and distribution. All of these contribute to no one granular mixture behaving exactly the same as another; in fact, due to the numerous factors existing, there is no blanket formula that can be applied to every single granular mixture.

In this paper we study the effects of particle size on a simplified underwater dispersion process. Specifically, we make qualitative observations of the general process, obtain crude estimates of the bulk velocity as the sand falls through a tank of still water, and measure the size of the pattern obtained when the sand has finally settled.

Experimental Setup

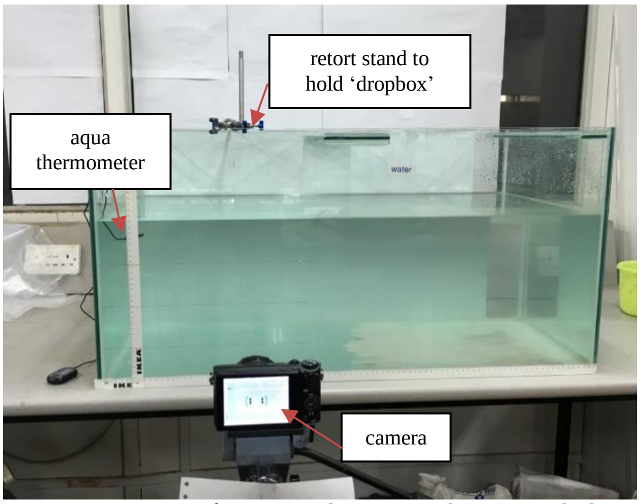

Figure 1: Components of experimental setup (aqua thermometer, high-speed camera on tripod with inbuilt gyroscope function, retort stand at back to hold 'dropbox')

Figure 1 shows the main components of the experimental setup. A large tank (dimensions 90×45×45 cm) with 40 cm depth of water was used, with graph paper lining the back wall and base of the tank for making measurements. The experiment was conducted in an enclosed, air-conditioned room, and the water temperature was monitored as well to ensure consistent conditions.

Four different sand types of varying granular diameter were used, listed in table 1.

Sand Type	Granular Diameter
W9	0.1 – 0.5 mm (± 8%)
W7C	0.56 – 0.70 mm (± 8%)
W6	1.5 – 3 mm (± 8%)
W5	3 – 6 mm (± 8%)

Table 1: Size range of the different sand types from PMBA data sheet, provided by the source (River Sands, www.riversands.com.au as of 13/4/2016)

In each experiment, a 'dropbox' with inner dimensions 5×5×4 cm (see figure 2) was packed gently with a single type of sand to a height of 2 cm. The 'dropbox' was then held upside-down (by retort stand) at a fixed height above the water surface, and then opened in a single motion to enforce consistency for all the experiments.

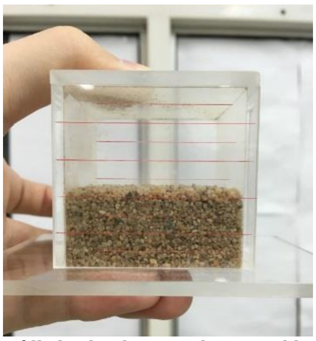

Figure 2: Partially-filled 'dropbox' and removable lid used for the experiments

The underwater dispersion process, from release to settling, was recorded using a high-speed camera (240 fps video). Due to the lack of image-processing or particle-tracking software, only crude bulk velocity measurements were made. Specifically, threads were spread across the front of the tank to visually separate the water depth into 10 cm intervals, and the average bulk velocity was obtained by tracking the time taken for the front of the dispersing sand to traverse each quarter.

Results: Uniform-Size Mixtures

General Observations

Figure 3: Spherical 'blob' observed during underwater dispersion for W6 sand (left) and W9 sand (right).

Figure 3 shows photos of two sand mixtures partway through the dispersion process. Although each sand sample was initially compacted into a cube in the 'dropbox', they all evolved into a spherical 'blob' during the dispersion process. The blob was composed of faster-moving particles which cycle from the head of the blob outwards along the edges back into the blob, or they join the slower particles making up a trailing tail behind the blob.

The relative velocities of the spherical 'blob' and the trailing tail are supported by work reported in [1, 2, 5, 6, 8, 9] – specifically, that the velocity in the wake of a large obstacle increases with proximity due to the reduced drag. Hence sand particles close to the spherical 'blob' tend to get reabsorbed, but if they move slightly further then they slow too much to catch up, and thus become part of the tail.

The shape evolution from 'cube' to 'spherical 'blob' occurs regardless of particle size. However, we observed that the finer mixtures (W9 and W7C sand) were able to maintain the spherical 'blob' for longer compared to the mixtures with larger particles (W6 and W5 sand). This difference is likely to be due to the larger particles also having irregular shapes, resulting in the mixtures being less compacted than those with smaller particles. The looser packing provides more openings for the water to flow through and break up the sand cluster, hence the mixtures with larger particles cannot maintain the spherical 'blob' as long as those with smaller particles.

