MOISTURE MOVEMENT IN BULK STOCKPILES

Abstract

Both drainage and evaporation are possible mechanisms for moisture loss in iron-ore and coal stockpiles. Some simple models are used to study both these mechanisms for various stages of stockpiling. The process of segregation of different particle sizes of the ore as it is stockpiled is also considered and this may have important implications for both drainage and evaporative moisture loss.

1. Introduction

During the mining and initial processing of mineral ore and coal it is common to use water to facilitate the processing and to ensure that the ore does not create undue levels of dust. When finally sent for delivery it is preferable that the product have as low a water content as possible commensurate with the need to keep the dust levels low. The removal of the added water takes place during the numerous handling processing involved in getting the ore by conveyor belt to a stockpile, where it is stored. For iron ore this storage period may last from a few days up to a week or two. Coal shipments are typically blends of coals from different mines and a coal stockpile may sit for a period of 6–8 weeks. The stockpile is then dug up ("turned over") and transported by open rail wagon to a port where it is either put directly on a ship or stored temporarily in another stockpile.

Bulk stockpiles measure up to 20 m high and can be several hundreds of metres long. They are created by depositing the ore from a conveyor belt by way of a boom from around 20 m above the ground onto the pile (see figure 1). The ground on which the stockpile rests is generally prepared by digging out and then infilling with crushed ore so that there is no substantial change in properties between the pile and the underlying ground.

CRA asked the MISG to help develop a model of moisture movement in stockpiles in order to quantify where the water was currently being removed from the ore and to identify possible methods that would increase the rate of loss. The mining companies have a number of problems with ore with high moisture content. For example, if iron-ore is too wet when it is tipped out of a railway wagon it does not flow out but falls all at once causing damage to the hopper into which is is being dumped.

While the general principles discussed in this Report are applicable to a range of materials, the modelling and results will only be given for iron-ore stockpiles. Typical dimensions and parameter values are given in Table 1.

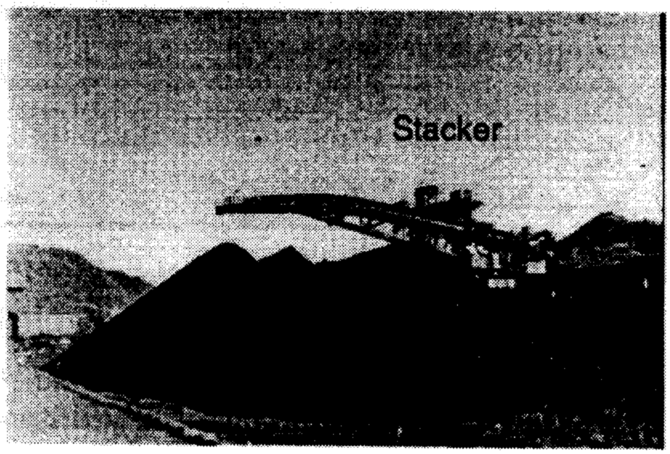

Figure 1: Stacking process for a coal stockpile.

Quantity	Symbol	Values
Height of stockpile	h_0	$15\,\mathrm{m}$
Width of base	2ℓ	$40\,\mathrm{m}$
Density of iron-ore	ρ_o	$4.6 \times 10^3\,\mathrm{kg\,m^{-3}}$
Density of water	ρ_w	$1.0 \times 10^3\,\mathrm{kg\,m^{-3}}$
Void space	ε	40%
Saturated hydraulic conductivity	K_s	$2.6 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$
Saturated moisture content (by mass)	w_s	12%
Saturated moisture content (by volume)	θ_s	39%
Fully drained moisture content (by mass)	w_m	4%
Fully drained moisture content (by volume)	θ_m	16%

Table 1: Table of typical data for an iron-ore stockpile.

In Section 2 a simple one-dimensional model of drainage in a porous medium is used to estimate drainage times for a given uniform initial moisture content. Evaporation is considered in Sections 3, 4 and 5. In Section 6 a computational model of particle segregation during the stockpiling process is used to study how different size ore-particles are distributed in a stockpile. These investigations allow us to make some recommendations for stockpiles to enhance moisture loss.

2. Stockpile drainage

The model of the drainage process assumes that the ore can be considered as a partially saturated porous media. This is quite reasonable as the water content is typically low enough to ensure that the air can get into the gaps between the ore particles. Such unsaturated flows do not sustain large pressure gradients as the air ensures that the water pressure is substantially atmospheric. The water can however move under the influence of gravity and pressure gradients induced by variations in the surface tension. Such surface tension variations are typically modelled as depending on the size of the inter particle gaps and the amount of water present in those gaps, (see Bear (1988) and Philip (1970) for a general background in this area).

