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Effect of construction method and bench height on particle size segregation during waste rock disposal

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ABSTRACT
Waste rock segregation and heterogeneity can increase the hydrogeotechnical and geochemical instability of waste rock piles, but characterising segregation quantitatively in the field is difficult because of the large dimensions of these structures. In this study, a discrete element model (PFC3D) was calibrated on two real cases and used to simulate the flow behaviour of waste rock during disposal. The effect of the construction method, the bench height, and additional factors (e.g. mine truck payloads and push velocities) on particle segregation was investigated. Segregation degree and relative particle diameters of waste rock at different locations in the pile were compared to propose practical solutions and reduce segregation and heterogeneity during deposition. Results indicated that simulated bench heights and mine truck payloads had limited effect on segregation. A smaller proportion of large particles in the original waste rock can increase segregation. Lateral disposal and increasing the push velocity tend to reduce segregation.

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KEYWORDS
Waste rock disposal; segregation; discrete element simulation; construction method; bench height

1. Introduction

Large amounts of waste rock are generated by mining operations and are generally stored on the surface in piles or dumps [1–4]. Waste rock piles are constructed by repeatedly dumping waste rock along the slope using various methods, such as end-dumping and push-dumping [5,6]. Construction methods are usually selected depending on economic and environmental concerns [7], topography [8] and haul truck fleet [9].

These construction methods usually cause waste rock segregation with coarser particles moving further down to the bottom of the pile and smaller particles tending to remain closer to the deposition point and near the top of the slope [10]. Meanwhile, fine particles can move through the voids between larger particles and sink down towards lower layers [11]. Stratification also develops as inclined, fine-grained and coarse-grained layers form along the pile surface [12]. Finally, stratification also occurs at the surface of benches where waste rock can be crushed and compacted by the heavy equipment during construction [3,4]. Overall, segregation and stratification lead to high degree of spatial variability within waste rock piles [13,14]. The geotechnical and hydrogeological properties, including porosity, density, hydraulic conductivity, and shear strength of waste rock, can therefore vary significantly, both vertically and horizontally, thus increasing the

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risk for localised water flow and geotechnical instabilities [15–17]. The localised water flow also contributes to increase oxygen and water flux in the piles, potentially accelerating the oxidation of reactive minerals and the generation of acid mine drainage (AMD) [18]. Therefore, effective control of segregation is crucial for improving the hydro-geotechnical and geochemical stability of waste rock piles.

Construction method is often considered one of the main causes for waste rock segregation. End-dumping method involves directly depositing waste rock particles from the top of the pile, causing them to fall along the slope [6,19]. Push-dumping method consists in dumping waste rock on the surface of the pile and then push it to the edge using dozers [20]. Both methods lead to different degrees of waste rock segregation [21,22]. Some field observations have shown that the bottom of the slope can contain around 40% of the total maximum particles when push-dumping method is used and up to 75% with end-dumping method [21]. However, the effect of the construction methods on waste rock segregation is complicated to quantitatively investigate because of various influence factors and natural heterogeneity of waste rock. For example, mine truck payloads, which typically range between 150 t and 380 t [23] and the speed at which dozers push waste rock may also affect segregation [24]. So, the effect of construction methods on waste rock segregation is still not clear, but limited techniques can be found to efficiently characterise and distinguish particle movements during waste rock disposal.

Another factor which can strongly influence segregation is the bench height [24]. Observations report that the higher the pile size, the more significant the segregation [4,25]. Bench heights vary a lot depending on the operational constraints and stability concerns [26]. Quantitatively evaluating the effect of the bench height on waste rock segregation is still challenging because it is difficult to access to the large-scale waste rock piles which can reach hundreds of metres high. In addition, it is also impossible to sample and characterise large particles (sometimes >2 metres) in the field.

Therefore, this research aimed to investigate the effect of construction method and bench height, among other factors of influence, such as waste rock particle size distribution, payload, and push velocities, on waste rock segregation. Discrete element simulations, using particle flow code 3D [27], were calibrated on real cases and sensitivity analyses were conducted. Waste rock segregation along the slope was evaluated based on segregation degree and relative particle diameters. Finally, numerical simulation results were used to propose recommendations to limit segregation during waste rock disposal.

2. Methodology

2.1. Waste rock materials

Two types of waste rock were considered in this study: waste rock from Quebrada Blanca mine [28] and waste rock from the Canadian Malartic mine [29].

Quebrada Blanca mine is located in Tarapacá region in Chile. The operation produces copper cathodes using dump leaching, solvent extraction, and electrowinning [30]. The material itself is not exactly waste rock because it is concentrated enough to produce copper. However, the material properties and the deposition method are very similar to typical waste rock materials and dumps. Also, the ore will become a waste after extraction will have been completed. By commodity, material from Quebrada Blanca mine will therefore be referred to as waste rock in the following. The pile is constructed with end-dumping method using mine trucks. The height of the pile is around 20 m with slope angles between 30° and 40° [28]. Waste rock from Quebrada Blanca mine is characterised by minimum and maximum diameters of 0.1 m and 2.66 m, respectively, with a coefficient of uniformity $C_U = 4.1$ and a coefficient of curvature $C_C = 1.1$ (Figure 1). The specific gravity of waste rock in Quebrada Blanca mine is not reported and a specific gravity of 2.76 was assumed in this study.

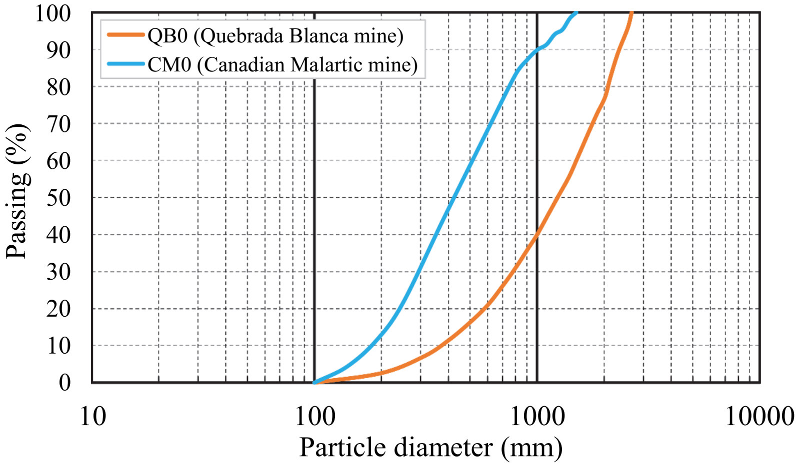

Figure 1. Waste rock PSD curves of (QB0) Quebrada Blanca mine and (CM0) Canadian Malarticmine. These PSD curves were scalped based on their field PSD curves.

The Canadian Malartic mine is an open-pit mine located at Abitibi-Témiscamingue, Quebec, Canada. The waste rock pile is constructed in 10 m benches with 11.5 m terraces between benches for an overall slope angle of 21.8°. The slope angle of each bench is around 37° [31]. The total height of the waste rock piles reaches 100 m in most sections [32]. Waste rock from the Canadian Malartic mine is characterised by a minimum and a maximum diameter of 0.1 m and 1.5 m, respectively, with a coefficient of uniformity $C_U = 2.9$ and a coefficient of curvature $C_C = 0.9$ (Figure 1). The specific gravity of waste rock in the Canadian Malartic mine is around 2.76 (measured by the authors, using ASTM C127, 2015).

2.2. Calibration and validation of simulations

Discrete element method (DEM [33]); is efficient to simulate the flow behaviour of granular material and therefore provides a useful alternative to overcome field challenges [11,34,35]. DEM can simulate the motion of waste rock particles by calculating the stress and deformation of contacts when particles interact with each other or with boundary walls [33,36]. In DEM models, particles move independently and interact at contact points based on assigned contact models [27,37,38].

The number of contacts between particles will increase with particle number, thus significantly increasing the calculation time for field-scale models. Such simulation may even crash when evolving millions of contacts. In this study, waste rock particles were then simulated using spheres so that the calculation pressure can be significantly reduced. However, spheres cannot directly reflect the irregular shape effect of waste rock particles. Rolling resistance linear (rrlinear) contact model [39] was therefore used to indirectly consider shape effect by considering the rolling and collision effect of irregular particles during particle collisions. In this contact model, friction coefficient (μ) and rolling resistance coefficient (μ_r) were main parameters controlling particle movement [40]. These parameters were calibrated using a new calibration method for large-scale waste rock piles. This new calibration method involves model calibration using repose angle tests and validation using segregation tests at both laboratory and field scales (Figure 2). The details of the calibration and validation can be found in the authors' publication in Qiu and Pabst [35].