Bulk Velocity Evolution

Figure 4 shows the bulk falling velocity for different sand types, averaged over the entire falling distance and four separate experiments; while figure 5 shows the bulk falling velocity in each successive quarter of water depth.

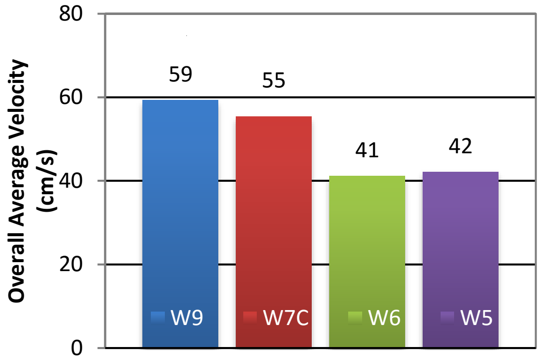

Figure 4: Overall average falling velocity for different sand sizes, ±1 cm/s.

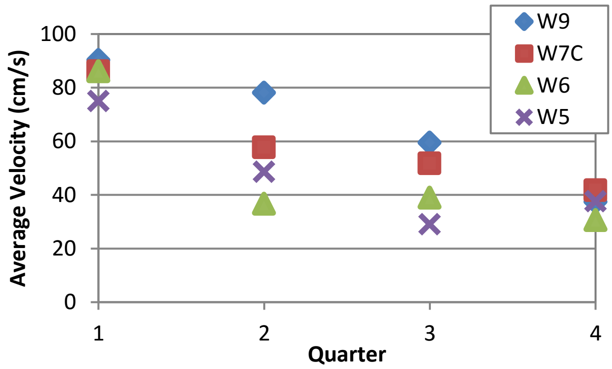

Figure 5: Average bulk velocity in each quarter, for different sand sizes, ±1 cm/s.

From figure 4, we see that generally the bulk velocity decreases with increasing particle size, so the finest particles (W9) reach the bottom of the tank fastest. However from figure 5, this relationship is no longer consistent. While it is still true that the two mixtures with finer particles (W9 and W7C) have higher average velocities in all four quarters, the two mixtures with larger particles appear not to hold to that relationship throughout the dispersion process.

This can actually be explained using the well-known drag force equation ($F_d=0.5C_d\,\rho AV^2$), if the bulk shape evolution described previously is also taken into account. In the first quarter, all the mixtures are still clustered together and hence the drag force is largest on the mixture with the largest particles (W5). However in the second quarter, the 'blobs' are beginning to be broken up. The 'blob' made up of W5 sand breaks up faster than that of 'W6' sand, and hence the drag on each W5 particle is much smaller than that of the still clustered W6 particles, resulting the W5 particles falling faster. This is 'reversed' again in the third quarter, where both 'blobs' are now fully broken up and thus the drag on the particles is now dependent solely on individual particle size. The slight discrepancy in the final quarter is likely due to the shape irregularity as mentioned earlier – the large W5 particles are significantly non-spherical, and hence experience non-constant drag forces as they rotate (and change the projected surface area) as they fall.

Final Dispersion Pattern

In all cases, the final dispersion pattern was circular – unsurprising, given the formation of the spherical 'blob' and the initially-still conditions of the water. However upon closer inspection of the patterns (shown in figure 6, for each of the four sand sizes), we observe that there is a distinct difference as the sand particles become coarser.

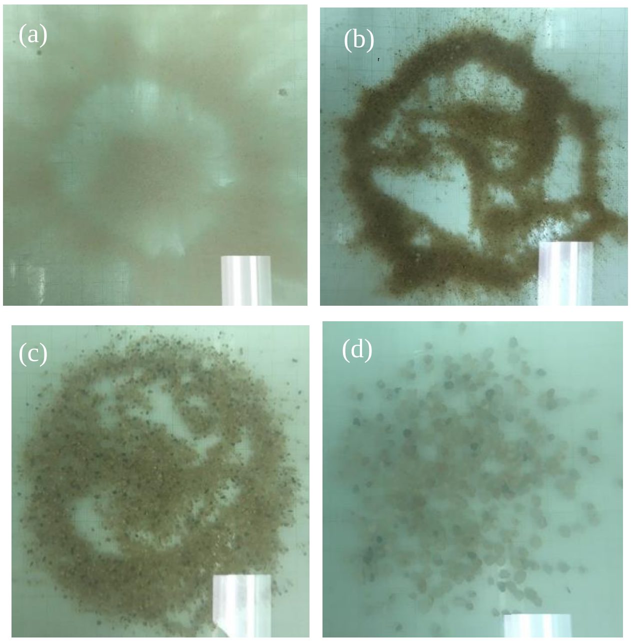

Figure 6: Dispersion patterns of (a) W9 sand, (b) W7C sand, (c) W6 sand, and (d) W5 sand.