Governing equations

The flow of water in an unsaturated porous medium is governed by the mass conservation equation

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot \mathbf{J} \tag{1}$$

where $\theta(\mathbf{x}, t)$ is the volume fraction of water to total volume of the medium (i.e. the moisture content) and $\mathbf{J}$ is the volume flux of water. The volume flux $\mathbf{J}$ may be expressed using Darcy's law as

$$\mathbf{J} = -K(\theta)\nabla(\Psi - z) \tag{2}$$

where $K(\theta)$ is the hydraulic conductivity, Ψ is the suction potential and z is the vertical distance from the origin, measured in the direction of drainage. The term $\Psi - z$ is the total pressure head, with Ψ being due to capillary forces within the pores resulting in a suction against gravity and the remainder is the gravitational potential.

Substituting equation (2) into the mass conservation equation (1) gives Richard's equation (Philip, 1988)

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(\theta)\nabla\Psi) - \frac{\partial K}{\partial z}. \tag{3}$$

To solve Richards' equation it is necessary to provide functional forms for the hydraulic conductivity K and the suction potential Ψ. This is usually done empirically.

CRA provided data for iron ore samples from a Paraburdoo mine in Western Australia which had been analysed by CSIRO Division of Soils. An accurate data fit for $K(\theta)$ was given by

$$K(\theta) = K_s \left(\frac{\theta - \theta_m}{\theta_s - \theta_m} \right)^3, \tag{4}$$

where K_s is the hydraulic conductivity for saturated flow, θ_s is the saturated moisture content and θ_m is the water content that cannot be removed by drainage. Typical values are given in Table 1. For the suction potential Philip (1988) suggests

$$\Psi = \frac{1}{\alpha} \log \left(\frac{K(\theta)}{K_s} \right) \tag{5}$$

where α is a positive constant determined empirically for the type of soil. The constant α is called the sorptive number. Philip (1988) states α is directly proportional to some characteristic pore radius R, given by

$$\alpha = \frac{R}{7.4 \times 10^{-6}},$$

with R measured in metres and α measured in units of m^{-1}. For an iron-ore stockpile, if a pore radius of 1 cm is assumed then an estimate for the value of α for iron-ore is $\alpha = 1.4 \times 10^3\,\mathrm{m}^{-1}$. This value is somewhat larger than obtained for typical soils (for fine-textured soils, $\alpha \simeq 0.2\,\mathrm{m}^{-1}$, Philip, 1988).

Approximate equations

Let us now introduce the scaled variables Θ, $\mathbf{X}$ and T defined by

$$\Theta = \frac{\theta - \theta_m}{\theta_s - \theta_m}, \qquad \mathbf{X} = \frac{\mathbf{x}}{h}, \qquad T = \frac{3K_s}{(\theta_s - \theta_m)h} t. \tag{6}$$

Substituting (4) and (5) into Richards equation (3), and transforming to the scaled variables using (6) we obtain

$$\frac{\partial \Theta}{\partial T} = \mu \boldsymbol{\nabla} \cdot \left(\Theta^2 \boldsymbol{\nabla} \Theta \right) - \Theta^2 \frac{\partial \Theta}{\partial Z}, \qquad \text{with} \quad \mu = (h\alpha)^{-1}.$$

The dimensionless parameter α represents the ratio of the capillary suction forces to gravity. For an iron-ore stockpile μ is very small; typically $\mu \simeq 4 \times 10^{-5}$. A zeroth order approximation can be made by neglecting the term arising from the suction potential. This leaves us with the equation

$$\frac{\partial \Theta}{\partial T} = -\Theta^2 \frac{\partial \Theta}{\partial Z}. \tag{7}$$

In fact this model is valid even in a stockpile whose height varies over the area of the stockpile, as the only force acting in this reduced problem is gravity which can only produce a flux in the vertical direction. Hence each vertical section of the stockpile does not notice the other parts.

For most of the drainage time the capillary fringe will be small compared to the size of the stockpile, and α^{-1} will also be small, indicating that the size of the capillary fringe will increase as drainage occurs. These observations are crucially dependent on the assumption that the properties of the stockpile are uniform. For existing stockpiles the capillary fringe may vary by many orders of magnitude, and there will be certain parts of the stockpile where μ is no longer small and water will be held in the pores by surface tension against the force of gravity.

Solution

Equation (7) only needs one boundary condition to be satisfied. In this case the appropriate condition is no flux in at the upper surface which translates to $\Theta = 0$ at $Z = 0$. The problem cannot in fact consider the case of evaporation as it is impossible to get water to flow toward the upper surface with this model as gravity only produces fluxes downwards. In a similar manner this model does not notice what condition is imposed at the base of the pile, although we do assume free drainage into the base so that a saturated layer is not produced.

If evaporation or the base condition needed to be included then analysis would be necessary in thin regions (boundary layers the size of the appropriate capillary fringe) near these boundaries. We shall not consider these as they represent only a small part of the total flux of water out of the pile if α is small.