Calibrated friction coefficient and rolling resistance coefficient were $\mu = \mu_r = 0.47$ for Quebrada Blanca mine, resulting in a repose angle of 37.3° ± 1.2° (similar to 35° to 40° measured in the field [28] and calibrated friction and rolling resistance coefficients were

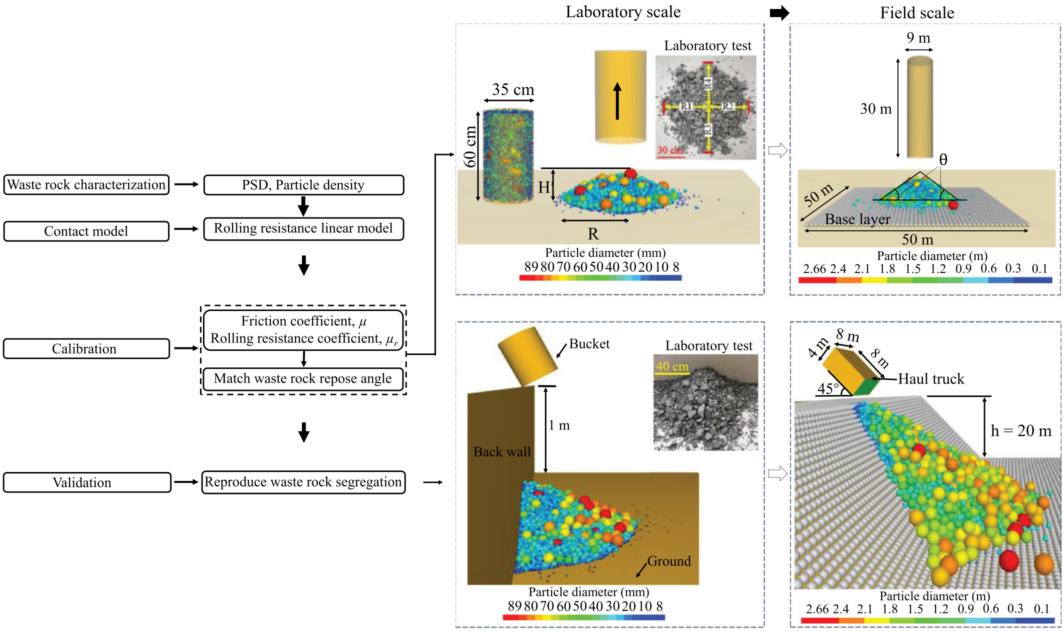

Figure 2. Calibration and validation of simulation models in both laboratory scale and field scale. Field-scale segregation was validated according to the field measurement. Dumped waste rock particles in simulations were colored depending on their diameters.

Table 1. Main parameters used in PFC3D to simulate waste rock segregation during disposal. Particle density (β) and local damp (α) were measured in the laboratory. Other parameters were determined by model calibration ([35]; see text for details).

Parameters	Quebrada Blanca mine	Canadian Malartic mine
Particle density, β (kg/m^3)	2760	2760
Friction coefficient, μ	0.47	0.44
Rolling resistance coefficient, μ_r	0.47	0.44
Local damp, α	0.4	0.4
Effective modulus, E (Pa)	1×10^6	1×10^6
Stiffness ratio, k*	2.5	2.5
Normal critical damping ratio, β_n	0	0
Shear critical damping ratio, β_s	0	0

$\mu = \mu_r = 0.44$ for Canadian Malartic mine, resulting in a repose angle of 37.4° ± 1.6° (similar to 37° measured in the field [31]. The calibrated models were then validated by well reproducing the segregation properties in the field.

Waste rock was considered cohesionless granular material so no viscous behaviour was considered and normal and shear critical damping ratios were set to 0 ($\beta_n = \beta_s = 0$). Local damp (α) was applied to simulate energy dissipation and calibrated using drop tests in the laboratory. Drop tests are usually used to determine the contact damp of granular materials. In this study, waste rock particles with a diameter of 0.1 m were freely dropped from one metre high, and the rebound height of each particle was measured using a camera. Drop tests were repeated 20 times and the rebound height varied between 0.05 m and 0.2 m with an average of around 0.1 m. The rebound heights of irregular waste rock particles were simulated by adjusting local damp from 0.1 to 0.9, and finally a local damp $\alpha = 0.4$ well matched the tested rebound heights. The effective modulus $E = 1 \times 10^6$ Pa was used to maintain the system within the rigid limit while optimising the calculation speed [27]. The effects of local damp and effective modulus were clearly analysed in Qiu and Pabst [35]. The calibrated parameters for simulations in this study are summarised in Table 1.

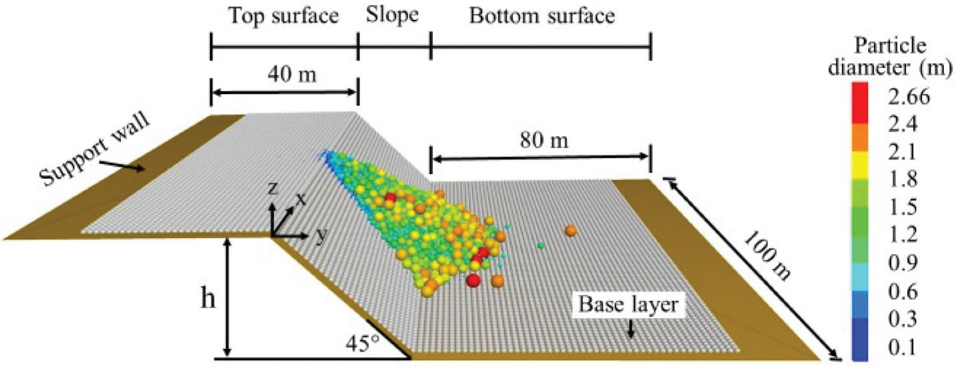

Figure 3. Simulation model for waste rock disposal. h [L] represents the bench height and varies between 10 and 25 m depending on the cases. Base layer is composed of 1 mdiameter balls (in grey; see text for details). Dumped waste rock particles are colored depending on their diameters (from 0.1 m in blue to 2.66 m in red).

2.3. Simulations of waste rock segregation during field disposal

2.3.1. General simulation approach

Field-scale simulation models were built to investigate segregation properties during waste rock disposal (Figure 3). The support walls (in yellow colour in Figure 3) represented the ground and physical boundaries of the models. The length of the support walls in x-axis direction was 100 m. The length of the support walls in y-axis direction was 40 m for the top surface and 80 m for the bottom surface. An inclined wall was initially generated to simulate an already existing waste rock slope to reduce calculation time. The initial slope angle was slightly greater than the repose angle to prevent its influence on the results. This initial slope did not significantly affect the final result but contributed to decrease the number of dumps to reach this final state observed in the field. The bench height (h in Figure 3) was adjusted depending on the simulated cases (see next section for more details). The support walls were covered by a base layer made of fixed 1 mdiameter balls (grey balls in Figure 3) to simulate waste rock surface so that dumped waste rock could directly interact with existing waste rock particles. The contact properties of the base layer were set the same to dumped waste rock particles. The effect of support layer and base layer was discussed in 'Result analysis and discussion' section. Waste rock was dumped from the top edge of the bench slope using end-dumping method and push-dumping method.

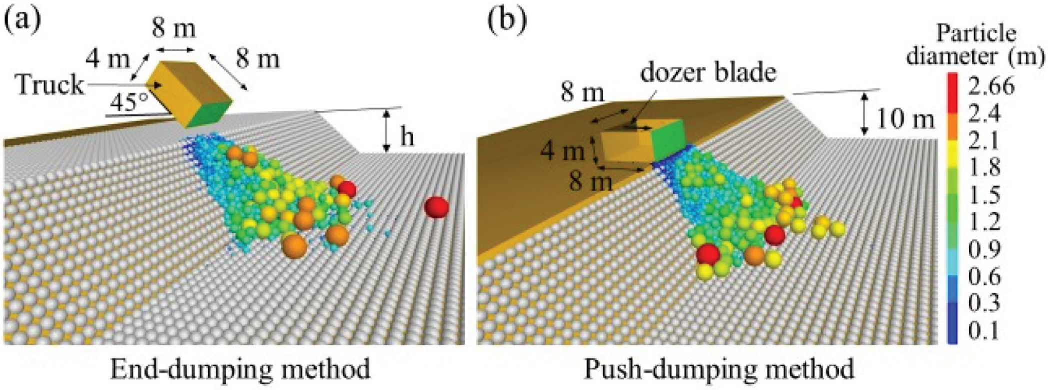

Figure 4. Simulation of waste rock disposal using (a) end-dumping method and (b) push-dumping method. h [L] represents the bench height which varies between 10 and 25 m depending on the cases. Dumped waste rock particles are colored depending on their diameters (from 0.1 m in blue to 2.66 m in red).

2.3.2. Simulations of end-dumping method

End-dumping method was simulated by dumping waste rock directly from the top of the bench (Figure 4a). An 8 m (width) × 8 m (length) × 4 m (height) box was generated to simulate the mine truck and was inclined at 45° to represent the maximum lifting angle of common mine trucks (e.g. CAT 794AC model [41]). The vertical distance between the bottom of the mine truck (i.e. the box in Figure 4a) and the top of the bench was 1.5 m, which corresponded to the dump height of large mine trucks (typically between 1 m and 2 m for CAT 794AC model [41]). Each waste rock dump (around 300 t) was generated within the simulated box and was disposed of by deleting the bottom wall of the box (green wall in Figure 4a) so that the waste rock could fall and move along the slope.

Four different bench heights were simulated, i.e. 10 m (case A1), 15 m (case A2), 20 m (case A3), and 25 m (case A4) (Table 2). Waste rock was dumped until the slope was completely covered (along the y-axis), which represented a total of 4, 16, 30 and 66 dumps of waste rock for bench heights of 10 m, 15 m, 20 m and 25 m, respectively. In practice, more dumps are expected to form a parallel layer with similar segregation as the surface layer in the model.

