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Abstract: We present the results of an experimental study of granular segregation on a large number of rectangular grain piles built by dropping simultaneously glass beads of two different sizes. During the construction process, we control the height of the injection point, the amplitude and velocity of its displacement and the injection flow rate for each kind of grain. The final spatial distribution of the grains is determined by a quantitative image analysis. A phase diagram for the segregation-mixing states as a function of the experimental parameters is presented along with a quantification of the different types of segregation patterns through a suitable criteria. Contrary to the assertions of other authors, we clearly demonstrate here that stratification phenomenon may be observed even for beads with the same round shape but different size. We also find that the free fall height of the grains, the ratio between the discharged masses of the different types of grains and the amplitude of the horizontal motion have the greatest influence on segregation.

Novel aspects on the segregation in quasi 2D piles

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Abstract

We present the results of an experimental study of granular segregation on a large number of rectangular grain piles built by dropping simultaneously glass beads of two different sizes. During the construction process, we control the height of the injection point, the amplitude and velocity of its displacement and the injection flow rate for each kind of grain. The final spatial distribution of the grains is determined by a quantitative image analysis. A phase diagram for the segregation-mixing states as a function of the experimental parameters is presented along with a quantification of the different types of segregation patterns through a suitable criteria. Contrary to the assertions of other authors, we clearly demonstrate here that stratification phenomenon may be observed even for beads with the same round shape but different size. We also find that the free fall height of the grains, the ratio between the discharged masses of the different types

of grains and the amplitude of the horizontal motion have the greatest influence on segregation.

1. Introduction

In recent years, a great deal of work has been performed about the behavior of granular materials. In particular, mixing and segregation processes are still topics of intensive research due to their technological importance and strong industrial applications. Many industries like cement, paper, coal and fertilizers, seek to improve quality through a better use of raw materials and optimizing the processing plants. Fluctuations in the properties of raw materials, such as ores and limestone, require that blending equipment provides a high-quality end product [1].

Segregation takes place every time this dry material is handled [2-4]. In cement production, raw material is stored as pyramidal heaps and, although empirical homogenization techniques are used with good results, segregation is observed due to the broad distribution of grain sizes.

Two of the most commonly used stacking methods are the Chevron and Windrow ones. Basically, these methods consist of stacking a large number of layers on top of each other. In the Chevron method, material is deposited by an injection point that moves upwards with an alternative motion following the growth in height of the stockpile. In the Windrow method, material is deposited by a stacker moving both in the upward direction of growth of the heap as in the transverse direction. This mode prevents segregation and compensates the unfavorable effect of Chevron mode stacking [2].

An additional problem is the fact that the range of grain sizes in these heaps is very broad. The relative amount of particles of a given size in the mixture is strongly related to the grinding process, and, particularly, to the degree of wear of the hammers used in the mills. Furthermore, the chemical composition of the grains was found to be correlated with their size and geometry [5].

Despite the efforts to prevent segregation, this phenomenon always occurs when a mixture of grains of different size is simply poured onto a heap [6-11] and the large grains spontaneously segregate near the bottom of the pile, whereas the small ones segregate near the pouring point at the top of it.

In recent works, a spontaneous stratification was observed for grains differing both in size and in shape [12-14]. Granular mixtures of small-rounded grains and large cubic grains stratify in alternating layers parallel to the surface of the pile as they are poured in the cell.

Makse et al. [12,15-19] have studied experimental and analytically stratification and segregation. According to the experiments [12], the control parameter for stratification appears to be the difference of the repose angles δ of the pure species. For $\delta > 0$ (small rounded or less faceted grains and large cubic or more faceted grains) stratification was observed. On the other hand, strong segregation, but not stratification occurred when $\delta < 0$, corresponding to a mixture of small cubic grains, and large-rounded grains. The stratification instability is related to the fact that, when $\delta > 0$, there appears a competition between size segregation and shape segregation: the large-cubic grains tend to size segregate at the bottom of the pile, while at the same time, they tend to shape segregate at the top of the pile.

More recently, it was reported that the dynamics of stratification was governed by a “kink” mechanism [19]. They identified experimentally that the rolling grains segregate during the avalanche, resulting in a sub-layer of small grains underneath a sub-layer of large grains. This phenomenon is then followed by the formation of a kink, i.e., an uphill wave at which grains are stopped at the bottom substrate. Finally, the kink moves uphill forming the pair of layers.

In addition, Grasselli and Herrmann have studied, experimentally, heaps of binary granular mixtures made of sand (rough) and glass spheres (smooth) that exhibit different internal structures [13]. They studied the pile morphology as a function of the ratio of the sizes of rough to smooth particles. For values below 0.8, the piles present flow segregation, i.e., segregation driven by flow where the large beads move to the base and the small ones keep at the center of the pile. Granular stratification is found to occur only for a size ratio greater than 1.5. They observed that stratification depends on the wall separation of the cell where the pile is built and on the mass flux of the grain mixture.

On the other hand, the characterization of segregation patterns has also been performed through the definition and measurement of a wide variety of indices [14,20,21], most of them related to the mixing degree of the system [22,23]. In general, they refer to the variance of some quantity measured over the whole sample volume or over testing volumes in which the system is divided for that purpose. In all cases, one seeks to choose a criterion characterizing properly the system under study.

In this paper we present experimental results obtained for a large number of granular piles built up using a versatile moving device with a discharge point that can oscillate horizontally and move vertically keeping a fixed distance to the top of the pile, thus resembling the Chevron method. We pay especial attention to the patterns obtained when varying the size of the injected grains, the ratio of their discharged masses, the free fall height and the amplitude of the horizontal motion. We present and compare the phase diagrams obtained for the different flow regimes as a function of the mentioned variables, demonstrating the existence of stratification even for beads with the same round shape but different size. We also present a method for characterizing the different flow regimes through a quantitative analysis from the pictures of the final grain packings.

2. Experimental Setup

The experimental device allows one to build piles of, at most, two different species of grains inside a quasi bi-dimensional transparent acrylic plexiglass cell (400mm length, 150mm height and 10mm thickness). The piles can be constructed with a controlled vertical and horizontal relative motion between the grain injection point and the top of the pile in formation. A sketch of the experimental set-up is displayed in Figure 1. It essentially consists of a fixed grain feeding system with its outlet at the injection point (IP in Figure 1), and a cell where the pile is constructed (C in Figure 1), which can move vertical and horizontally as mentioned above.

The feeding system consists of two vibrating feeders and a 3D and D static mixers in series [21,24-28]. Each feeder contains a single kind of grain whose mass flow can be controlled. The mixers guarantee that segregation in the piles is due to the build-up process and that the kinetic energy of the grains is the one gained along the vertical path between the injection point and the top of the pile.

The vertical and horizontal movements of the cell are performed by appropriate motors coupling the two types of motion. During the construction process, the distance between the injection point and the top of the pile is fixed thanks to a control system with two transducers (see Figure 2). Each pair of transducers detects the presence of the grain packing at the corresponding level; a servo control system uses these signals to adjust the position of the transducer-injection assembly so that the surface of the packing is located between the transducers barriers. The distance between the barriers (5mm) is larger than the larger grain size used in the experiments (3mm), thus, a single grain cannot intercept both barriers at the same time. The injection point can be fixed within a precision of 10%.

Finally, the control system for the horizontal motion allows one to set the amplitude and velocity of the cell movement. The amplitude is controlled by two movable switches that inverse the movement of the frame while the magnitude of the velocity is controlled by the input tension of the DC motor, varying between 2 to 13mm/s [29].

3. Image analysis

The device described above allows us to obtain piles to study the phenomenon of segregation and mixture. The measurement technique is based on visualization, i.e., taking pictures of the final configuration of the grains in the pile.

After building the pile, the cell is carefully centered and uniformly illuminated to obtain an optimum image processing. To distinguish them, the grains are dyed with two different colors according to their sizes. We use alcohol inks because they allow dyeing the beads uniformly, leaving their surface smooth. The image method uses the light reflected by each grain to identify its center, and the surroundings to identify its size.

The photos are taken with a Nikon D70 digital camera of 6.1 Megapixels and a DX Zoom Nikon lens 18-70mm. The distance between the focal plane of the camera and the cell remains constant at approximately 90 cm.

Each picture is treated by a set of programs written in MATLAB that converts the image obtained with the camera in an indexed image with a four color map: two colors correspond to the stained grains, the third color corresponds to the light reflected by the beads (commonly white) and the fourth is the background color of the cell (commonly black).

In Figure 3(a), we show a typical picture (with a black background) acquired after the pile is finished. In Figure 3(b), the center coordinates of the glass beads obtained through the image processing are shown by different symbols depending on their size.

The efficiency in the image processing depends on the quality of the picture, the staining of grains, the camera and the program parameters. One can have a qualitative idea of the method performance and then decide whether to repeat the treatment, by examining the output image obtained by the image process.

4. Results and discussion

4.1 Qualitative Analysis

In order to study segregation in piles, we analyze experimentally the influence of the following control parameters: size ratio of grain species, injection flow, height of the injection point, and the magnitude of the longitudinal displacement for the case of experiments with horizontal motion.

We work with three different sizes of glass beads (3, 2 and 1mm diameter) using two size ratios, 3:1 and 3:2. The mean diameter value and the dispersion for each kind of glass bead are: 3.095mm ± 0.265mm; 1.705mm ± 0.295mm and 1.015mm ± 0.175mm. We set the injection flow for individual species to two values: 0.2 g/s and 0.4 g/s. We use all combinations of these values, leading to ratios: 1:1, 1:2 and 2:1, between the flow rates.

Let us denote by m_{LS} the ratio of the final total masses for the two types of grains, i.e., $m_{LS} = \frac{m_L}{m_S}$, where m_L corresponds to the large grains and m_S to the small ones.

The distance between the top of the pile and the discharge point (h) is varied from 10 to 50mm.

For experiments with horizontal motion, the speed of the injection point is fixed at 10.0mm/s, and the amplitudes for horizontal motion (A) are 100 and 200mm.