The solution of the nonlinear partial differential equation (7) can be found using the method of characteristics or by assuming a similarity solution of the form $\Theta(Z,T) = f(Z/T)$. Either approach gives a solution

$$\Theta(Z,T) = \begin{cases} (Z/T)^{1/2} & \text{for} \quad Z < \Theta_0^2 T, \\ \Theta_0 & \text{for} \quad Z > \Theta_0^2 T, \end{cases}$$

where Θ_0 is the initial dimensionless moisture content. Characteristics curves are given by $Z = \Theta_0^2 T$ along which Θ is constant. Figure 2 illustrates this solution.

There are two regions that occur. The first is a region where the initial water just drains vertically and there is sufficient flux from above to replenish the region so the water fraction remains constant. Above this region is a zone stretching to the upper surface where the flux is insufficient and so the water fraction reduces.

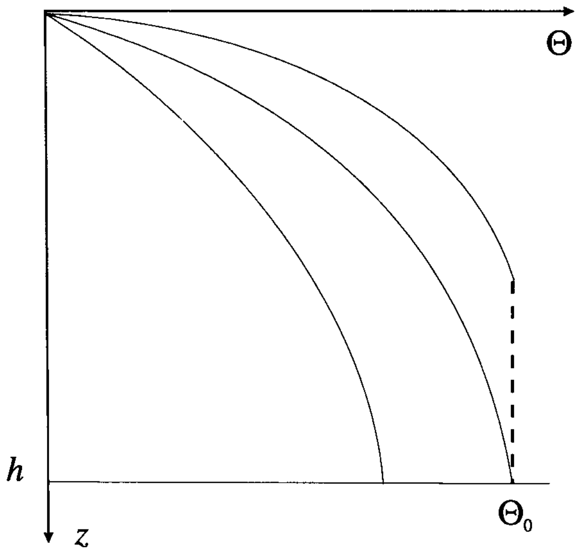

Figure 1: Typical moisture curves.

After a sufficient time the region of constant water fraction exits the base and the whole pile reduces in water content. Additional calculations can be made for particular shapes of stockpile simply by averaging the appropriate vertical columns to see how the average total water content reduces as time increases.

In terms of original variables the moisture content θ is given by

$$\theta(z,t) = \theta_m + (\theta_s - \theta_m)^{3/2}\left(\frac{z}{3K_s t}\right)^{1/2} \quad \text{for} \quad z < 3K_s\frac{(\theta_0 - \theta_m)^2}{(\theta_s - \theta_m)^3}t.$$

This gives a time-scale for a column of height h_0 to drain to where every point is below the initial water content θ_0. This time t_1 is given by

$$t_1 = \frac{h_0}{3K_s}\frac{(\theta_s - \theta_m)^3}{(\theta_0 - \theta_m)^2}.$$

Average moisture content

It is useful to examine the time dependence of an average moisture content over the stockpile. For the moisture content for times after the first drainage period t_1 we can define an average value for a column of height h as

$$\bar{\theta}(t) = \frac{1}{h}\int_0^h \theta(z,t)\,dz = \theta_m + \frac{2}{3}\frac{(\theta_s - \theta_m)^{3/2}}{\sqrt{3K_s}}\sqrt{\frac{h}{t}}.$$

An average over the entire stockpile, of height h_0 and width 2ℓ, is given by

$$\hat{\theta}(t) = \theta_m + \frac{4}{9}\frac{(\theta_s - \theta_m)^{3/2}}{\sqrt{3K_s}}\sqrt{\frac{h_0}{t}}.$$

Note that this value is independent of the width 2ℓ.

From this we can calculate a second drainage time-scale giving the time to drain from an initial water content θ_0 to the average value $\hat{\theta}$. This time t_2 is given by

$$t_2 = \frac{16h_0}{243K_s}\frac{(\theta_s - \theta_m)^3}{(\hat{\theta} - \theta_m)^2}.$$

The time, then, for the average moisture content to become $\hat{\theta}$ is given by $t_1 + t_2$. For $\hat{\theta} = 0.286$ (corresponding to 8% by weight) and using the values in Table 1 we calculate $t_1 = 1.6$ hours and $t_2 = 1$ hour. The value of the hydraulic conductivity K_s is not accurately known, since it is highly dependent on the composition fine particles in the ore. Since these times are inversely proportional to the hydraulic conductivity a decrease in the hydraulic conductivity by a factor of ten will result in an increase in the drainage time by a factor of ten.

3. Water loss during turning over

CRA have noticed a moisture content loss of about 1% by weight after a stockpile has been turned over. We examine whether this loss could be attributed to the escape of water vapour caught in the voids.

We assume that the void space is totally filled with saturated water vapour. Using the results that the partial pressure of saturated water vapour is about 0.03 atm (Perry, 1984) then the saturated water vapour concentration, c_{sat}, is given by $c_{\text{sat}} = (p_{\text{sat}}/RT)M_w$, where p_{sat} is the saturated vapour pressure, R is the gas constant, T is the temperature and M_w is the molecular weight of water. With $p_{\text{sat}} = 0.3\,\text{atm}$ and $T = 300\,K$, then $c_{\text{sat}} = 2.2 \times 10^{-2}\,\text{kg}\,\text{m}^{-3}$. With a void fraction of, say, 0.4 this means that $1\,\text{m}^3$ has about 9 gm of water vapour under these conditions. If all of this is released during turning over, the moisture loss is orders of magnitude smaller than 30 kg which is about the 1% by weight loss which is observed.