Firstly, the diameter of the circular pattern increased with particle size: ~32 cm for W9, ~24cm for W7C, ~22cm for W6, and ~20cm for W5 sand. Note that there is a 0.2 cm uncertainty in these measurements due to the graph paper used.

Secondly, as the particle diameter increased, the observed outer ring with a smaller filled circle in the centre became less distinct. Figure 6d (the largest sand size, W5) shows the roughly circular patch corresponding to the scattered sand cloud that formed after the break-up of the spherical 'blob'. This is also reflected in figure 6c. However in figures 6a and 6b (the finer particle sizes, W7C and W9), the spherical 'blob' shape was maintained for much longer. This means that the particles had a higher velocity upon impact, resulting in the larger pattern size. Additionally, the fast-moving particles in the spherical 'blob' settled in a larger outer ring after impact, leaving the slower-moving particles in the tail to settle in the centre. This explains the qualitatively different characteristics in figure 6a and 6b compared to 6d.

Results: Non-Homogeneous Mixtures

Typically, granular mixtures used in actual applications are not of a strictly uniform size. Hence, we can expect that the overall behaviour of a non-homogeneous granular mixture will be a combination of the observations made earlier for nearly-uniform mixtures.

Here we consider two non-homogeneous mixtures, both made up of all four sand sizes. The difference between the two is that in one case the sand is arranged, from top to bottom, in increasing particle size; while the other has the order reversed. This second scenario reflects a more realistic situation wherein a granular mixture tends to segregate by size after excitation (for instance after transportation), with the largest particles on top and the smallest particles at the bottom [4].

For consistency, 1 cm depth (in the 'dropbox') of each sand size is used. All other conditions are similar to what was used in the previous experiments.

Figure 7 shows photographs of the two non-homogeneous mixtures prior to release. Note that the sand is released from the 'dropbox' upside-down, and hence the order of the particle size is now opposite from how they were packed. Thus, for the mixture with the largest particles on top, the particles will enter the water in order of increasing size. Similarly, for the mixture with the smallest particles on top, the particles will enter the water in order of decreasing size.

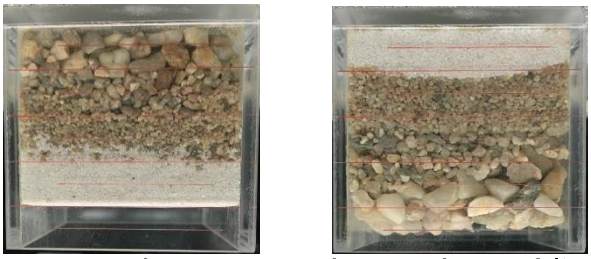

Figure 7: Two non-homogeneous cases – largest particles on top (left), and smallest particles on top (right).

Table 2 and figure 8 show the experimental results obtained for both non-homogeneous mixtures.

Largest particles on top	**Smallest particles on top**
Average velocity: 57 ± 1 cm/s	Average velocity: 53 ± 1 cm/s
Dispersion pattern diameter: 28 ~ 30 ± 0.2 cm	Dispersion pattern diameter: 30 ± 0.2 cm

Table 2: Average bulk velocity and dispersed pattern diameter for both non-homogeneous cases

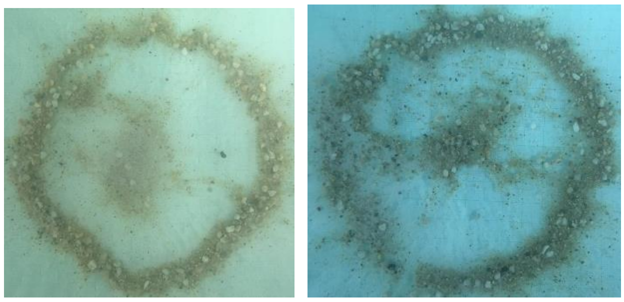

Figure 8: Dispersion patterns of non-homogeneous mixtures: largest particles on top (left), and smallest particles on top (right).

Qualitatively, both dispersion processes were significantly different, although they reached nearly similar final states as reflected in table 2 and figure 8 above. This is unsurprising, given that both mixtures are similar with only a difference in initial arrangement.