To analyze the influence of the injection flow, we build up piles with grains of size 2 and 3mm, with h = 10mm and different mass ratios. Figure 3(a) and (c) shows typical images of these piles. In experiments with $m_{LS} < 1$, we observe a strong segregation, i.e., a low number of large grains in the central region, as reported by Williams [2,8]. Comparing (a) with (c) in Figure 3, notice that the influence of m_{LS} on the segregation patterns is not significant: the volume distribution of the different species is in direct relation to the mass ratio, i.e., segregation pattern is not affected by m_{LS} in this case.

For piles built up with grains of 1 and 3mm, h = 10mm and $m_{LS} < 1$, we observe alternating bands of large and small grains. A typical pile showing stratification [15,19,30,31] is shown in Figure 4(a). It is evident from the experiments that the main variable determining the presence of bands is the ratio between the sizes of the grains. On the other hand, it is important to recall that Makse et al. [15,19] argued that stratification phenomenon was associated with the competition of two segregation mechanisms: segregation due to the grain geometry and segregation due to the difference in size. In our experiments, we observe stratification although the particles differ only in size. For $m_{LS} > 1$ stratification begins to disappear, giving rise to flow segregation, thus, one can conclude that stratification needs, as a second condition, that

$m_{LS} < 1$. This last condition alone is not sufficient to ensure the formation of bands, as Figure 3(c) demonstrates for ratio 3:2.

In order to study the influence of the height of the injection point, we perform experiments with h = 50mm. Figure 4 (b) and (c) show piles for size ratios 3:1 and 3:2, with a height of 50mm and mass ratios 0.60 and 0.90, respectively. Note that the value for m_{LS} in Figure 4(b) is comparable with the one in Figure 4(a), nevertheless, stratification becomes fuzzy due to the increse in the height. On the other hand, when comparing Figure 4(c) with Figure 3(a), a significant enhancement of the mixing is visible, although the value of m_{LS} is not exactly the same in both cases. For a larger height, grains reach the top of the pile with a greater kinetic energy and "jumping" throughout the slope. For that reason, their distribution in the pile will depend on the properties of the collisions between grains. For grain injections closer to the top of the pile, (as can be seen in Figures 3 and 4(a)) grains roll down the surface. Then, segregation takes place and the dominant mechanism is the interaction between the rolling grains and the layer of grains just below, and this interaction depends on the size of the rolling grains [26,27,32].

We also carry out experiments with horizontal movement of the injection point, using two different amplitudes (100mm and 200mm). In each case, we also vary the height of the injection point, the injection flow and the size ratio, as in the previous experiments.

Figure 5 shows piles for size ratio 3:1, h = 10mm, $m_{LS} < 1$and amplitudes of 100mm (part (a)) and 200mm (part (b)). Comparing this figure with Figure 4(a), we see that, as the amplitude is increased, the top of the pile becomes more rounded, the stratification disappears and the mixture of grains is improved. It should be noted that we always observed an increment in the degree of mixing for all the parameter values. The horizontal movement seems to interfere with the way in which the grains interact with the surface (either rolling or jumping) causing a disorder in collisions which ends favoring the mixture. As the horizontal amplitude increases, the disorder is even more evident, as seen in the figure.

In order to summarize all the results and to have a better overview of the influence of the different parameters on the resulting segregation/mixing patterns, the corresponding phase diagrams are displayed in Figure 6.

For size ratio 3:1 (Figure 6 (a)) we find basically four possible final structural configurations for the piles, depending on the parameters used for their construction: mixture (M), stratification or bands (B), segregation-mixture (SM) and segregation-stratification (SB). These last two cases correspond to those showing mixture (or stratification) in the central region of the pile, but still presenting a segregation effect on the tails, like, for instance, in the case of Figure 4 (b) that belongs to the SB state.

For a small mass of coarse grains ($m_{LS} < 2$ approximately) and a low injection height, we obtain piles with stratification. As h increases and $m_{LS} < 1$, the resulting piles show a segregation-stratification pattern. For these parameter values we never find a mixture pattern. For $1 < m_{LS} < 2$ and $h > 10mm$ the stratification disappears, giving place to a segregation-mixture pattern.

On the other hand, for a greater mass of coarse grains ($m_{LS} > 2$, approximately) it is not possible to obtain stratified piles, and, as the height of the injection point is increased, the resulting patterns shift from flow segregation to mixture.

For size ratio 3:2 (Figure 6 (b)) we obtain only three possible final structural configurations: segregation (S), mixture (M) and segregation-mixture (SM), i.e., stratification vanishes for this size ratio. For small values of m_{LS}, the piles always show segregation and, when m_{LS} is increased, they present a higher degree of mixing. The mixture is improved as m_{LS} and h increase.

The results presented above lead us to characterize quantitatively the degree of segregation present in the piles as a function of the experimental parameters. Furthermore, this quantification should be able to distinguish between the two kind of segregation behavior obtained in our experiments, i.e., flow segregation and stratification. For that purpose, we define two segregation indices as will be explained in detail in the next section.

4.2 Quantitative Analysis

As mentioned above, there are several possible definitions for a segregation index and they will depend on the details of the experiment and the size of the particles involved in it. In our case, we choose two indices to capture the main segregation patterns present in our experiments but, they do not pretend to be absolute indices of segregation (in the sense they are not a single number characterizing the amount of segregation of the whole system) but they do adapt to the geometry of our problem.

For a given sample of volume V, one can evaluate the ratio of the volume occupied by the large particles to the total volume V. This is a measure of the segregation in terms of the larger particles and this ratio will depend on the way that V is chosen in the pile. For that reason, we define the indices I_H and $I_\perp$ as:

$$I_{H,\perp} = \frac{2n_L}{\frac{an_S}{27} + n_L} - 1 \quad ; \quad \begin{cases} a = 1 \;\; for \;\; size \; ratio \; 3:1 \\ a = 8 \;\; for \;\; size \; ratio \; 3:2 \end{cases} \tag{1}$$

In the equation, the factor *a/*27 represents the cube of the ratio of the radii in each of the cases studied.

In equation (1), the samples to calculate I_H for a given pile are taken over vertical strips all with the same volume and perpendicular to the horizontal axis of the pile (Figure 7 (a)). On the other hand, the corresponding samples to evaluate $I_\perp$ are taken over strips (all with the same volume) parallel to the free surface of the pile and perpendicular to the vector $\vec{d}_\perp$ (Figure 7 (b)). Actually, the averages of these two quantities over the full sample should be the same if each band has the same area. It is by comparing the values of I_H and I_∞ and their variation with distance in the pile, that we will obtain information on the different segregation patterns.

We should say that, in all the experiments, it has been verified that both patterns at the front and at the back of the cell, were the same. Therefore, and because the flow is only on the surface, we assumed that the pattern is reproduced inside the pile. This is valid up to a cell thickness around 30 grains. For this reason we used the volume factor a/27.

The indices range from -1 ($n_L = 0$) to 1 ($n_S = 0$), where the extreme cases correspond to a complete segregation of the particles, i.e., $I_{H,\perp} = -1\,(I_{H,\perp} = 1)$ means no large (small) particles in the sample volume. A value of zero corresponds to the presence of the same volume of large and small particles in the sample.

To illustrate the behavior of the two indices, we first analyze two ideal cases like those shown in Figure 7 (c) and (d) where flow segregation at the base of the pile and a stratification case are sketched. The mass ratio m_{LS} in this case corresponds to the ratio of the surface areas representing large grains (gray area) and small grains (white area) in Figure 7. m_{LS} is equal to 0.64 in part (c) and to 1.1 in part (d).

In Figure 8 we show the values for I_H and $I_\perp$ for both ideal cases as a function of the horizontal coordinate *x* of the right half of the pile and as a function of the distance $\left|\vec{d}_\perp\right|$. As observed, I_H increases with *x* for the pile in Figure 7 (c), changing from negative to positive values, as expected. For a stratified pile, I_H remains almost constant around a value that matches the fictitious concentration of small and large grains used to build the ideal pile. On the other hand, $I_\perp$ fluctuates between positive and negative values for the stratified case and remains constant for the other case and equal to -0.22, as expected for a mass ratio equal to 0.64.

The analysis above reflects the importance of using both indices, because I_H alone would indicate a mixture for a stratified pile and, on the other hand, $I_\perp$ would give a mixture for the pile in Figure 7 (c).

It is important to note that the amplitude of the fluctuations for $I_\perp$ will depend on the size of the sample volumes taken to evaluate the index. In the case of a volume close to that of each segregation band, the index will drastically oscillate between -1 to 1 like in Figure 8.

In Figure 9 (a)-(d) we show the results for $I_\perp$ and I_H for several piles with size ratio 3:1 and different values for the construction parameters, as indicated. The right half of the pile is divided in ten equal sample volumes to calculate the corresponding segregation index inside each volume. For that reason, each curve has 10 points corresponding to each of the sample volumes. It is worthy to mention here that the value of m_{LS} used in each experiment does not always match the mass ratio obtained from the image analysis because the latter only considers the grains belonging to the side of the pile to be photographed.

For $m_{LS} < 1$ the three cases shown in Figure 9 (a) show an oscillatory behavior for $I_{\perp}$, indicating the presence of stratification. The amplitude of the oscillations is related to the formation and intensity of stratification, but also to the width chosen for the sampling volume. It is important to note that a too wide (or narrow) volume will not properly account for the presence of bands. For the case h = 10mm, the fluctuations in $I_{\perp}$ are more pronounced than for h = 25 and 50mm. This demonstrates a less important stratification for the two last cases. This is in agreement with the experimental observation that the increment in h discourages banding formation.

In Figure 9 (b), the behavior of I_H shows an increase of the segregation of large particles as we go towards the tail of the piles in all cases. The analysis of the behavior of I_H alone would imply the presence of a flow segregation: small particles in the center of the pile and large particles at the tails, starting at $x \approx 500mm$, and with small fluctuations due to the presence of isolated large particles in the center of the pile. However, the fluctuation in the values of $I_{\perp}$ is a demonstration of the presence of bands of different thickness. This is consistent with the pictures shown in Figure 4 (a) and Figure 4 (b) for h = 10mm and h = 50mm, respectively.

On the other hand, for $m_{LS} > 1$ (Figure 9 (c) and (d)) I_H indicates a moderate segregation for the three values of h (recall the greater number of large particles) that slowly increases from the center to the tail of the piles: small particles being mainly at the center and large particles at the tails. Very small fluctuations in the behavior for $I_{\perp}$ indicate the presence of incipient bands.