4. Moisture loss by evaporation

We consider moisture loss from individual particles through the stockpile. We also consider evaporation from a water-air interface.

Evaporation from particles

In this section we look at the rate of evaporation of water from the surface of a particle of a given size. As we show, the moisture loss by this mechanism is faster for small particles and can be significant.

Evaporation involves mass transfer and the theory of mass transfer across boundary layers is fairly well established (Bird *et al.,* 1960). It is based on the correlation

$$\mathrm{Sh} = 2 + A\mathrm{Re}\mathrm{Pr}^{1/3} = \frac{kL}{D},$$

where Sh is the Sherwood Number and Re and Pr are the Reynolds and Prandtl Numbers, respectively, and A is a constant which depends on the species evaporating, temperature, etc. The mass transfer coefficient k_m, is given by

$$k_m = \frac{D}{L}\mathrm{Sh},$$

where D is the diffusion coefficient and L is the boundary layer thickness. The flux per unit area from the particle surface J, is given by

$$J = k_m \Delta c,$$

where Δc is the concentration difference between the surface of the particle and the bulk.

The rate of evaporation for a particle is given by JA where A is a measure of the particle surface area, $\approx \pi d^2$, and d is the diameter, so that

$$JA = k_m \pi d^2 \Delta c = \mathrm{Sh}\,\frac{D}{d}\pi d^2 \Delta c = \mathrm{Sh}\,\pi D d \Delta c,$$

where we have assumed that a measure of the boundary layer thickness is the particle diameter. We can estimate the moisture evaporation rate as a function of the particle size. The number of ore particles per m^3 is $\dfrac{(1-\varepsilon)}{\pi d^3/6}$, where ε is the porosity of the material. The rate of water evaporation from these particles is

$$\mathrm{Sh}\,\pi D d \Delta c \frac{(1-\varepsilon)}{\pi d^3/6} = 6\mathrm{Sh}\,D\,\Delta c \frac{(1-\varepsilon)}{\pi d^2}.$$

We can now express moisture loss as a % weight loss for saturated material:

$$600\,\mathrm{Sh}\,D\,\Delta c\,\frac{(1-\varepsilon)}{d^2((1-\varepsilon)\rho_s + \varepsilon\rho_w)},$$

where ρ_s and ρ_w are the densities of the solid and water, respectively. Typical values of the Sherwood Number are in the range 2 to 10 and $D \approx 2.5 \times 10^{-5}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ (Holman, 1992) , and if we assume that the evaporation occurs into a dry atmosphere so that $\Delta c = 2.2 \times 10^{-2}\,\mathrm{kg\,m^{-3}}$, then we get the estimations in Table 2.

d	$\frac{d\%}{dt}$:Wt % s^{-1}
1mm	0.16 – 0.80
1cm	0.016 – 0.0080
10cm	$1.6 \times 10^{-5} - 8.0 \times 10^{-5}$

Table 2: Moisture loss by evaporation from particles.

5. Diffusion/convection driven evaporation

The rate of evaporation from a single particle is proportional to the excess water vapour concentration above equilibrium. The constant of proportionality β is estimated to be $1/t_{\text{eq}}$, where t_{eq} is a characteristic time, estimated in the previous section. We investigate two possible mechanisms for the loss of this water vapour through the top of the stockpile, diffusion and convection.

Diffusion as a mechanism for moisture loss

A characteristic time for diffusion is given by L_c^2/D, where L_c is a characteristic length and we take D as the diffusion coefficient of water vapour in air. If we take L_c as the stockpile height, $L_c \approx 20$m, and $D \approx 2 \times 10^{-5}\,\text{m}^2\,\text{s}^{-1}$, we have $L/D^2 \approx 10^9$ seconds and so clearly diffusion cannot be a mechanism to decrease the overall stockpile water content on a reasonable timescale.

Forced convection as a mechanism for moisture loss

We investigate the possibility of using forced convection as a mechanism for enhancing water vapour loss. Let $c(z,t)$ be the concentration of water vapour in the void space measured in $\text{kg}\,\text{m}^{-3}$. Including a source term for the rate of transfer of water vapour from the particle surfaces to the void space and ignoring diffusion gives the mass balance equation

$$\frac{\partial c}{\partial t} + v\frac{\partial c}{\partial z} = -\beta(c - c_{\text{sat}}) \qquad (8)$$

where v is the uniform forced convective velocity of air in the pores which we assume enters from the bottom of the stockpile at $z = 0$. Here c_{sat} is the saturated water vapour concentration and β is a measure of the rate of transfer of moisture from particles into the void space.