Largest Particles on Top

Upon release, we observed that the finest particles (W9) take the lead initially as they were the bottom-most layer, and form the spherical 'blob'. However as the dispersion progresses, the larger particles punch through the 'blob' of smaller particles to the front. This is due to them gaining velocity rapidly from being in the direct wake of the 'blob', hence negating the larger drag acting on them. An immediate consequence of this 'punching through' by the large particles, is that the spherical 'blob' of finer particles is no longer cohesive and breaks up rapidly. In addition, with the loss of the wake, the trailing, slower particles are no longer shielded and thus are unable to catch up. The final result is a scattered cloud of particles, with the largest particles closest to the bottom and the finest particles at the top falling the slowest. This is a direct reversal of the initial particle arrangement.

Due to this arrangement, when the particles finally reach and settle at the bottom of the tank, it is the largest particles that arrive first and with the highest velocity. Hence they bounce (outward) and form the outer ring, while the slower, finer particles settle into a circular patch in the centre as shown in figure 8a.

This appears to be the opposite of the observations made for the uniform-sized mixtures – the mixture with large particles did not have an outer ring (figure 6d), and the mixtures with fine particles were concentrated mostly in an outer ring with a small inner circular patch (figure 6a). However we point out that there is no contradiction here since in both cases it is relative velocity that determines where the sand falls: the faster moving particles form the outer ring, and the slower ones make up the inner circular patch.

In terms of average bulk velocity, this non-homogeneous mixture is comparable to the two cases with only small particles (see figure 4). This is due to the larger particles being able to speed up in the wake of the initial spherical 'blob', thus attaining speeds similar to the mixtures with smaller particles.

Smallest Particles on Top

This mixture was arranged immediately reverse of the other, with the largest particles falling out first. It was thus more apparent that the larger sand particles were unable to maintain the spherical 'blob' very shortly after entering the water. The finer particles very quickly overtook the larger ones, but without the 'punching through' that was observed in the other non-homogeneous mixture, resulting in a spherical 'blob' formed mostly of fine particles and a trailing tail of mostly large particles.

Following this, the larger particles in the tail were quickly reabsorbed into the wake of the 'blob' – in the video footage this is immediately obvious as there are nearly no trailing particles present when the 'blob' reached lower half of the tank.

This observation was not made for the previous non-homogeneous mixture, largely due to the early break-up of the spherical 'blob' when the larger particles broke through. The larger particles did not form a spherical 'blob' later, so there was no wake to result in a similar occurrence.

As a result of majority of the particles being involved in the spherical 'blob', the final dispersion pattern obtained was a ring composed of all the different sizes, with only a very small circular patch formed by the trailing tail. This is the only visual difference between the two non-homogeneous mixtures' final states, as the size of the final pattern is similar for both.

When we compare the overall bulk velocity between the two non-homogeneous cases, this mixture has a lower velocity, even though it is still relatively high compared to the results in figure 4. This can again be attributed to the formation of the spherical 'blob', but since its formation was later in the process – after the finer particles overtook the larger particles – the resulting reduction in drag was less and thus the overall velocity lower.

Conclusions

Generally, the falling sand particles form a spherical cluster with a thinner trailing tail of slower particles. The fastest particles emerge at the head of the cluster and move upwards and outwards around its periphery; they are then either reabsorbed into the cluster, or leave the cluster and become part of the tail. Upon reaching the base of the tank, the faster particles forming the cluster tend to bounce before settling in a wide ring, while the slower particles in the tail settle in a circular patch within the larger ring.

From our experiments, we see that this general behaviour is affected significantly by the individual particle size. Specifically, larger sand particles do not maintain the spherical cluster as easily as smaller sand particles; on top of the slower velocity due to greater drag forces acting on them. As a result, for a sand sample made up of larger particles, even though it forms a spherical 'blob' initially, it is broken up very quickly and hence during the majority of the dispersion process the sand falls as a relatively slow, scattered cloud. This results in a circular patch of dispersed sand. On the other hand, a sample of small sand particles forms and maintains a fast-moving spherical 'blob' with a slower trailing tail. The relative difference in velocity causes the spherical 'blob' to settle in a large outer ring, while the slower tail settles as a smaller circular patch in the centre.

When the sand sample has a range of sand sizes, both these behavioural extremes are exhibited but with obvious differences depending on the initial non-homogeneity of the sand. In this paper the particles were arranged vertically by size, resulting in some observations such as smaller particles overtaking the larger, as well as the larger particles penetrating and breaking up the spherical 'blob' formed by finer particles. We expect that in a non-homogeneous mixture that is not so stratified any observed behaviour will not be as dramatic, but these results are sufficient to emphasise the significance of (non-)homogeneity in both particle size as well as arrangement, on the bulk behaviour of a granular mixture.

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