In Figure 10 the segregation indices for size ratio 3:2 and $m_{LS} < 1$ are plotted for three different heights. The sample volumes employed here are equal to 8, sufficient enough given the size ratio. $I_{\perp}$ in part (a) shows to be practically constant with some fluctuations for the last points related to the sample volumes near the slope. This behavior reflects the fact that no stratification is found for size ratio 3:2, as already explained in the previous section. The small displacement toward greater values for h = 50mm is related to a greater m_{LS} in that case. The other index shows the presence of segregation at the ends of the piles, especially for low values of h. For h = 50mm, the segregation phenomenon practically disappears, indicating that the pile has a good mixing level in almost all its volume. This behavior is illustrated by Figure 3 (a) for h = 10mm and Figure 4 (c) for h = 50mm.

Finally, Figure 11 shows the results for I_H belonging to the piles in Figure 5. Recall these piles are built up with lateral amplitudes A = 100mm and A = 200mm. The indices are compared with the case with no lateral movement. The sample volumes employed here are equal to 8. For A = 100mm, the difference in extension for the curve is because the pile for this case is a bit smaller than the other two. $I_{\perp}$ is not shown here because stratification is never present with a lateral movement. The behavior of I_H for the two values of A oscillates, indicating no segregation tendency in most of the volume, in contrast with the behavior of I_H for A = 0. Only the tails of the piles show a smooth segregation pattern, especially for A = 100mm.

As shown so far, the segregation indices defined here successfully quantify the qualitative aspects discussed in the previous section.

5. Conclusions

A complete study on the segregation of rectangular grain piles built by dropping simultaneously glass beads of two different sizes has been presented.

The experimental set-up presented here largely reproduces the mechanisms used in industry to build up granular piles. For this reason, the conclusions found here can be easily transferred to that field.

The results found demonstrate that, under certain conditions, bands (striae) can be formed due to combined effects as grain bearings and the outbreak of small avalanches and despite the fact that particles only differ in size. The phase diagrams indicate that stratification shows up only for 3:1 size ratio, low values of h and $m_{LS} < 1$. On the other hand, flow segregation patterns occur for moderate heights and $m_{LS} > 1$ or for large heights but $m_{LS} \leq 1$ in the case of 3:1 size ratio, while, for 3:2, flow segregation is always present for $m_{LS} < 1$ at all heights.

In general, for higher injection points, the greater kinetic energy causes the distribution of the grains to depend on their collision properties. This mechanism reduces segregation, independent of the ratio of the sizes.

Displacement of the injection point reduces segregation. The horizontal movement allows the percolation of grains in different layers while they roll on the surface.

The definition of the two indices of segregation $I_{\perp}$ and I_H, allows a good characterization of the different patterns found, especially those presenting bands.

The competition between segregation and stratification needs to be explored in more detail. Future efforts are conducted in that direction.

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Figure Captions

Figure 1: Experimental device scheme. F: feeder, 3DM: 3D mixer, 2DM: 2D mixer, IP: injection point, C: cell.

Figure 2: Vertical movement's control system. PT: phototransistor, h: distance between the injection point and the top of the pile.

Figure 3: (color online) Typical pictures after built up of piles for an injection point height equal 10mm and a size ratio 3:2. Large grains are red and small ones are blue. (a) $m_{LS} = 0.54$. (b) Center coordinates of the glass beads obtained through the image processing: filled symbols correspond to large particles and empty symbols to small ones. (c) $m_{LS} = 1.12$.

Figure 4: (color online) (a) A typical pile showing stratification for size ratio 3:1, h = 10mm and $m_{LS} = 0.61$. (b) Pile with h = 50mm, size ratio 3:1 and $m_{LS} = 0.60$. (c) Pile with h = 50mm, size ratio 3:2 and $m_{LS} = 0.90$.

Figure 5: (color online) Piles built up with lateral movement of the injection point. The size ratio is 3:1 and h = 10mm. (a) A = 100mm and $m_{LS} = 0.8$; (b) A = 200mm and $m_{LS} = 0.64$.

Figure 6: Phase diagrams for experiments without horizontal movement. (a) Size ratio 3:1. The lines separate the different segregation-mixture states: M, mixture; B, bands or stratification; SM, segregation-mixture; SB, segregation-stratification. (b) Size ratio 3:2.

The lines separate the different segregation-mixture states: S, segregation; M, mixture; SM, segregation-mixture.

Figure 7: (a) Schematic view of the partition of the volume of the pile into sample volumes to calculate the segregation indices (a) I_H and (b) $I_\perp$. Segregation patterns are sketched in (c) for a flow segregation at the base of the pile, assuming $m_{LS} = 0.64$ and in (d) for a stratification case with $m_{LS} = 1.1$.

Figure 8: Análisis of the ideal segregation patterns of Figure 7 (c) and (d). (a) I_H as a function of the horizontal coordinate x of the right half of the pile, and (b) $I_\perp$ as a function of the distance $\left|\vec{d}_\perp\right|$.

Figure 9: Segregation indices for size ratio 3:1 as a function of horizontal distance x and perpendicular distance $\left|\vec{d}_\perp\right|$, respectively. (a) and (b): $I_\perp$ and I_H for $m_{LS} < 1$ and three different heights for injection, as indicated. (c) and (d): $I_\perp$ and I_H for $m_{LS} > 1$ and three different heights for injection, as indicated.

Figure 10: Segregation indices for size ratio 3:2 and $m_{LS} < 1$. (a) $I_\perp$ and (b) I_H. The different injection point heights mass ratio values are indicated in the figure.

Figure 11: Segregation indices $I_\perp$ and I_H for size ratio 3:1 with h = 10mm and different lateral amplitudes for the injection point. The mass ratio m_{LS} is indicated in each case. The pictures of the piles correspond to those in Figure 5 (a) and (b), respectively.