The equation (8) is amenable to solution by the method of characteristics. We assume that the forced convection brings in air with a moisture content c_a

in $\mathrm{kg\,m^{-3}}$. For $t > \tau = h_0/v$ the solution is

$$c = (c_{\text{sat}} - c_a)e^{(-\beta/v)z} + c_{\text{sat}}, \tag{9}$$

where τ is the time for "fresh" air of water vapour content c_a to travel through the stockpile. Let F be the vapour mass discharge per unit area of stockpile surface in $\mathrm{kg\,m^{-3}\,s^{-1}}$, then ignoring the moisture removed in the initial transient $t < \tau$, F is given by

$$F = \left[(c_{\text{sat}} - c_a)e^{(-\beta/v)h_0} + c_{\text{sat}}\right] v, \tag{10}$$

where we take the height of the stockpile to be h_0 m. If we want a 1% loss of moisture by weight in the stockpile, then we want $M_0 = 0.01\rho_s h_0\ \mathrm{kg\,m^{-2}}$ to be lost by convection, where ρ_s is the density of the stockpile. The time for this loss is given by

$$t_0 = \frac{0.01\rho_s h_0}{F}.$$

With $L = 20\,\mathrm{m}$, if we use a convective velocity of $1\,\mathrm{mm\,s^{-1}}$ and assuming that the time for equilibration between the moisture on the particles is small, that is, β is large, then

$$F \approx c_{\text{sat}} v.$$

With $c_{\text{sat}} = 2.2 \times 10^{-2}\,\mathrm{kg\,m^{-3}}$ and $\rho_s = 3 \times 10^3\,\mathrm{kg\,m^{-3}}$, then

$$t_0 \approx 10^6 \mathrm{s}.$$

This estimate is based on stockpile characteristics and the moisture loss takes about 11 days. In addition, there are obvious difficulties with providing forced convection in a stockpile. However, it may be feasible to use forced convection in the rail wagons used to transport the ore to the port. In fact, it raises the possibility of using air scoops on the wagons to provide the convective air flow.

Surface evaporation

Let us assume moisture evaporates from a liquid surface inside the stockpile. Just above the surface the pores are saturated with water vapour. Outside the stockpile the air is dry so water vapour diffuses from inside the stockpile to the outside air. The region $z > s(t)$ is liquid and vapour occupies $0 < z < s(t)$ where the liquid-vapour interface is a moving boundary.

Let $c(z,t)$ denote the concentration of water (per unit volume of void space). Assume c satisfies a diffusion equation

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial z^2}, \qquad 0 < z < s(t)$$

with boundary conditions

$$c(0,t) = c_a, \qquad c(s(t),t) = c_{\text{sat}},$$

where c_a is the concentration of water vapour in the air surrounding the stockpile and c_{sat} is the saturated water vapour concentration. A mass balance on the moving boundary $z = s(t)$ gives

$$(c_L - c_{\text{sat}})\frac{ds}{dt} = D\frac{\partial c}{\partial z}\bigg|_{z=s(t)},$$

where c_L is the concentration of water in liquid form in the void space. This mass balance states that the water excess to that converted from liquid to vapour diffuses back through the stockpile towards the surrounding air.

The solution for $c(z,t)$ is obtained by assuming a Boltzmann transformation $c(z,t) = f(z/\sqrt{t})$ and a form of the moving boundary $s(t) = \gamma\sqrt{4Dt}$, where γ is a constant. We obtain

$$c(z,t) = c_a + (c_{\text{sat}} - c_a)\frac{\text{erf}(z/\sqrt{4Dt})}{\text{erf}(\gamma)}$$

where γ satisfies

$$\sqrt{\pi}\gamma e^{\gamma^2}\text{erf}\gamma = \frac{c_{\text{sat}} - c_a}{c_L - c_{\text{sat}}}. \tag{11}$$

Typically $c_a \ll c_{\text{sat}} \ll c_L$ which means that $(c_{\text{sat}} - c_a)/(c_L - c_{\text{sat}}) \simeq c_{\text{sat}}/c_L$ is a small number. A useful approximation can be obtained by expanding the left-hand-side of equation (11) for small γ. Thus we produce an approximate formula for the time t to penetrate a distance s as

$$t = \frac{c_L s^2}{2c_{\text{sat}}D}.$$

Taking $c_{\text{sat}} = 2.2 \times 10^{-2}\,\text{kg}\,\text{m}^{-3}$, $c_a = 0$ for a dry atmosphere and $c_L = 1.0 \times 10^3\,\text{kg}\,\text{m}^{-3}$ then $(c_{\text{sat}} - c_a)/(c_L - c_{\text{sat}}) = 2.2 \times 10^{-5}$. The effective diffusivity in a porous medium is smaller than the diffusivity in air. To estimate this Cussler (1984), page 187, suggests an effective diffusivity coefficient for a periodic array of spheres as

$$D = \frac{\varepsilon}{1 + (1-\varepsilon)/2}D_{\text{air}}$$

where ε is the void space fraction and $D_{\text{air}} = 2.5 \times 10^{-5}\,\text{m}^2\,\text{s}^{-1}$ is the diffusivity in free air. This gives $D = 7.6 \times 10^{-6}\,\text{m}^2\,\text{s}^{-1}$. We calculate it takes $3.0 \times 10^3\,\text{s}$ (49 minutes) for a penetration depth of 1 mm and $3.0 \times 10^5\,\text{s}$ (81 hours) for a penetration depth of 1 cm.