A 600 t payload (Case B1) was simulated using the same haul truck as described above, with a dimension of 8 m (width) × 8 m (length) × 4 m (height). The greater mass of waste rock was generated in the same box by using a smaller initial porosity (0.4 instead of 0.65 for a 300 t payload) in the stage of particle generations. Consequently, only payloads were different while other conditions, such as the width and height of the haul truck or the PSD of the simulated waste rock material remained unchanged, thus facilitating the comparison of the simulation results.

The effect of waste rock PSD was also investigated by dumping Canadian Malartic waste rock (case C1), with all the other parameters similar to case A1 (Table 2).

2.3.3. Simulation of push-dumping method

Push-dumping method was simulated by pushing waste rock on the top edge of the 10 m high bench (Figure 4b). An 8 m (width)×8 m (length)×4 m (height) box was generated on the surface of the bench to represent a dozer with an 8 m wide blade (close to CAT D11CD model dozer [41]. Around 300 t of waste rock were generated for each dump. At the beginning of the simulations, the front wall (green wall in Figure 4b) was deleted, and the box was moved towards the slope with a certain speed (between 0.1 m/s – case C1 and 0.6 m/s – case C6) to push the waste rock in the slope. The same process was repeated for each dump.

2.3.4. Quantification of segregation

Each simulation used in this study was repeated five times with five different random seeds (e.g. 10001 to 10,005) to check the repeatability of the simulations. Random seed is the basic code that ensures the repeatability of particle generation in PFC3D [27]. Different

Table 2. Summary of parametric simulation cases. QB0 and CM0: PSD of waste rock from Quebrada Blanca mine and Canadian Malartic mine, respectively. N/A: not applicable. Each case was simulated five times with various random seeds.

Case	Pile height (m)	PSD	Push velocity (m/s)	Payload (tonnes)	Construction method	Number of dumps
A1	10	QB0	N/A	300	End-dumping	4
A2	15					16
A3	20					30
A4	25					66
B1	10	QB0	N/A	600	End-dumping	4
C1	10	CM0	N/A	300	End-dumping	4
D1	10	QB0	0.1	300	Push-dumping	4
D2			0.2			
D3			0.3			
D4			0.4			
D5			0.5			
D6			0.6			

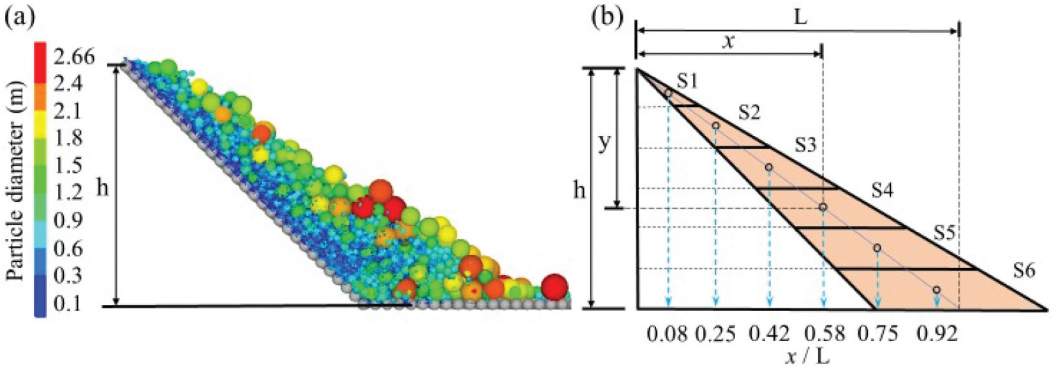

Figure 5. (a) Cross section of simulated waste rock slope (typical example) and (b) location characterization of the six sections along the slope. *x* / L [-]: relative location of each section with *x* [L] the horizontal distance of the section center to the deposition point and L [L] the horizontal length of the slope. h [L]: bench height. y [L]: vertical distance to dump point. Dumped waste rock particles are colored depending on their diameters (from 0.1 m in blue to 2.66 m in red).

random seeds can alter the initial relative positions of particles in a specific volume (i.e. different initial particles packing states) without affecting the PSD of the simulated waste rock. Results presented in the following are average values calculated from these five simulations.

Segregation is usually evaluated by segregation indices, such as the relative particle diameter [42], coarsening index [35,43], relative segregation index [44] and modified segregation index [45]. In this study, relative particle diameters (D_{10}/D_{10}', D_{50}/D_{50}', D_{95}/D_{95}') and segregation degree (χ) [35] were used to characterise waste rock segregation. Relative particle diameters were defined as the ratios D_{10}/D_{10}' (also D_{50}/D_{50}', D_{95}/D_{95}') where D_{10} and corresponds to 10% passing of the PSD in the slope (after deposition and segregation), and D_{10}' corresponds to 10% passing of the original PSD. A negative segregation degree indicates that waste rock was finer than the original material and a positive value indicates waste rock was coarser than the original material.

The segregation degree (χ [46] of waste rock in each section was determined as:

$$\chi = \frac{\log d_{tested} - \log d_0}{\log d_{CQ} - \log d_0} \tag{1}$$

Where $\log d_0$: the logarithmic mean particle size of the original waste rock before disposal, d was in mm in this study; $\log d_{tested}$: the logarithmic mean particle size of waste rock in the local section, and $\log d_{CQ}$ the logarithmic mean particle size of the coarsest quartile. The coarsest quartile represents the fraction of particles larger than the diameter D_{75} of the original gradation [47]. The logarithmic mean particle size is often considered a representative parameter for delineating the PSD curve and can be calculated as [44]:

$$\log d = \sum_{i=1}^{n} (P_i - P_{i-1}) \log \sqrt{D_i \cdot D_{i-1}} \tag{2}$$

Where D_i and D_{i-1} [L]: consecutive particle diameters corresponding to passing P_i and P_{i-1}.

The slopes in all the cases (and independently of their height and length) were equally divided into 6 sections in the vertical direction (Figure 5). The PSD curve, relative particle diameters and segregation degree in each section were determined from simulation results.

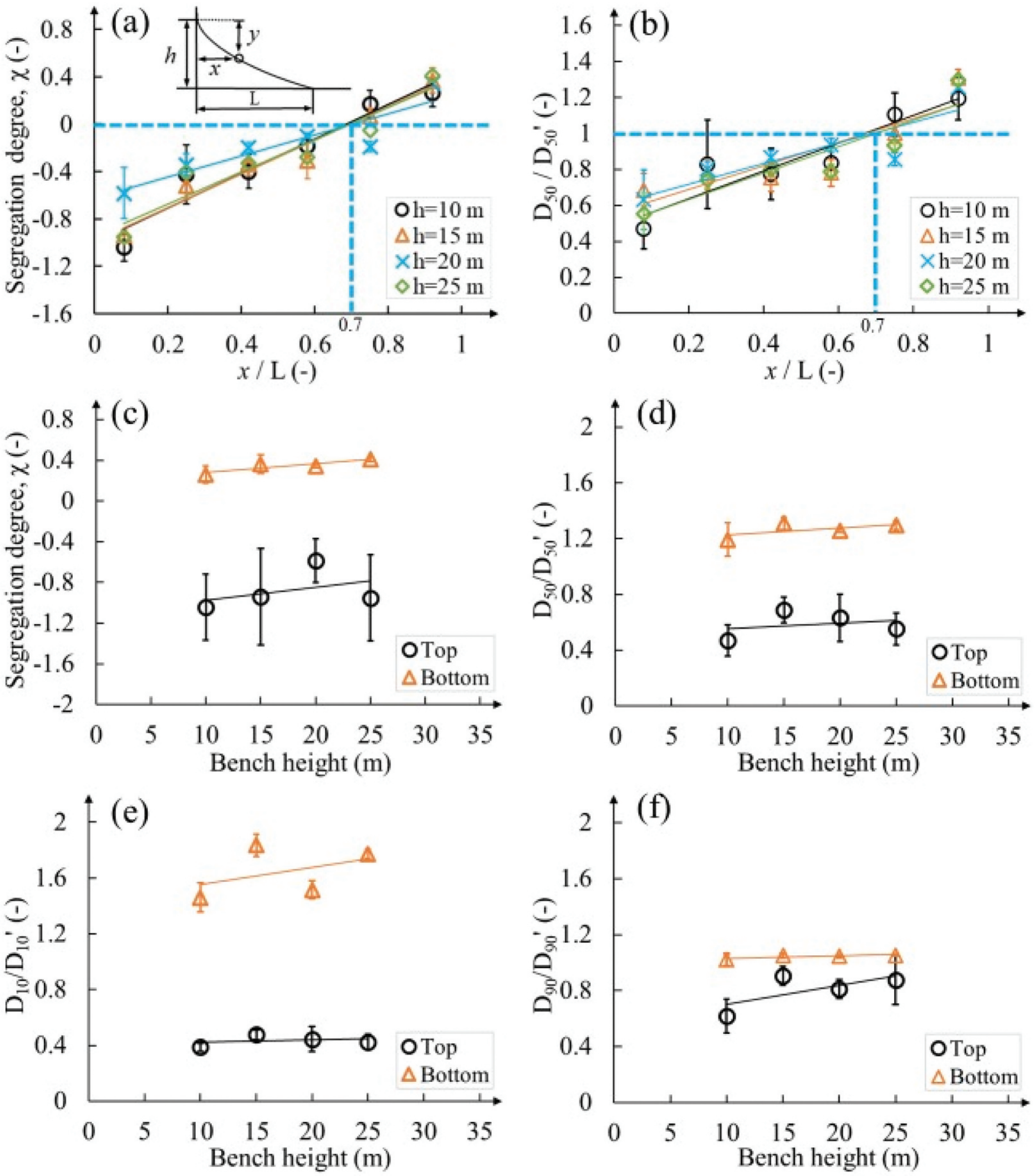

Figure 6. Characterization of waste rock segregation simulated for different bench heights using end-dumping method. Variation of (a) segregation degree and (b) D_{50} / D_{50}' with the relative location *x* / L. (c) Segregation degree, (d) D_{50} / D_{50}', (e) D_{10} / D_{10}' and (f) D_{90} / D_{90}' as functions of the bench height, and at the top (black circle, *x* / L = 0.08) and bottom (orange triangles, *x* / L = 0.92) of the slope. *x* [L]: horizontal distance to the deposition point. y [L]: vertical distance to dump point. L [L]: total horizontal length of the slope. h [L]: bench height. Error bars represent standard deviation.