Figure 1

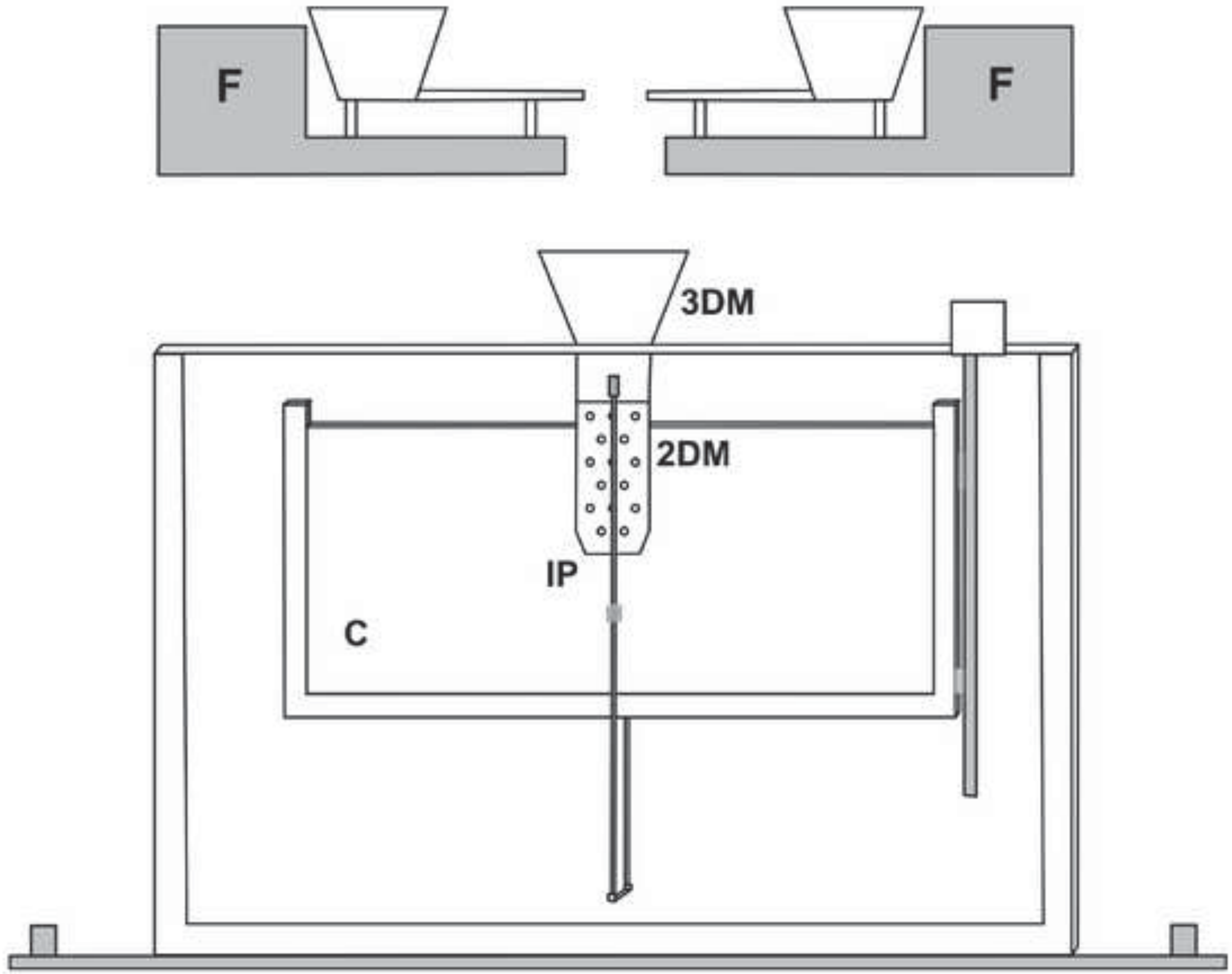

Figure 2
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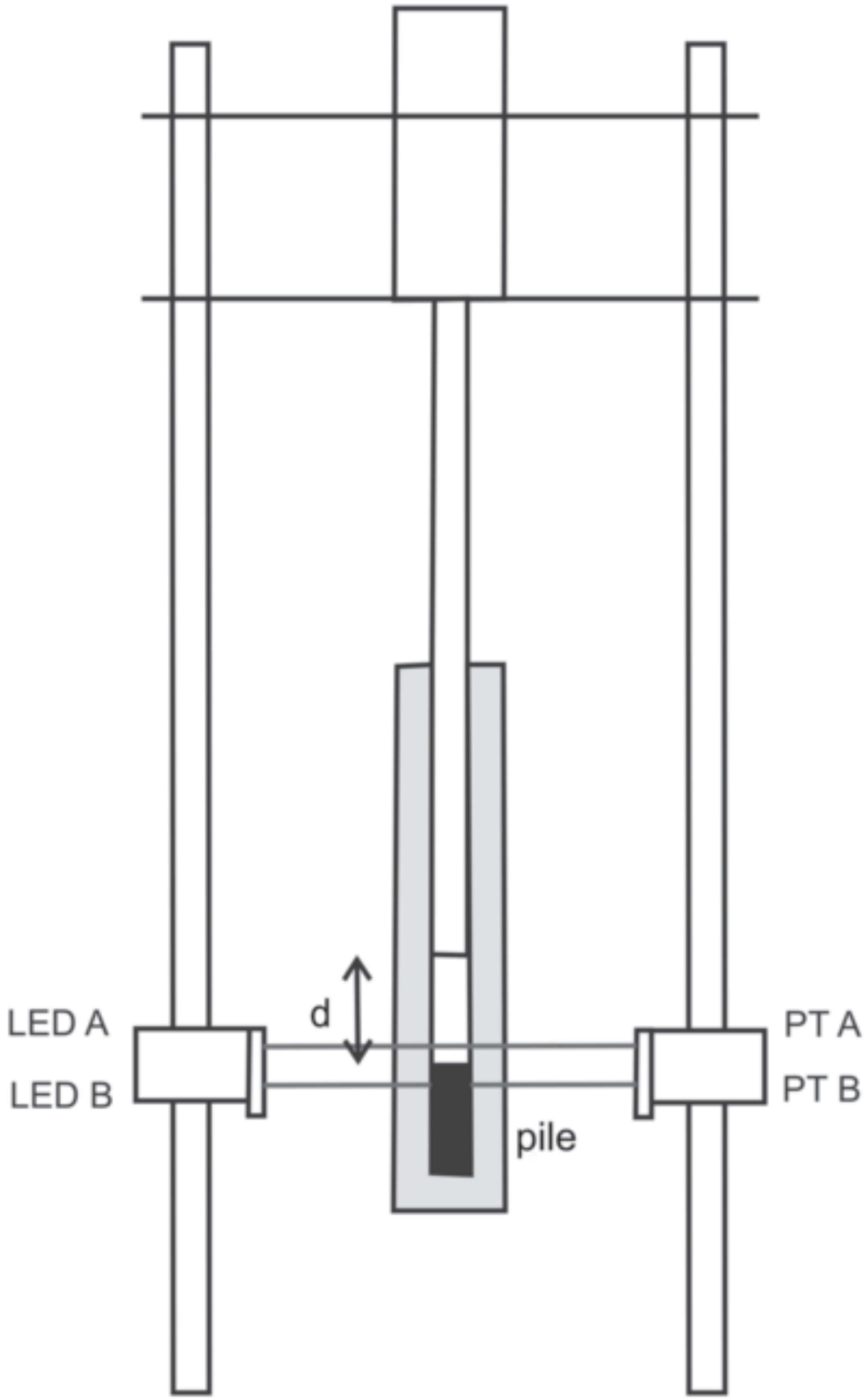

Figure 3
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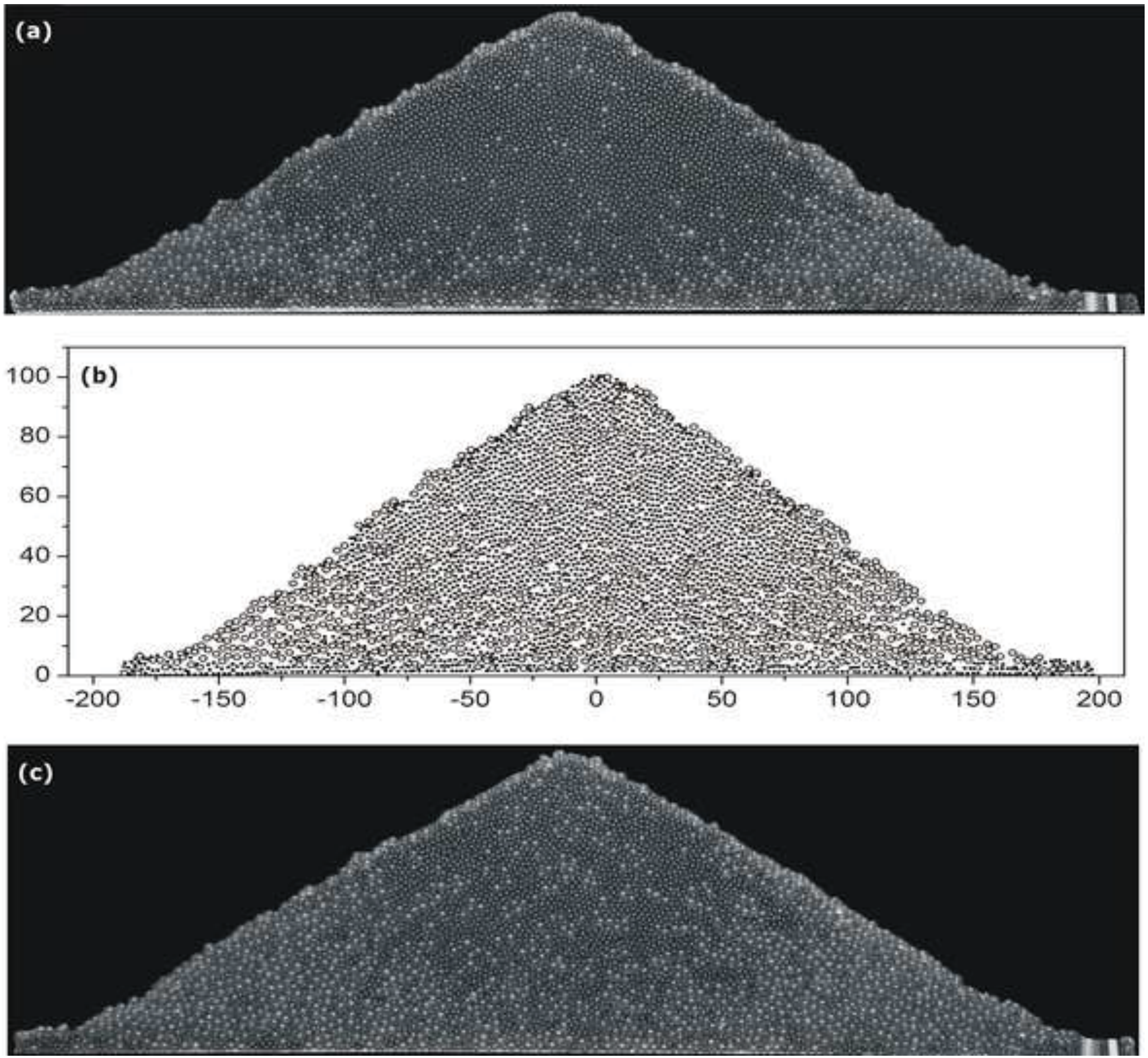