This demonstrates that evaporation from a surface is not a feasible mechanism for drying out the whole stockpile. However, it does raise the possibility of noticeable moisture loss occurring during the process of building the stockpile.

Exposed surface area calculations

If evaporation is an important mechanism for moisture reduction then it is important to have estimates of area available for evaporation at various stages of the overall movement of the ore from the washery to the port. A stacker builds a "chevron" stockpile in layers by moving forwards and backwards and dropping the ore along the centreline of the stockpile. We wish to calculate the total area exposed during the stacking process. We denote the number of layers (passes) by n, the angle of repose of the ore by γ, the length of the stockpile by L and we denote the additional cross-sectional area added to the pile on one pass of the stacker by A_0, assumed to be the same at each pass. Then, elementary geometry shows that the total slant surface area exposed during n passes, $A_s(n)$, is given by

$$A_s(n) = 4\,L\sqrt{\frac{A_0}{\sin\gamma\cos\gamma}}\sum_{i=1}^{n} i^{\frac{1}{2}}.$$

We use the data supplied for a typical stockpile at Paraburdoo. Here the length, L, is about 357 m, with a height of 20.3 m and a base width of 52 m so that the angle of repose, γ, is about 38°. The delivery rate to the stockpile is about 2200 (dry) tonnes per hour which corresponds to a cross-sectional area increment, A_0, of about $3.3\,\mathrm{m}^2$. It requires 148 stacker passes to construct such a stockpile over 8.3 days. The exposed area while stacking using the above data is about $4.5 \times 10^6\,\mathrm{m}^2$. We now estimate the area exposed when this material is on the conveyer belt. Assume the belt is w m wide and that the cross-section of the ore on the belt forms a sector which is one-third of a circle. Then, if V is the volume of the stockpile, then the equivalent belt-length is

$$L = \frac{12V}{\pi w^2},$$

and the area exposed, A_c, (m^2) is

$$\frac{12V}{\pi w}.$$

Using $w = 1.5\,\mathrm{m}$ this gives $A_c = 3.7 \times 10^5\mathrm{m}^2$, so that the exposed area while stacking is almost 10 times the area exposed while on the conveyer belt.

The average time that a layer is exposed on the stockpile before being covered is about 40 minutes. If the conveyer belt has a length L_c, then the exposure time on the belt is

$$T_c = \frac{\pi L_c w^2}{12\dot{V}},$$

where $\dot{V}$ is the conveyer volume flow rate. Using the above values, a conveyer belt length of 500 m and an estimate of the dry density of 2.5 tonnes m^{-3}, this gives an exposure time of about 22 minutes.

We conclude that if surface evaporation is important, it is more likely to occur on the stockpile than during transport by conveyer belt. The exposed surface area associated with the rail wagon transport is small.

6. Segregation from stacking and stockpile microstructure

Size segregation is the process by which large particles migrate towards the top of a flowing or vibrating granular material and small particles migrate towards the bottom.

During the building of a stockpile, segregation can occur in two ways:

- While material is being transported by conveyor to the stacker, segregation produced by vibration leads to smaller material being at the bottom. After falling from the end of the stacker, the stream becomes nearly vertical, with the smaller particles on one side and the larger on the other. This would lead to a stockpile with more fines on one side and more coarse material on the other.
- As the particles flow down the sides of the stockpile the smaller particles have a larger chance of being trapped by the stationary material. This can contribute to layers of fines being formed.

Simulations of the formation of a stockpile were performed using the CSIRO Granular Flow package. Here a stream of particles was dropped onto a horizontal surface and a pile allowed to grow. In all cases a binary mixture of fines and coarse material was used with a 5:1 ratio of particle number. Figure 3 shows two snapshots of the central region of a stockpile built from a mixture of 15 cm and 5 cm particles. The fines are 36% of the cross sectional area and the stockpile is 10 m wide. Note that the final microstructure is far from uniform. The fine and coarse material each clump together.

Figure 4 shows a sequence from the building of a 15 m wide stockpile composed of 10 cm coarse and 4 cm fine particles. The fines represent 44% by volume of the stockpile. Note the clumped microstructure and the tendency to larger volume fractions of the coarse material both on the surface and at the edges.