3. Results

3.1. Effect of bench height

Four different bench heights (i.e. 10 m, 15 m, 20 m, 25 m) were simulated in this study using end-dumping method. All cases showed significant waste rock segregation along the slope, with an increase of finer particles (compared to the original material) at the top of the bench and an accumulation of coarse particles at the bottom (Figure 6). For all cases, segregation degree was negative and smaller than −0.58 at the top of the slope (x / L = 0.08) and was positive and greater than 0.35 at the bottom of the slope (x / L = 0.92) (Figure 6 a and b). Also, relative particle diameters (D_{10} / D_{10}', D_{50} / D_{50}', D_{90} / D_{90}') were all smaller than 0.98 (<1) at the top and larger than 1.05 (>1) at the bottom of the slope (Figure 6, d – f). More generally, waste rock was coarser than the original material when x / L > 0.7, for all the bench heights (Figure 6, a and b).

Bench height did not exhibit clear effect on waste rock segregation at the top of the slope. For example, the segregation degree at the top of the slope (x / L = 0.08) was between −1.04 (10 m bench) and −0.58 (20 m bench) (Figure 6c). High variations of segregation degree and relative particle diameters were observed at the top of the slope. The minimum and maximum standard deviation of segregation degrees for the simulated bench heights (10–25 m) were 0.22 and 0.48, respectively. The standard deviation of the ratio D_{90} / D_{90}' at the top of the slope was also relatively high and could be up to 0.18 (25 m bench) (Figure 6f). The reason for this variability was that the top of the slope contained a limited number of coarse particles, therefore bringing uncertainties to the segregation degree. For example, a single 150 cm diameter block can lead to 0.15 difference in the segregation degree at the top of the slope. Also, the investigated volume (S1 in Figure 5b) was smaller at the top than that at the bottom of the slope, therefore increasing the variability of particle distribution. For example, for a 10 m high slope, the average mass of waste rock was around 32 t at the top of the slope, which was much smaller than that (around 375 t) at the bottom.

Bench height had limited effect on waste rock segregation at the bottom of the slope. For example, segregation degree at the bottom of the slope was comprised between 0.26 and 0.38 (Figure 6c), and D_{50} / D_{50}' ranged between 1.19 and 1.31 for all the cases (Figure 6d), indicating that bench height had insignificant effect on these values. Relatively low variations of the segregation degree and relative particle diameters were observed at the bottom of the slope. The maximum standard deviation of the segregation degree was only 0.09. The maximum standard deviation of D_{90} / D_{90}' at the bottom was also very small and did not exceed 0.04 (Figure 6f). The maximum standard deviation of D_{10} / D_{10}' was 0.11 at the bottom, which was slightly greater than that (i.e. 0.09) at the top of the slope (Figure 6e). The fact that the variability is significantly smaller at the bottom of the pile can be explained by the abundance of large particles (D >1.5 m), which accounted for around 40% of the total simulated particles.

In this study, only bench heights smaller than 25 m were simulated based on usual recommendations for design and operation of waste rock piles to ensure geotechnical stability [4]. This choice was also the result of numerical constraints [48]. Simulating higher benches would indeed have significantly increased the calculation time and exceeded the maximum number of particles that can be simulated. Consequently, additional simulations would be necessary to confirm the trends observed in this study, especially in cases where higher benches are considered (e.g. in pit backfilling [49].

3.2. Effect of waste rock PSD

The effect of waste rock PSD on segregation was investigated by comparing simulations of 4 dumps of waste rock from Quebrada Blanca mine (QB0; previous results) and Canadian Malartic mine (CM0 in Figure 1), for a 10 m high bench using end-dumping method. The simulated waste rock segregation for Canadian Malartic mine matched well the field observations [29]. For example, the difference between the simulated and measured D_{50} / D_{50}' was smaller than 0.1 for the six sections along the slope (S1 to S6 in Figure 5b).

The difference of waste rock segregation for the two types of waste rock mainly focused on the bottom of the slope. For example, the difference of D_{50} / D_{50}' between the two types of waste rock was smaller than 0.16 at the top and middle (x / L ≤ 0.75) but was 0.4 at the bottom of the slope (x / L = 0.92) (Figure 7). In other words, segregation was more marked with waste rock from Canadian Malartic mine than from Quebrada Blanca mine. Such

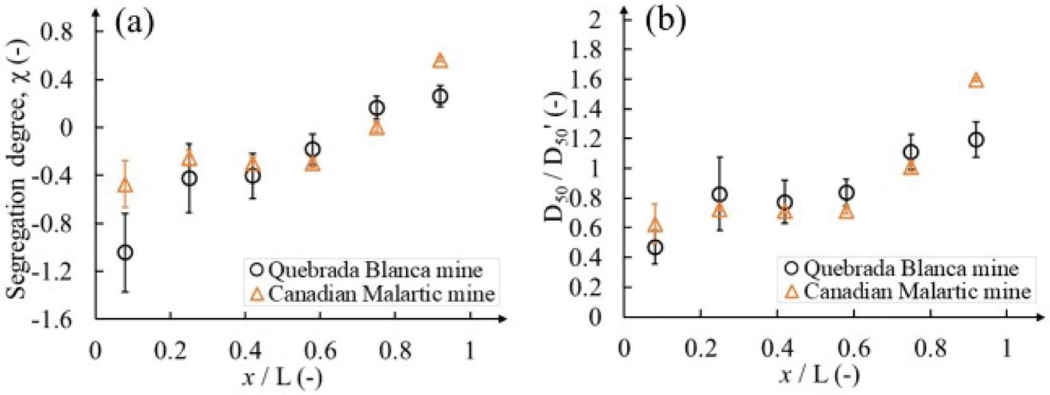

Figure 7. Simulated (a) segregation degree and (b) D_{50} / D_{50}' as functions of the relative location *x* / L for waste rock from Quebrada Blanca mine (black circles) and Canadian Malartic mine (orange triangles) using end-dumping method. Error bars represent the standard deviation.

difference was caused by initial material PSDs (before the deposition). Large particles (>1 m) of the original waste rock accounted for only 10% of the total particle mass for Canadian Malartic, but 60% for Quebrada Blanca mine. However, the percentage of large particles at the bottom of the slope (x / L = 0.92) was significantly greater for Canadian Malartic mine (70%) than that for Quebrada Blanca mine (40%). In practice, reducing the quantity of the largest particles and homogenising particle sizes could therefore contribute to limit segregation.

In practice, controlling waste rock particle sizes can be difficult and is mainly determined by blasting which depends on different basting parameters, such as rock mass factors and explosive factors [50,51]. Powder factor, i.e. the quantity of explosives (in kg) consumed per tonne of blasted rock, directly affects original waste rock sizes (greater powder factors result in finer waste rock [52]). The powder factor for blasting in Canadian Malartic mine was between 0.28 and 0.34 kg/t [32], but more generally, it is between 0.24 and 0.66 kg/t in hard rock mine [51]. The mean particle size of blasted rock is sensitive to the powder factor and can decrease by 20% when the powder factor increases from 0.3 to 0.47 kg/t [52]. A higher powder factor is therefore recommended to reduce the amount of large particles in the waste rock and thus contribute to limit segregation. However, further research is required to investigate the relation between the safety range of the powder factors and the original waste rock sizes. Alternatively, crushing the largest waste rock particles before disposal [53] could also be beneficial, but more studies are required to find a balance with increased costs for such operations.

3.3. Effect of mine truck payloads

The effect of the mine truck payload on waste rock segregation was investigated by dumping 4 dumps of waste rock using payloads of 300 t and 600 t (cases A1 and B1 in Table 2) from the top of a 10 m high bench using end-dumping method. Simulations showed that increasing mine truck payload tended to slightly reduce waste rock segregation during disposal, especially close to the top of the slope. In the finer sections (x / L ≤ 0.58), the segregation degree for a 600 t payload was generally greater than that for a 300 t payload, showing a maximum difference of 0.28. For example, the segregation degree at the top of the slope was −1.04 ± 0.33 for a 300 t payload and −0.76 ± 0.35 for a 600 t payload (Figure 8a). D_{50} / D_{50}' for a 600 t payload was 30% greater than that for a 300 t payload at the top of the slope.