Figure 3_color

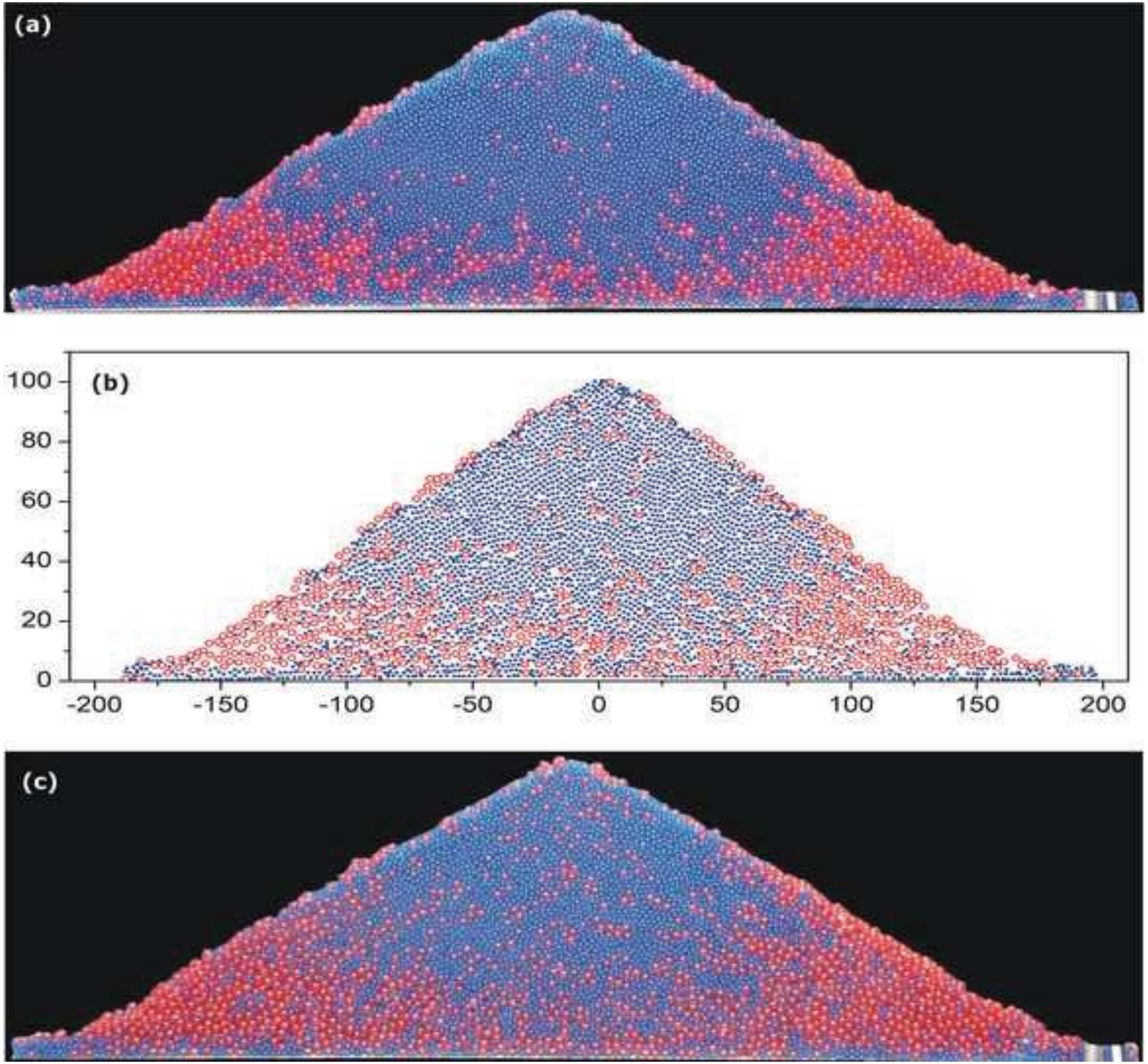

Figure 4
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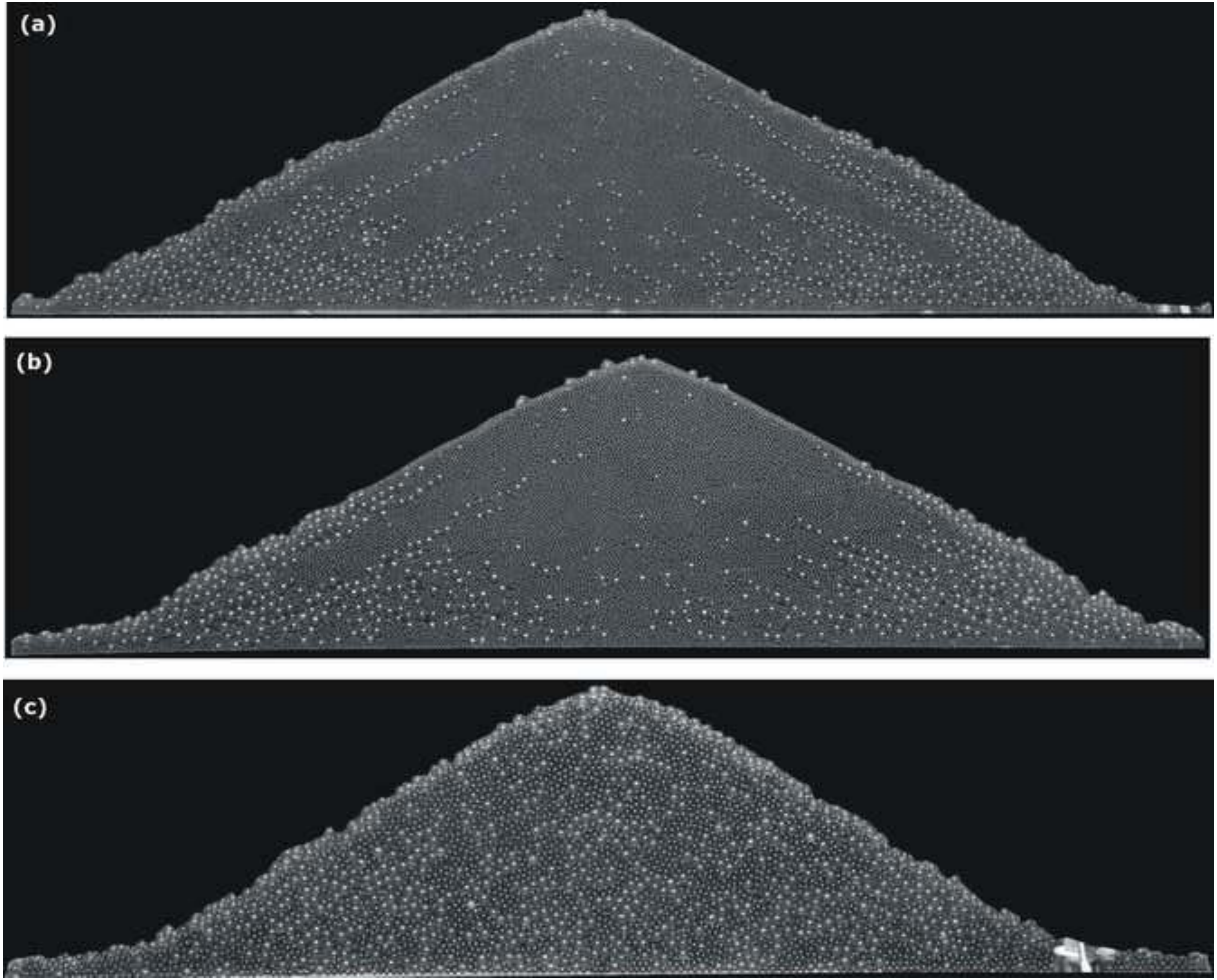

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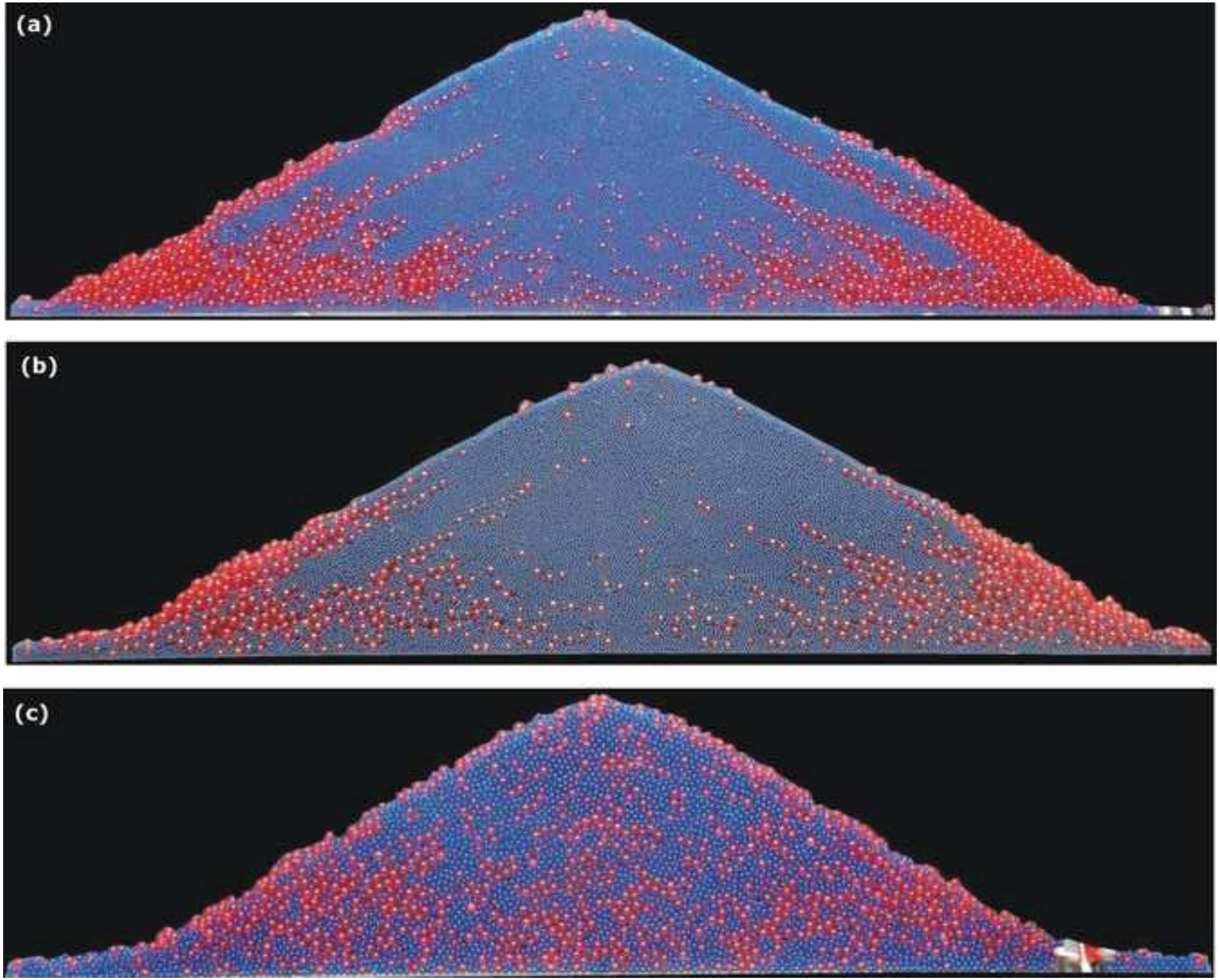
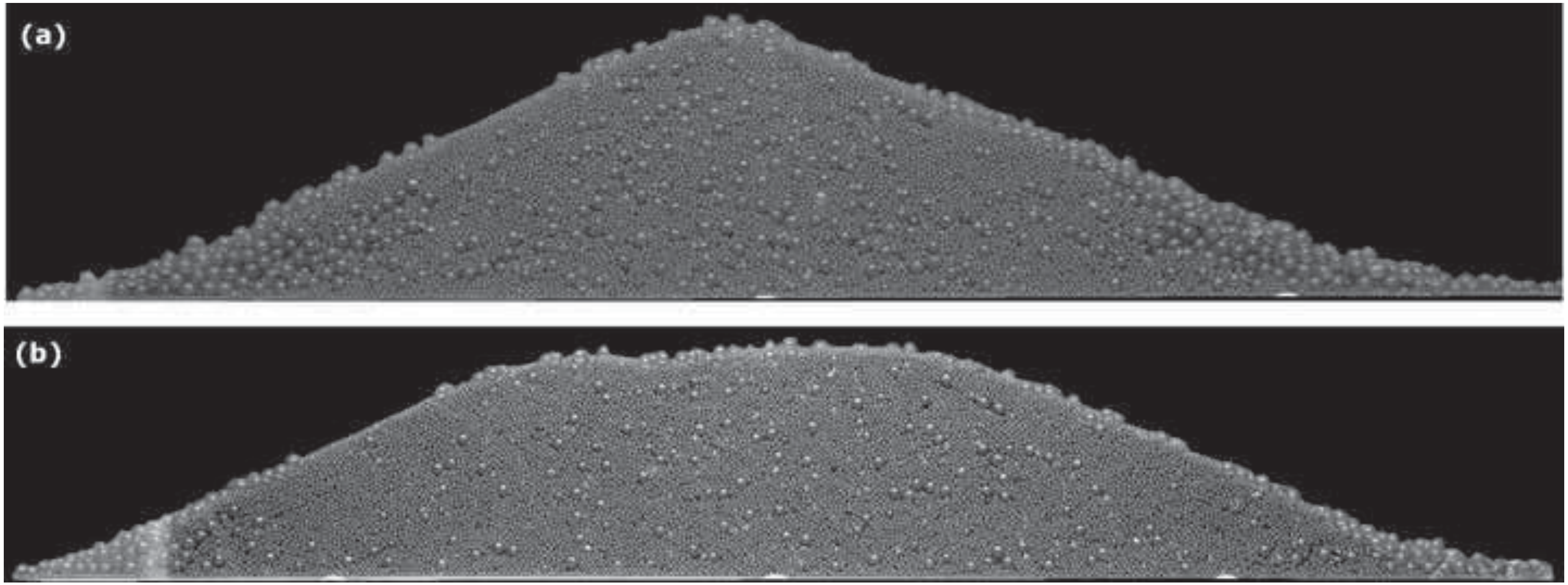