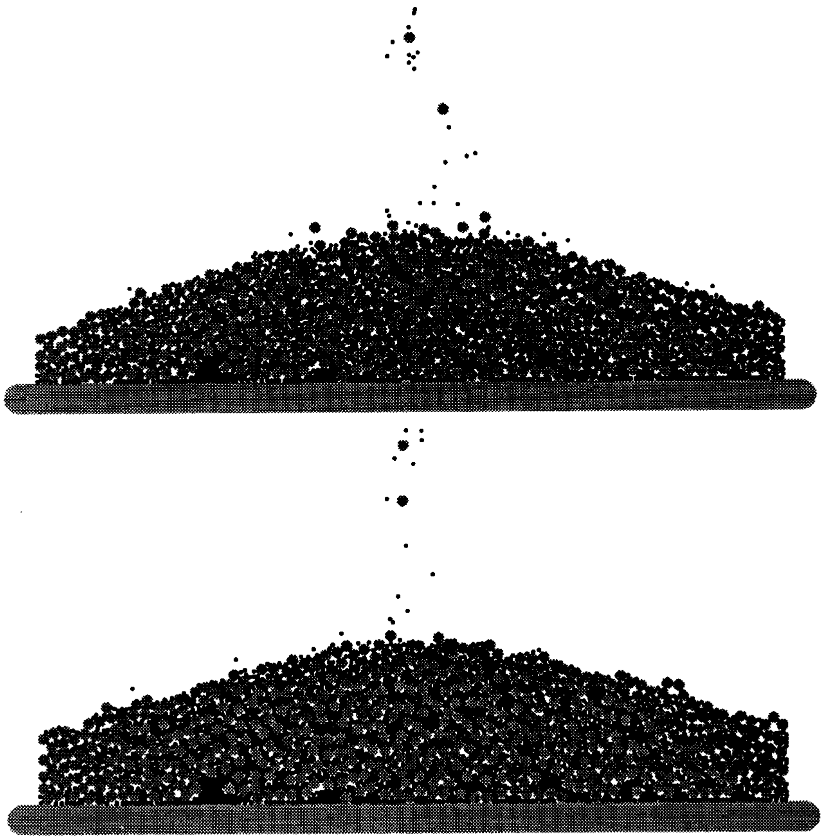

Figure 3: Middle of stockpile. Particles 15 cm and 5 cm diameter in 1:5 ratio.

The following observations can be made from the simulations:

- The microstructure of the stockpile is far from uniform. The fines tend to congregate together, as does the coarse material. These clumps of fines tend to be very elongated and show a tendency to be somewhat aligned with the sloping sides of the stockpile. This clumped microstructure can result from either geometric constraints of a stable packed microstructure or from segregation. The geometric requirements mean that a packed microstructure that is able to support its weight should have minimal voids. In these simulations there are 5 small particles for each large one. The optimal arrangement of these five small particles around the large one is not obvious. However, a tendency for the small particles to congregate in small groups would clearly minimise the voids. It is possible that a fair proportion of the clumping phenomenon results from these geometric constraints to form stable microstructures. Conversely, the clumps of fine particles typically exceed the 5–10 particle groups that would be expected.