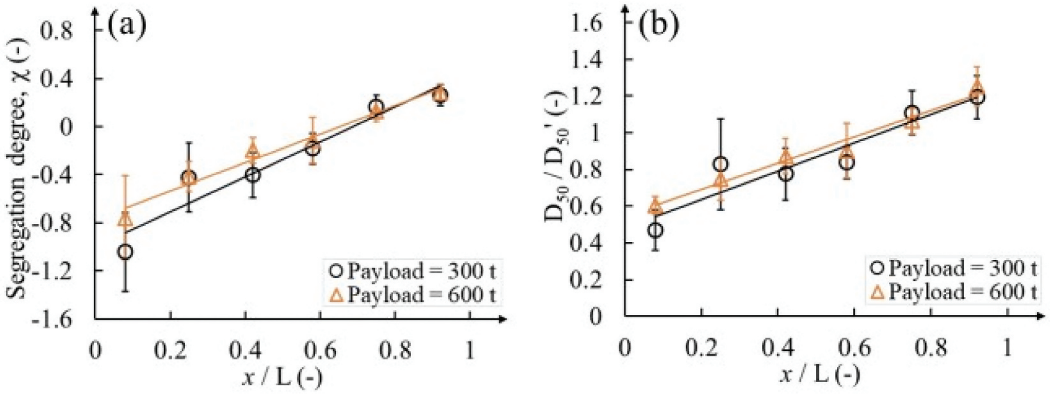

Figure 8. Simulated (a) segregation degree and (b) D_{50} / D_{50}' as a function of the relative location *x* / L with payloads of 300 t (black circles) and 600 t (orange triangles) using end-dumping method. Error bars represent standard deviation. Solid lines represent the fitted trendlines.

The effect of the payload was less marked at the bottom than that at the top of the slope. For example, in coarser sections (x / L ≥ 0.75), the difference of segregation degree for 300 t and 600 t payloads was smaller than 0.04. Similarly, D_{50} / D_{50}' for a 600 t payload was almost the same as that for a 300 t payload (with difference smaller than 4%) at the bottom of the slope (Figure 8b). Despite these differences, trends were very similar, and payload therefore seemed to have a very limited effect on segregation, at least under the tested conditions. The results seem to indicate that a greater payload resulting in a larger quantity of smaller particles (e.g. D <0.2 m) moving together and contribute to restrain the movement of coarser particles, thus decreasing segregation in a similar manner to agglomeration effect for fine particles [25,46].

3.4. Segregation with push-dumping method

The effect of push-dumping and end-dumping methods on segregation was compared by dumping a total of 1200 t waste rock (i.e. 4 dumps) on a 10 m high bench using both methods. The relative location, where segregation degree $\chi = 0$, was around x / L $= 0.68$ for both end-dumping and push-dumping methods. The push-dumping method tends to generate more segregation than end-dumping method in this study (Figure 9). For example, the

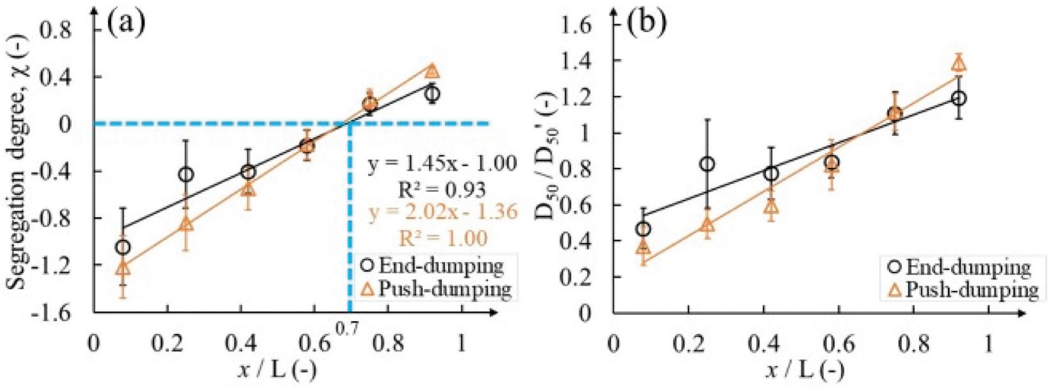

Figure 9. Simulated (a) segregation degree and (b) D_{50} / D_{50}' as functions of the relative location *x* / L when using end-dumping method (black circles) and push-dumping method (orange triangles). The push velocity was 0.2 m/s in these simulations. Error bars represent standard deviation. Solid lines represent the fitted trendlines.

segregation degree at the top of the slope (x / L = 0.08) was −1.04 ± 0.33 for end-dumping method and −1.21 ± 0.27 (−16%) for push-dumping method (Figure 9a). The segregation degree at the bottom of the slope (x / L = 0.92) was 0.26 ± 0.09 for end-dumping method and 0.46 ± 0.03 (+77%) for push-dumping method (Figure 9a). Similar trends were also observed from the distribution of D_{50} / D_{50}' along the slope. For example, D_{50} / D_{50}' for push-dumping method was 21% smaller (0.37 ± 0.11) at the top of the slope, and 16% greater (1.39 ± 0.05) at the bottom than that for end-dumping method (Figure 9b). The main reason for the difference caused by construction method is that end-dumping method generated greater initial velocities, which, in turn, contributed to reduce waste rock segregation. However, this effect was also observed because the simulated bench heights were limited in this study, and because of that, energy accumulation had less effect on segregation than initial energy.

Waste rock showed higher degree of heterogeneity along the slope with end-dumping method than that with push-dumping method. For example, the maximum standard deviation of D_{50} / D_{50}' was 0.25 for end-dumping method and 0.14 for push-dumping method. End-dumping method therefore seemed to bring higher variability to the velocities of particles because of the significant collision on the slope after dumping the mine trucks, which resulted in greater collisions and energy loss. In push-dumping method, particles were less disturbed by collision and moved more homogeneously along the slope.

The effect of push velocity on segregation was investigated by dumping 300 t waste rock on the 10 m high bench using push velocities comprised between 0.1 m/s and 0.6 m/s. Results showed that the segregation degree and relative particle diameters at the top of the slope tended

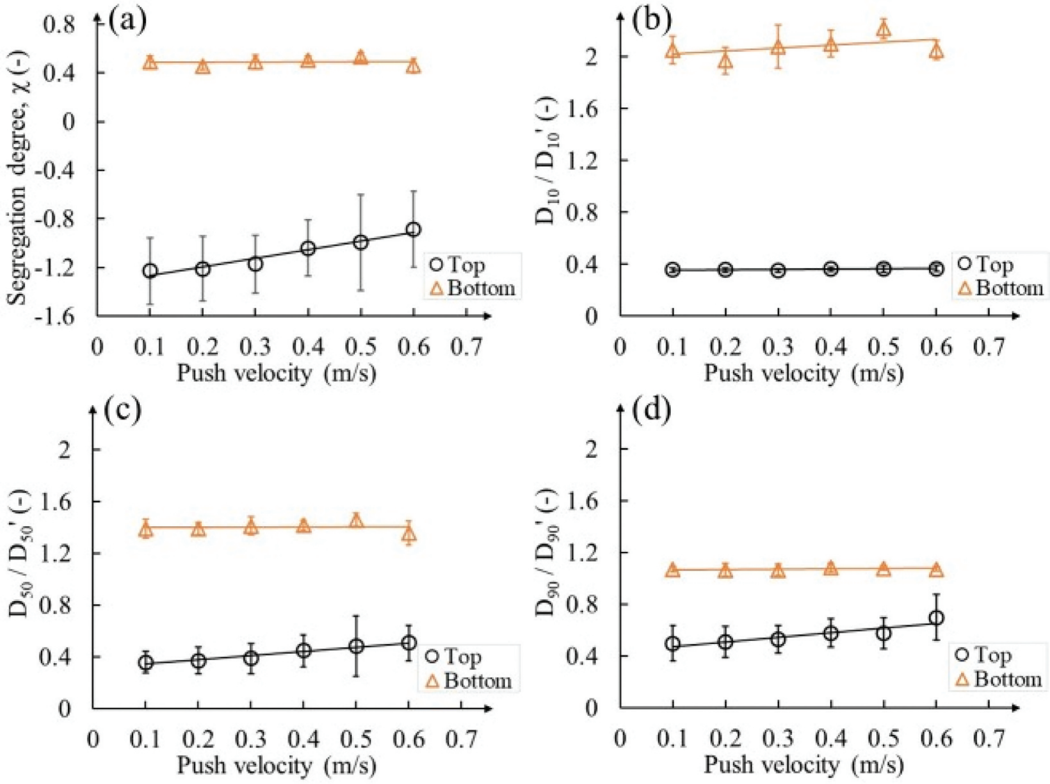

Figure 10. Simulated (a) segregation degree, (b) D_{10} / D_{10}', (c) D_{50} / D_{50}', and (d) D_{90} / D_{90}' as functions of the push velocity at the top (black circles, x / L = 0.08) and bottom (orange triangles, x / L = 0.92) of the slope. Error bars represent the standard deviation. Solid lines represent the fitted trendlines.