Figure 5



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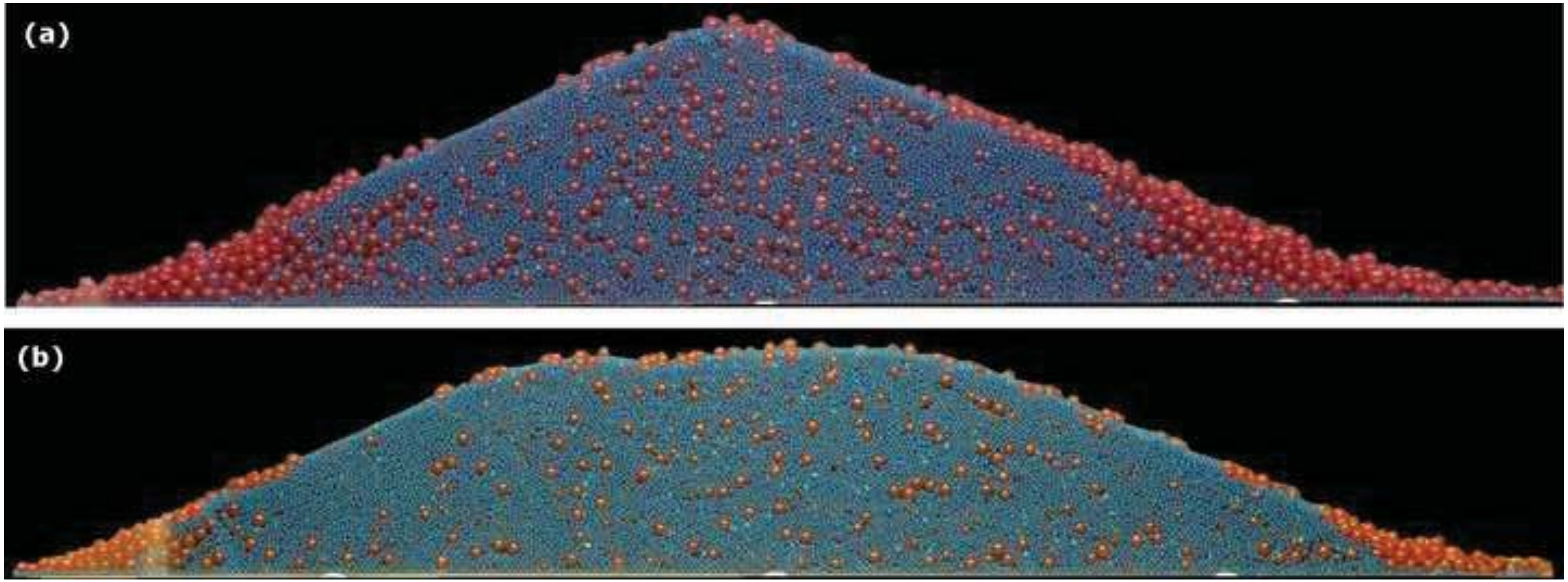

Figure 6

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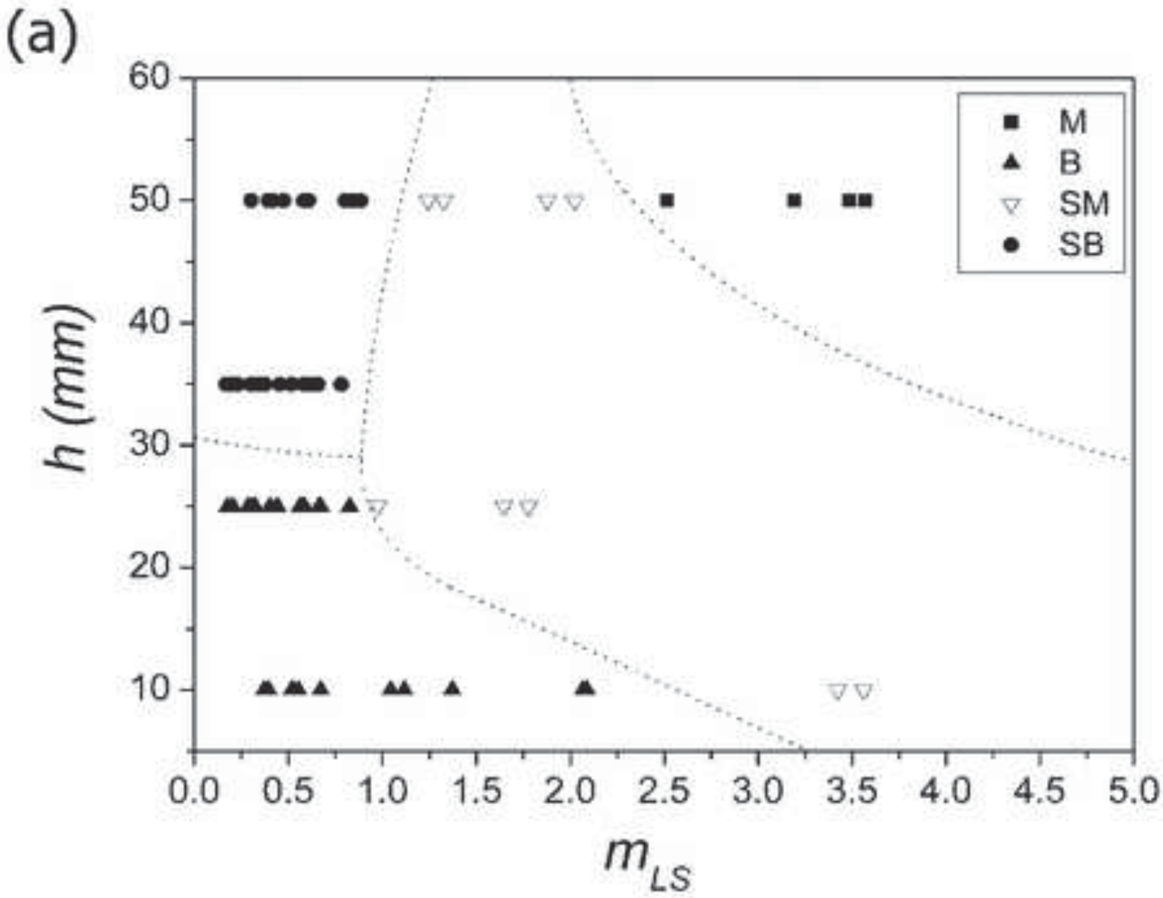