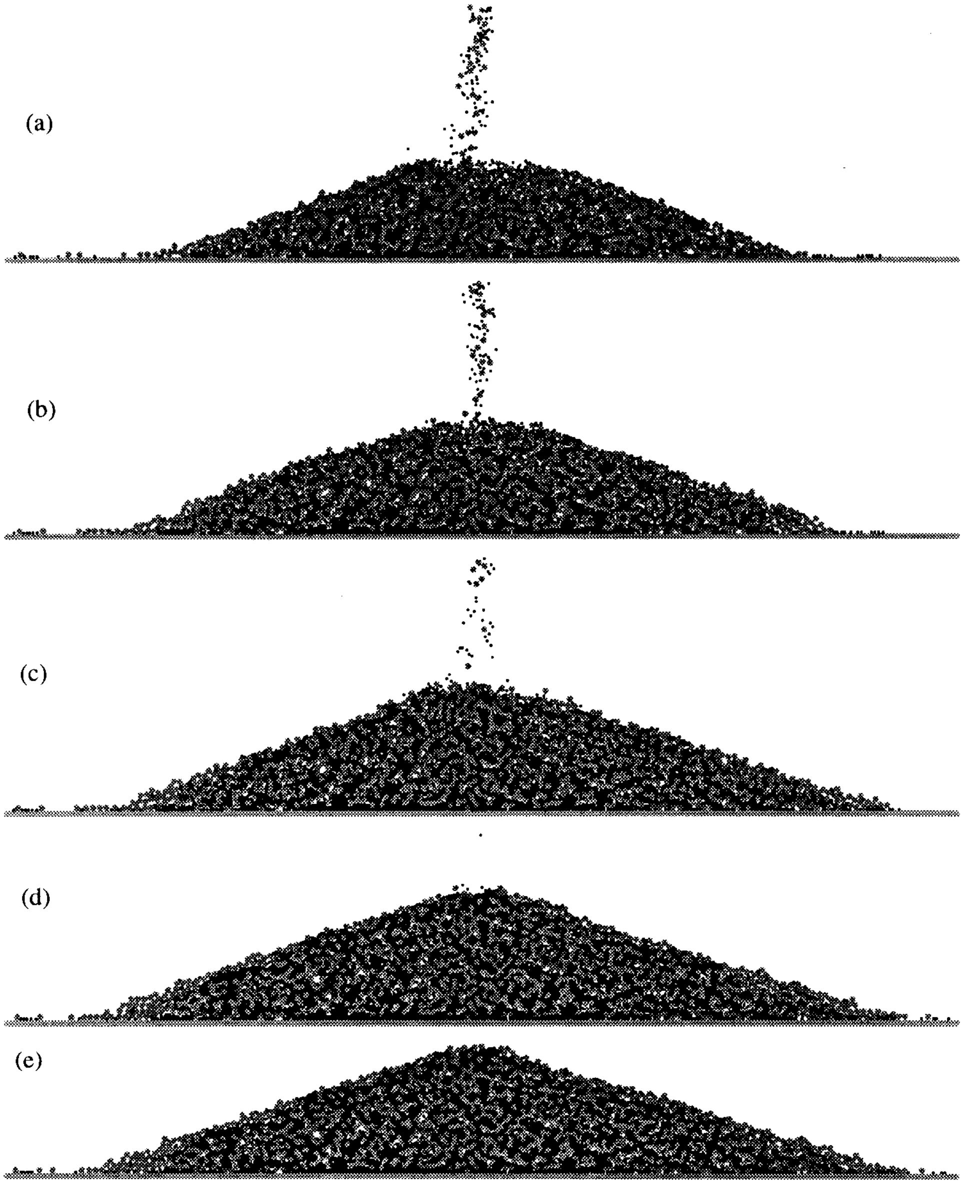

Figure 4: Full stockpile. Particles 10 cm and 4 cm diameter.

In addition, the coarse particles also show a tendency to being connected in lines or bands. This suggests that there are probably some mild segregation effects also occurring.

- The bottom of the stockpile is composed almost entirely of fines. This layer of fines will have a lower permeability than the rest of the stockpile and will inhibit draining.

- There is a clear tendency for coarse material to dominate the edges of the stockpile. Large particles have more momentum and can roll over obstacles that would trap fines. This effect seems to become greater as the size of the stockpile increases. For the small stockpile in figure 4(a) (the upper frame), the enhanced fraction of coarse material at the edges is slight. For larger stockpiles (see left edge of figure 4(e)), the coarse material clearly dominates near the edges. A possible explanation is that the avalanching effect, (where material builds up higher on the slope and then avalanches down to the bottom), is increasingly important as the stockpile grows larger. For a small stockpile the falling material has enough momentum to travel the entire length of the slope to the bottom of the stockpile. For a larger stockpile, this initial momentum is insufficient for particles to reach the bottom without stopping. The material is deposited on the side and builds up. Eventually the yield stress for the microstructure is exceeded and the material shears. This leads to a small avalanche. The volume of material flowing down the slope is likely to be much larger than the volume deposited by the stacker in the same time. The mini-avalanche is therefore much more active and provides more scope for segregation processes to occur.

- There is a clear tendency for coarse material to cover most of the surface of the stockpile. This seems to be independent of both stockpile size and the stage of construction of the stockpile. The fines are added to the stockpile at a constant rate and yet are always under-represented on the surface. This indicates that the fines tend to fall through the surface layer of coarse particles and accumulate below. This would partially explain the banded microstructure observed. A possible explanation is that the flowing particles disturb the particles below. This opens small gaps in the microstructure into which the small particles already in the stockpile can fall. Fines in the flow would also tend to fall into these gaps. This is a variety of vibrational segregation. The steady trickle of particles agitates the nearby layers of the stockpile and leads to local size segregation. The effect is short range and the microstructure rapidly saturates with fines leading to the clumps. The role of avalanching in this is unclear.

- The existence of reasonably strong cohesive inter-particle forces produced by large moisture contents (about 8%) would enhance the segregation. Large particles would be less affected by the sticky, cohesive forces, whereas the fines would tend to stick to the top of the stockpile where they impacted. This would enhance (perhaps strongly) the tendency to form a banded microstructure of alternating regions of coarse and fine particles.
- It is expected that as the particle size range increases and the stockpile width increases the segregation effects will become greater and more complex.

Note that the angle of the stockpiles formed is 19°. This is close to the theoretical maximum of 22° for circular particles. The angle of repose for wet stockpiles of 35° results from the departure of iron ore particles from circular.

7. Discussion

On the basis of the results in this Report we would recommend that in order to increase moisture loss through drainage, stockpiles be built as low as possible. This would decrease the average moisture content as rapidly as possible. In addition we have shown that evaporation may well be an important moisture-loss mechanism. Dropping the ore, providing it does not cause any degradation in the particle size distribution, is one way to increase evaporative loss. Building the stockpile rapidly with thin layers of ore also provides another opportunity to increase the moisture loss. Forced convection also appears to be an avenue worth pursuing, especially if it can be carried out in the rail wagons on the way to the port. Finally, the work on segregation offers a novel approach to obtaining detailed information on stockpile structure.

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