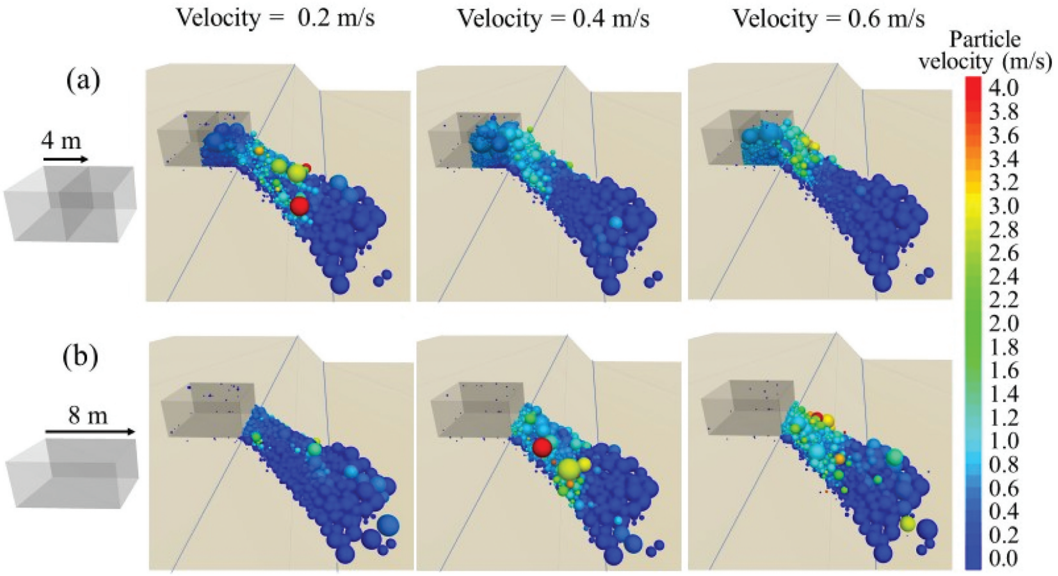

Figure 11. Waste rock velocities at push distances of (a) 4 m and (b) 8 m for push velocities ranging between 0.2 m/s and 0.6 m/s. The fourth dump moving on a 10 m bench was tracked. The color gradients represent particle velocities (from 0 m/s in blue to 4 m/s in red).

to linearly increase with the push velocity (Figure 10). In other words, segregation decreased with push velocity, i.e. waste rock at the top of the slope was coarser as the push velocity increased, but still remained finer than the original waste rock. For example, the segregation degree at the top of the slope was −1.23 for a push velocity of 0.1 m/s and −0.89 (+28%) for a push velocity of 0.6 m/s (Figure 10a). D_{50} / D_{50}' at the top of the slope was 0.36 for a push velocity of 0.1 m/s and 0.51 (+43%) for a push velocity of 0.6 m/s (Figure 10c). Similar segregation in the heap formed by filling multi-sized particles though a hopper also indicates that increasing the feeding rate (i.e. increasing the initial velocity) would decrease particle segregation [30,54].

However, push velocity had a limited effect on waste rock distribution at the bottom of the slope. Segregation degree and relative particle diameters at the bottom of the slope were almost the same for all the push velocities. The segregation degree at the bottom of the slope was comprised between 0.46 and 0.53 and D_{50} / D_{50}' between 1.36 and 1.46 for the investigated push velocities (Figure 10 a and c). The main reason was that the effect of push velocities on coarse particles movement to the bottom of the slope was limited compared with their accumulated velocities induced by gravity. For example, the initial falling velocities of particles were almost the same (around 1 m/s) for different push velocities (Figure 11). The velocities of these coarse particles significantly developed to 3 to 4 m/s under gravity when they flowed to the middle of the slope.

Waste rock heterogeneity at the top of slope tended to increase with push velocity. For example, the standard deviation of the segregation degree at the top of the slope was 0.27 for a push velocity of 0.1 m/s and was 0.39 for a push velocity of 0.5 m/s (Figure 10a). The standard deviation of D_{50} / D_{50}' at the top of the slope was 0.08 for a push velocity of 0.1 m/s and was 0.23 for a push velocity of 0.5 m/s (Figure 10c). However, push velocity had limited effect on waste rock heterogeneity at the bottom of the slope. For example, the standard deviations of both segregation degree and D_{50} / D_{50}' were smaller than 0.06 at the bottom of the slope for all investigated push velocities. The effect of push velocity was therefore significantly smaller than the particle energy accumulated during its movement.

In practice, although the velocity of dozers may vary depending on the operators, recommendations are based on the drawbar pull of the dozers [55]. A higher drawbar pull generally requires a lower push velocity of 0 to 0.6 m/s for a 6 m wide blade with a drawbar pull of 100–150 t [41]. Maximizing push velocities can therefore contribute to reduce waste rock segregation, following usual recommendations based on the drawbar pull of the dozers for security reasons.

4. Result analysis and discussion

4.1. Practical considerations for waste rock disposal in piles

An optimal deposition of waste rock aims to reduce segregation. Controlling segregation can reduce the risks for geotechnical and geochemical instabilities in waste rock piles [2,6]. Based on this study, the following approaches are therefore recommended:

- Bench height did not exhibit a clear effect on waste rock segregation at the top of the slope, with segregation degree ranging between – 1.04 and – 0.58 for bench heights of 10 to 25 m. Bench height had a limited effect on waste rock segregation at the bottom of the slope.
- Waste rock from the two investigated mine sites mainly affected the accumulation of large particles at the bottom of the slope. A smaller proportion of large particles in the original waste rock can increase segregation. In practice, reducing the quantity of the largest particles and homogenizing particle sizes could therefore contribute to limit segregation.
- Increasing mine truck payloads tended to slightly reduce waste rock segregation at the top of the slope but had little effect on waste rock distribution at the bottom of the slope.
- Increasing push velocity tended to increase waste rock particle size at the top of the slope and can therefore contribute to reduce segregation.
- Construction methods had a strong impact on waste rock segregation during disposal. Push method tended to create more segregation than end-dumping method under the investigated bench height.

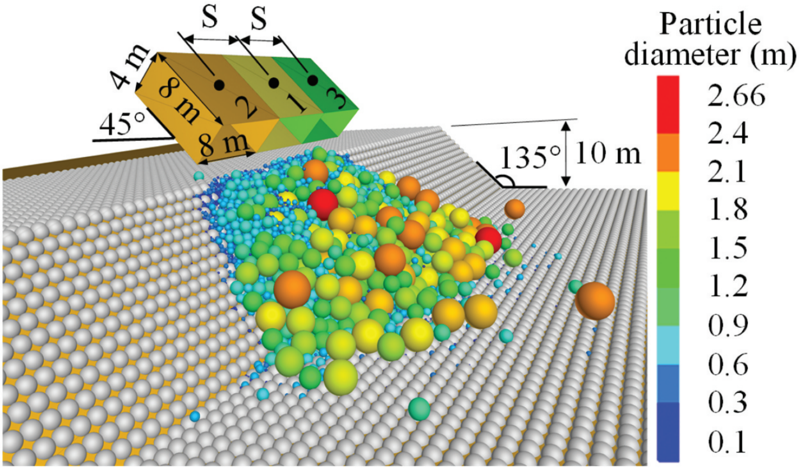

Figure 12. Model for lateral disposal on a 10 m high bench using end-dumping method. A total of 12 dumps were disposed sequentially and repeatedly from points 1 to 3 (4 dumps of 300 t waste rock per deposition point). S [L]: spacing between two sequential dumps (S = 4 m, 8 m and 12 m in this study). Dumped waste rock particles are colored depending on their diameters (from 0.1 m in blue to 2.66 m in red).

4.2. Effect of lateral disposal on waste rock segregation and heterogeneity

The effect of the studied influence factors on segregation was mainly investigated by dumping waste rock from one single point at the top of the slope. However, in practice, waste rock is commonly disposed of laterally, either sequentially or in parallel, i.e. almost concomitantly [4,56,57]. Lateral disposal could result in high variations of waste rock sizes along the lateral direction [57–59]. In this study, the effect of lateral disposal on waste rock segregation was investigated by dumping around 300 t of waste rock sequentially from three points on a 10 m high bench using end-dumping method (Figure 12). Waste rock was first dumped at point 1,