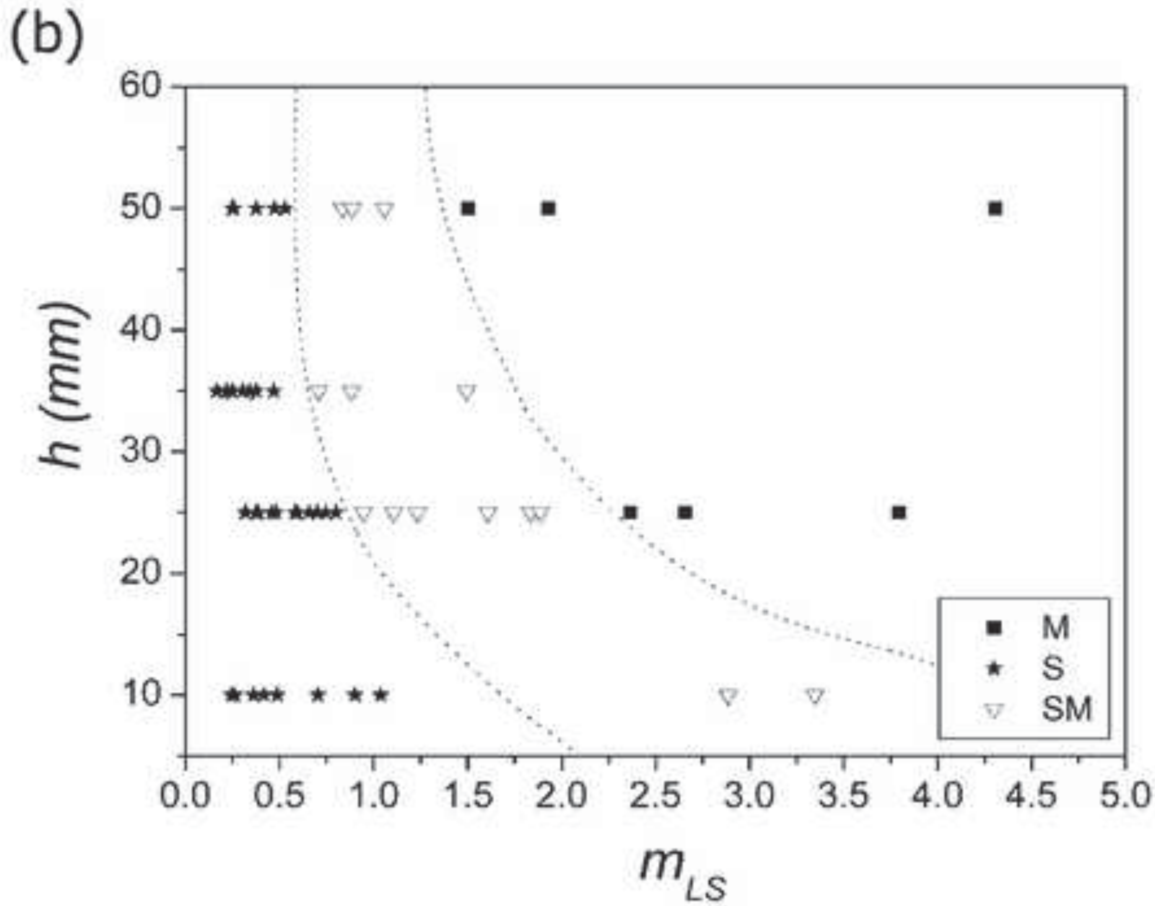

Figure 7
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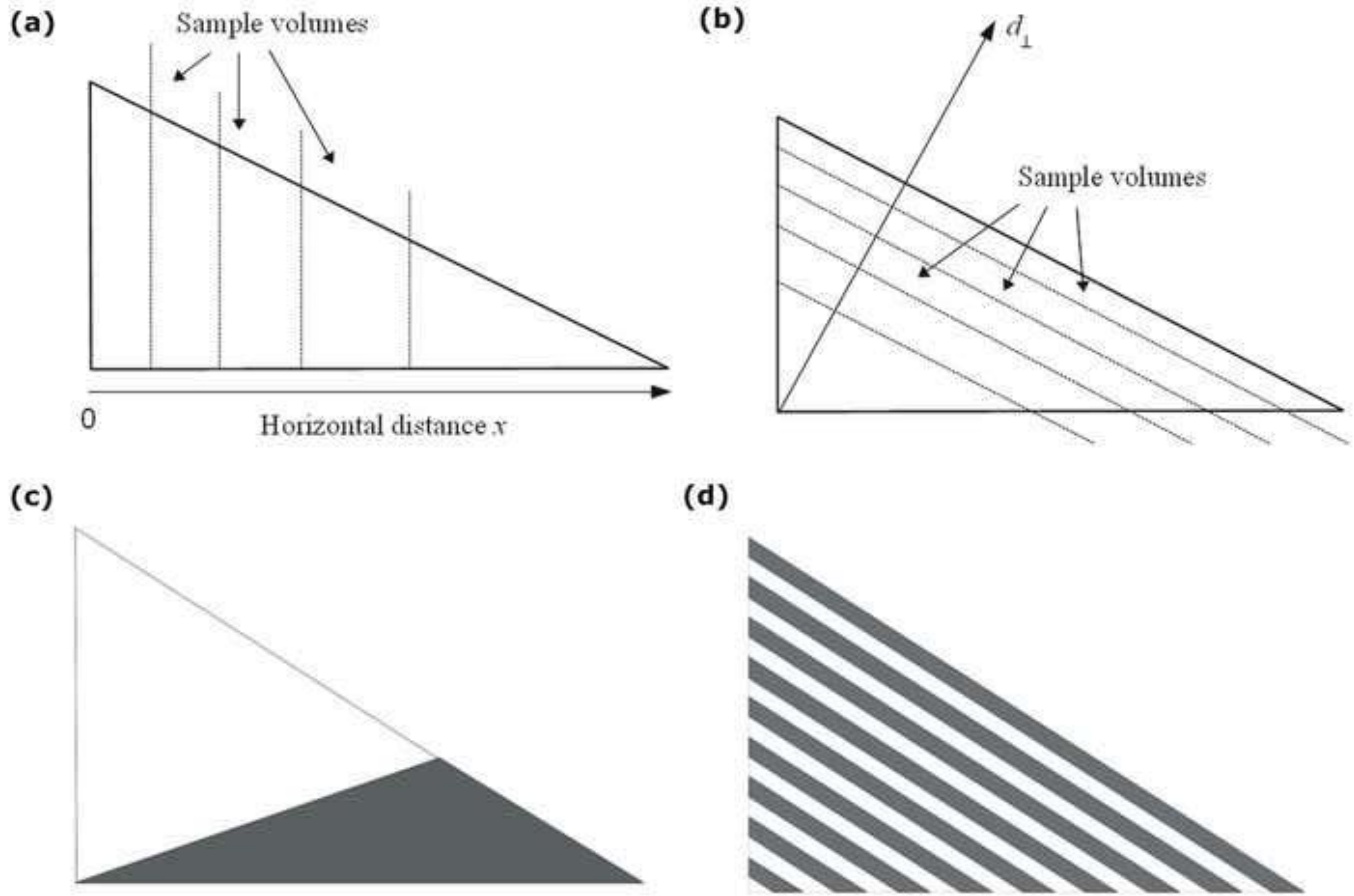

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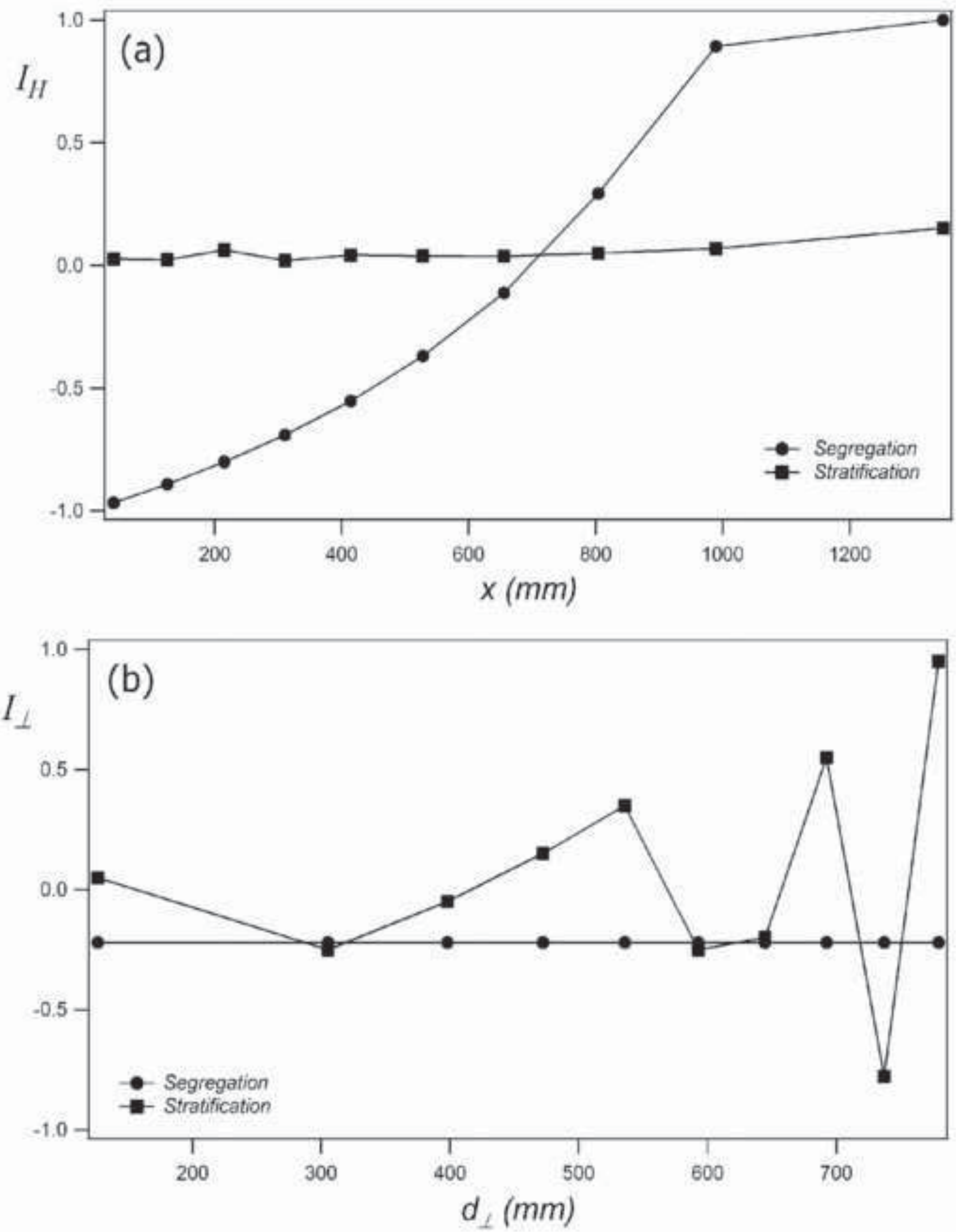