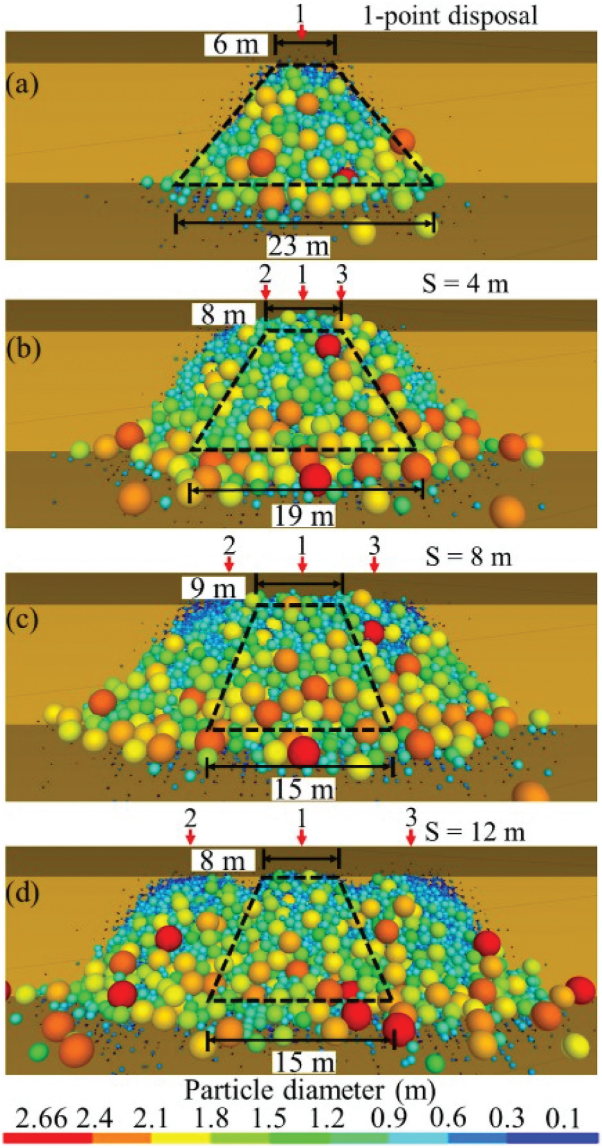

Figure 13. Waste rock distribution for (a) 1-point disposal and lateral disposal with dump spacing of (b) 4 m, (c) 8 m and (d) 12 m on a 10 m high bench using end-dumping method. (a): A total of 4 dumps were simulated from point 1. (b – d): A total of 12 dumps were simulated sequentially and repeatedly from points 1, 2 and 3 (4 dumps per point). Black dash lines cover the areas for waste rock that was dumped from point 1. S [L]: dump spacing between two sequential dumps. Dumped waste rock particles are colored depending on their diameters (from 0.1 m in blue to 2.66 m in red).

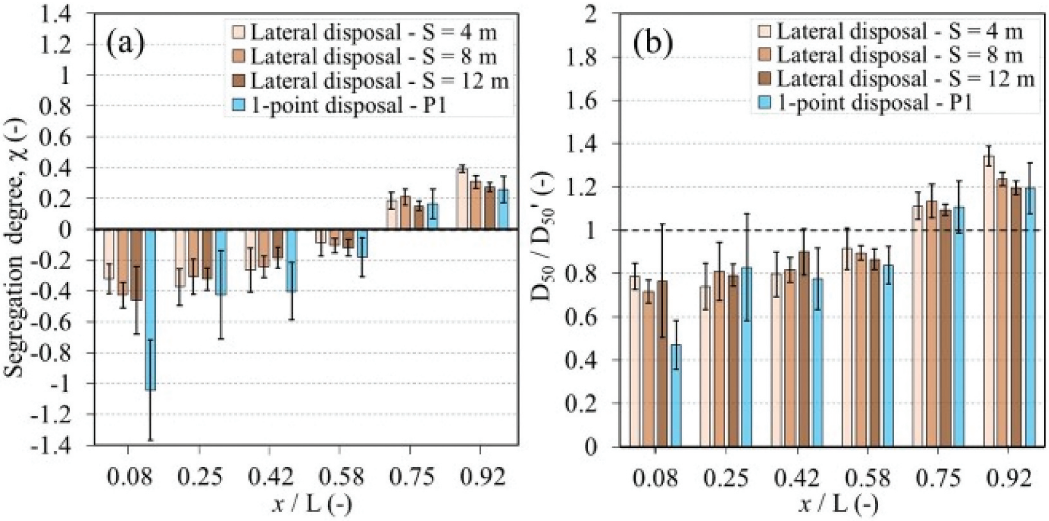

Figure 14. Simulated (a) segregation degree and (b) D_{50} / D_{50}' as a function of the relative location *x* / L both for lateral disposal and 1-point disposal using end-dumping method on a 10 m high bench. S [L]: spacing between two sequential dumps. Error bars represent the standard deviation (simulations were repeated five times).

and the second dump started at point 2 when waste rock in the previous dump stopped moving. A third dump was then simulated from point 3. A new disposal cycle started again with new dumps simulated at point 1, then point 2, and finally point 3. The dumping process continued until a total of 12 dumps were simulated, i.e. 4 dumps from each point. The total mass of waste rock dumped for lateral disposal was 3600 t in each case. The effect of the dump spacing between two sequential dumps was also investigated (4 m, 8 m and 12 m distance). Waste rock slopes were equally divided into 6 sections in the vertical direction (similarly to previous cases, see Figure 5). Segregation degree and D_{50} / D_{50}' in each section were obtained for each case and the results were compared with the base case A1 (1-point disposal in Figure 13).

Significant segregation was observed for all the cases with lateral sequential disposal. The segregation degree was generally smaller than −0.32 at the top (*x* / L = 0.08) of the slope and greater than 0.27 at the bottom (*x* / L = 0.92), and D_{50} / D_{50}' was smaller than 0.78 at the top of the slope and greater than 1.2 at the bottom (Figure 14b).

Simulations showed that lateral disposal tended to limit waste rock segregation compared to deposition from a single point. For example, the segregation degree at the top of the slope was −0.32 ± 0.19 for lateral disposal, i.e. 70% greater than that for 1-point disposal. Lateral disposal therefore tended to constrain waste rock movement in the lateral direction, but this effect tended to decrease with increasing the spacing between lateral dumps. For example, at the bottom of the slope, waste rock dumped from point 1 covered a width of around 23 m for a single point dumping, 19 m for a lateral dumping with 4 m spacing and 15 m for lateral dumping with 8 m and 12 m spacings (Figure 13). Lateral disposal therefore resulted in greater accumulation of particles at the top of the slope, including some coarse particles (e.g. >1.5 m), therefore resulting in the decrease of segregation compared to a 1-point disposal. Increasing dump spacing had limited effect on waste rock segregation. For example, the difference in segregation degree (also D_{50} / D_{50}') was smaller than 0.14 for each section of the slope, independently of the dump spacing (Figure 14). Lateral disposal with a dump spacing small enough to make sure dumps interact with each other, can therefore contribute to decrease segregation and homogenise waste rock along the slope. Increasing spacing too much would, however, result in the same results as for a single point dumping when lateral dumps do not interact anymore.

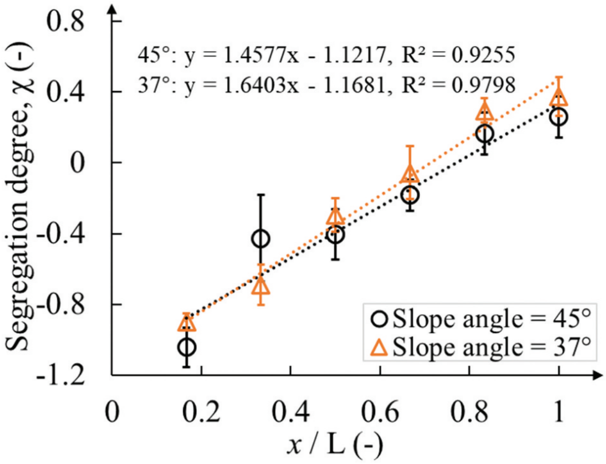

Figure 15. Simulated segregation degree as functions of the relative location *x* / L under slope angles of 37° (orange triangles) and 45° (black circles). Error bars represent the standard deviation.

Lateral heterogeneity under lateral disposal tended to be less pronounced than that with a single point disposal (1-pint disposal in Figure 13). For example, the maximum difference of segregation degree at the top of the slope was 0.55 for lateral disposal and 0.76 (38%) for single point disposal. The standard deviations of segregation degree and D_{50} / D_{50}' for single point disposal were also generally greater than those for lateral disposal (Figure 14). For example, the standard deviations of segregation degree at different sections were generally smaller than 0.1 for lateral disposal, but were always greater than 0.1 (and up to 0.33) for single point disposal (Figure 14a). There was, however, no clear relationship between heterogeneity and the relative location along the slope.

4.3. *Effect of existing initial slope angle*

Waste rock was dumped on an existing initial slope with an angle of 45° in this study. This slope angle was slightly greater than the natural slope angles, which usually range between 30° and 40° in practice [60,61]. The effect of the slope angle was then investigated by dumping waste rock on a 10 m high bench with a slope angle of 37°. Four dumps of waste rock were generated according to PSD QB0 (Figure 1) and dumped using end-dumping as the same dumping process for case A1. Waste rock dumped on a 37° slope showed clear segregation along the slope (Figure 15). The segregation degree increased from -0.9 ± 0.11 at the top of the slope to 0.37 ± 0.04 at the bottom.

Limited effect of initial slope angle on waste rock segregation could be observed in this study. For example, the difference of the segregation degree for two slope angles was smaller than 0.14 at the top and bottom of the slope (Figure 15). The small difference of existing initial slope angles didn't affect the results because the main purpose of this research was to investigate the effect of various influence factors on waste rock segregation under the same existing initial slope angle, resulting in limited effect on the trends observed in this study. However, more investigations are needed if further increasing the existing slope angles to much greater values because steeper slope angles tend to increase particle velocities, which in turn compensates for differences in particle masses and therefore reduces segregation [25,45,46].