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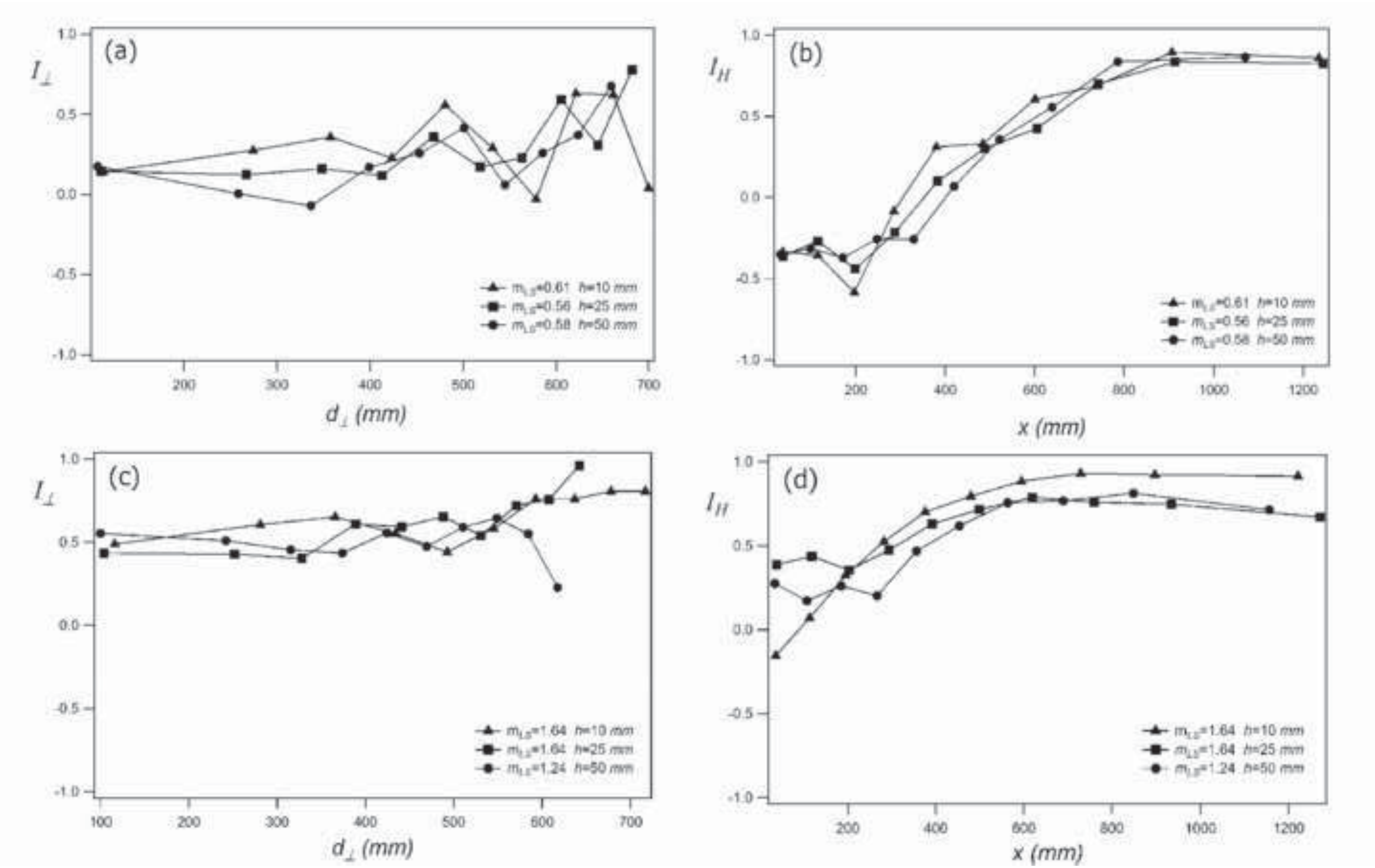

Figure 10
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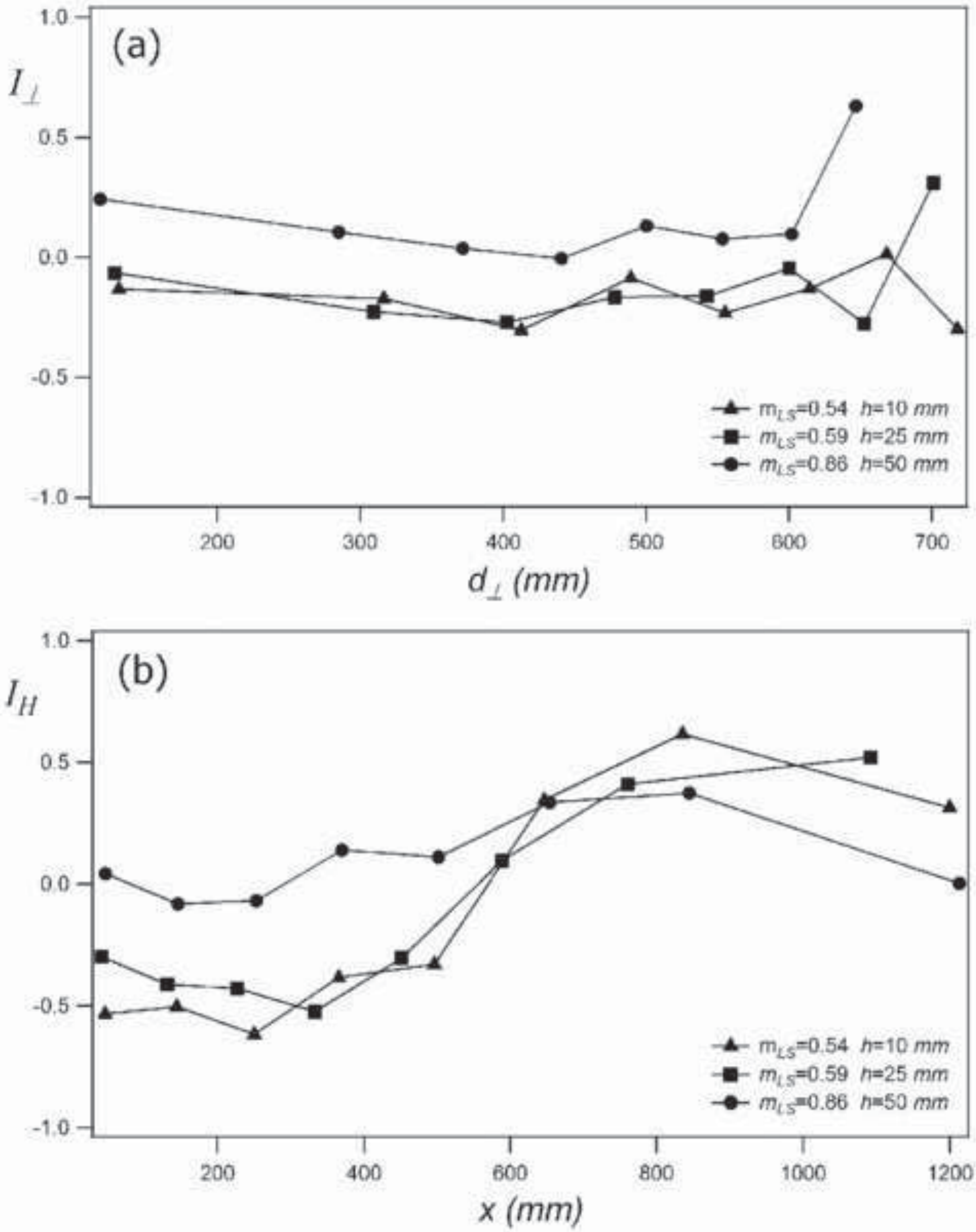
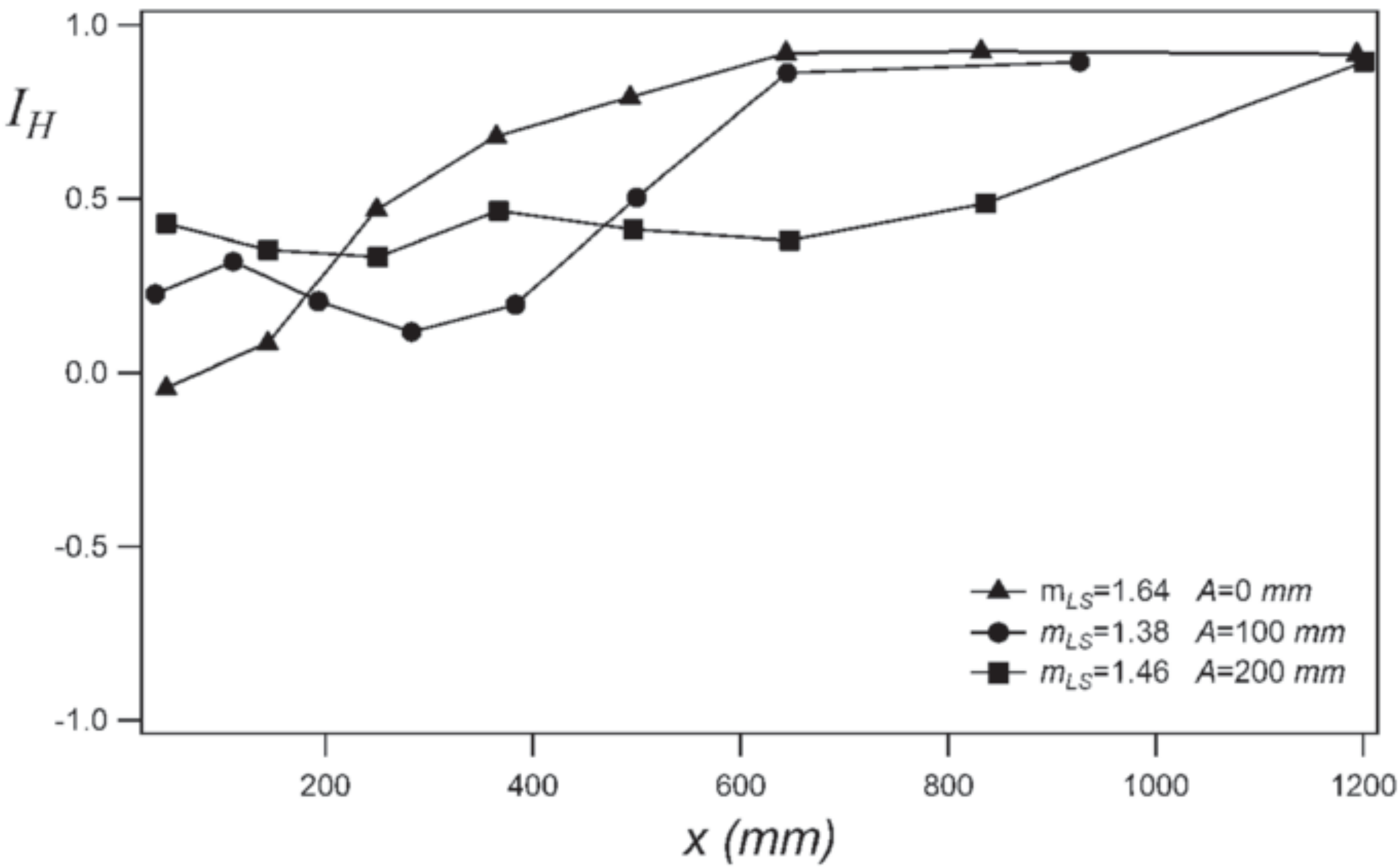


Figure 11



I_H
1.0
0.5
0.0
-0.5
-1.0
200
400
600
800
1000
1200
x (mm)
m_{LS}=1.64 A=0 mm
m_{LS}=1.38 A=100 mm
m_{LS}=1.46 A=200 mm

*Highlights

- Systematic study of segregation patterns in piles with two different grain size.
- Injection point and mass ratio can be varied through a versatile experimental set-up.
- Determination of a state diagram for segregation-mixing.
- Definition and measurement of two suitable segregation indices.
- Stratification is present although the grains only differ in their sizes.