4.4. *Effect of base layer*

The base layer was composed of large spheres with one metre in diameter because of the following two reasons: 1) the surface of the slope was usually covered with relatively large particles; 2) small

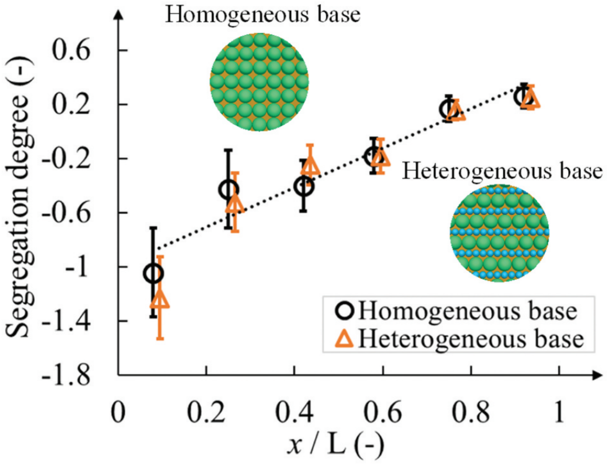

Figure 16. The segregation degree of waste rock along the slope with heterogeneous (in orange) and homogeneous (in black) base layers. Heterogeneous base layer contained particles with diameters of 0.5 m (in blue) and 1 m (in green). Homogeneous base layer contained particles with a diameter of 1 m.

amounts of large particles were needed to fully cover the slope so that the calculation pressure can be reduced. Such setting could be helpful to reduce the simulation time especially when large quantities of simulation cases were run for this study. In reality, the slope surface of waste rock pile contains coarse particles with different sizes. A base layer with particle diameters of 0.5 m and 1 m was therefore set to simulate the heterogeneous surface layer. The segregation degree with a heterogeneous base layer increased from -1.23 ± 0.3 at the top to 0.25 ± 0.09 at the bottom of the slope (Figure 16). The difference in the segregation degree for two base layers was smaller than 0.19 at the top sections ($x/L < 0.42$) and smaller than 0.01 at the bottom sections ($x/L > 0.58$) of the slope. These relatively limited differences indicated that the coarse base layer created limited effect on waste rock segregation properties during disposal.

4.5. Effect of young's modulus

DEMs simulations place substantial demands on the computational power, with some simulations mentioned earlier requiring more than 200 hours to reach convergence. One contributing factor to this prolonged duration is the inverse relationship between numerical time steps and the square root of the material's Young's modulus [62]. For representing the mechanical properties like UCS and shear strength through DEM simulations, it is customary to use a Young's modulus within the range of 10^8 to 10^{10} Pa [63,64]. However, the influence of Young's modulus on the simulated repose angle is relatively minor. The repose angle changes by only 1° even when the Young's modulus is transitioning from 10^{10} Pa to 10^5 Pa [34,65]. The flow patterns of gravel particles are not substantially changed when particle stiffness was reduced by a factor of 100 to 1000 from its measured value [66,67]. Hence, a reduction of stiffness by one order of magnitude could potentially expedite calculation time by 3 to 10 times without significantly perturbing the results [68,69], but this was not further investigated in this study.

5. Discussion

Waste rock disposal simulations in this study indicated that bench height and payload had limited effect on segregation and lateral disposal and increasing push velocity limited segregation. This study was conducted to investigate the trend of waste rock segregation caused by different construction methods and bench heights, but not to exactly reproduce the field waste rock flow behaviour. Despite these encouraging trends which may be useful to give operators practical recommendations to reduce segregation in the field, numerical simulations carried out in this study were based on a few assumptions that could somewhat affect these conclusions.

First, the minimum particle diameter simulated was 0.1 m, to increase the quantity of simulated waste rock without unrealistically increasing calculation time. For example, the number of particles was 9200 (with 1.8×10^5 contacts) for a 10 m bench and 1.5×10^5 (with 5.4×10^5 contacts) for a 25 m bench. The computational time reached 138 h for a 25 m bench, i.e. 55 times longer than for a 10 m bench. Actually, 100 kg waste rock with diameters between 0.5 cm and 1 cm would have generated 1.5×10^5 additional particles in PFC3D models. Simulating smaller particles with current computing ability for field scale simulations was thus practically impossible. Some techniques such as particle scale-up (e.g. Coarse-Graining technique [70]) have been developed to replace real particles by representative particles, substantially reducing the required number of particles and computational time [71]. However, the main limitation of these techniques is the determination of upscaling factors which determine the representativity of a simulated process [72]. Because of the particle diameter limitation, the ratio of bench height to the maximum particle diameter (e.g. 2.66 m in Quebrada Blanca mine) was only 3.8 for a 10 high bench, which was relatively small compared to typical values in the field (usually around 7).

Spherical particles were used in this study for field-scale simulations, incorporating a rolling resistance coefficient to account for shape-related effects. The advantage of using spheres is that spheres provide simple contact detection algorithm, resulting in a significant decrease of calculation time for large scale simulations [73]. However, although spheres, when calibrated with local damp, can reproduce the overall collision characteristics of waste rock with acceptable accuracy [74,75], the collisions in field waste rock are intricate, influenced by factors, such as particle size and shape effect [76,77]. Currently, the shapes of granular particles can be simulated using ellipsoid, spherocylinder, polyhedral and multisphere approach [78–81]. Particles with irregular shape can also be formed by clustering multiple spheres together, forming a clump or rigid blocks [82]. However, the number of contact points on the surface is directly related to the number of spheres inside the clump. The calculation time therefore significantly increases when using clumps rather than spheres (by up to 30 times [48], making simulations of large waste rock piles impractical. The coarse-graining method is a promising way to improve the calculation efficiency by scaling-up the size and parameters of representative particles [69]. The approach has, for example, been used for the simulation of large volume of iron ore pellets [83]. However, the applicability and representativity of the coarse-graining method for segregation monitoring still needs to be investigated and validated.

The recommendations regarding waste rock disposal (see above) were given with the objective of reducing segregation. The geotechnical stability of waste rock pile is, however, also affected by waste rock disposal but was not considered in this study. Segregation and heterogeneity usually create negative effect on the geotechnical properties, but sometimes also bring positive effect on pile's stability. For example, although segregation and heterogeneity can bring risks to water flow along irregular and diverted paths within waste rock piles [6,84], the presence of internal fine-grained layers (e.g. compacted layers during construction) sometimes also increase the factors of safety, resulting in positive effects on the geotechnical stability of waste rock piles [85]. More investigations on waste rock disposal are thus necessary to comprehensively control waste rock segregation by considering both hydrogeological and geotechnical stability.

6. Conclusion

PFC3D was used to simulate the flow behaviour of waste rock disposal and evaluate the effect of construction methods (i.e. push-dumping and end-dumping method) and bench heights (10–25 m) on waste rock segregation. Segregation degree (χ) and relative particle diameters (D_{10} / D_{10}', D_{50} / D_{50}', D_{95} / D_{95}') from the top to the bottom of the slope were compared to quantify waste rock segregation along the slope. Various influence factors, including mine truck payloads (300 t and 600 t), push velocities (0.1 to 0.6 m/s), lateral disposal, and waste rock PSD were investigated. The following conclusions were made based on the results of this study:

- In general, waste rock segregation was significant for all the different investigated factors. Segregation degree was always negative and smaller than −0.5 at the top of the slope and positive and greater than 0.3 at the bottom, indicating waste rock was finer at the top and coarser at the bottom of the slope than the original waste rock (before disposal). Diameter D_{50} at the bottom of the slope was always 2 to 4 times greater than that at the top of the slope for all the simulated cases in this study.
- Simulated bench heights (10 m to 25 m) and mine truck payloads (300 t to 600 t) had limited effect on waste rock segregation.
- Waste rock containing a smaller proportion of large particles were more prone to segregation. A greater power factor (yet respecting safety range) and crushing the largest particles is therefore suggested to homogenise waste rock and reduce segregation during disposal.
- Increasing the push velocity in push-dumping method (from 0.1 m/s to 0.6 m/s) tended to reduce segregation at the top of the slope but had limited effect on waste rock distribution at the bottom. Maximizing push velocities can therefore contribute to reduce waste rock segregation, following usual recommendations based on the drawbar pull of the dozers for security reasons.
- Push method tended to create more segregation than end-dumping method because end-dumping method generated greater initial velocities, which contributed to reduce waste rock segregation. However, this effect was also observed because of the limited bench height and because of that, energy accumulation had less effect on segregation than initial energy.
- Lateral disposal tended to limit waste rock segregation compared to deposition from a single point. Lateral disposal with a suitable dumping spacing (i.e. small enough to make sure the sequential dumps interact with each other) was beneficial to homogenise waste rock along the slope. Sequential dumps with a small dump spacing were recommended to reduce waste rock segregation in practice.

These recommendations should contribute to improve the deposition plan of waste rock on operating and future mine sites. However, this research focused on a few key operational influence factors and only for limited bench heights (mainly for numerical constraints), so further investigations taking into account the effect on the hydro-geotechnical and geochemical properties are recommended to improve segregation control and optimise waste rock disposal.

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