OPTIMISED DRAGLINE PLANNING MODEL

Pacific Coal provided data for typical operating parameters used in dragline operation. The problem for the Study Group was to investigate whether an optimal model of dragline operation could be developed.

The Study Group modelled the sequence of operations for a typical surface mining strip. Overall, a simulation approach seems necessary to fully represent the dragline operation. Some aspects of the operations that are amenable to optimisation are described in this report.

1. Introduction

In Australia, approximately 12% of total foreign earnings come from exporting coal. The walking dragline is used extensively to remove overburden in the surface mining of coal in Australia. A total of around 60 dragline machines are used to strip overburden from above about 35% of the coal mined in Australia.

It is estimated that an improvement of 1% in the efficiency of dragline operation would contribute an extra $35 million to Australia's export earnings.

There are a number of ways that draglines can be used to remove the overburden from above a coal seam. Figure 1 shows the method considered here.

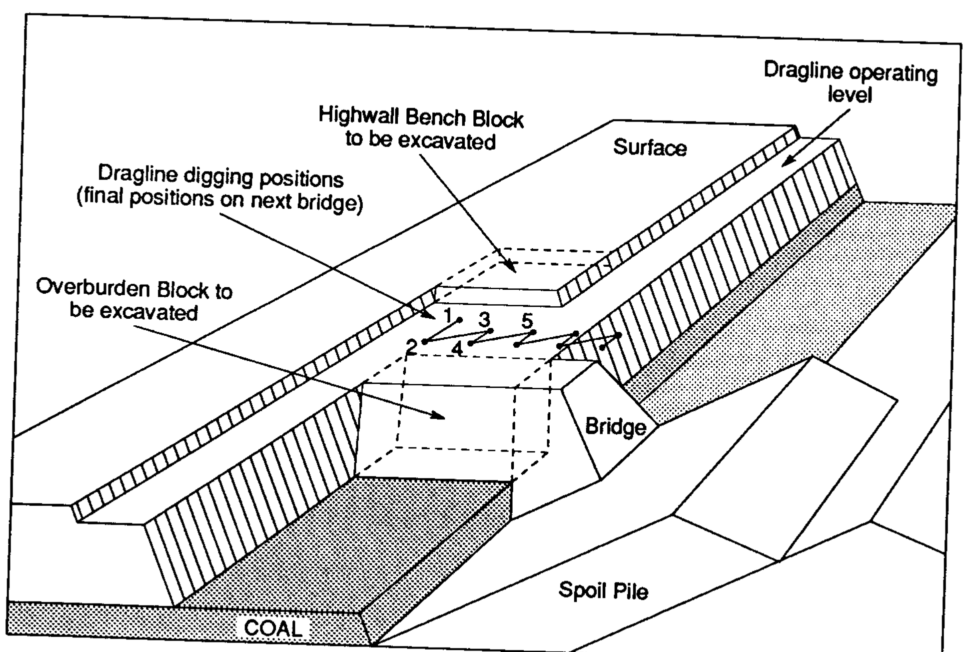


Figure 1: Overview of Dragline Operation

The dragline sits on an operating bench which is cut below the surface level.

A given dig cycle in the process of mining the coal involves the excavation of three blocks. The overburden and bridge blocks are removed to expose the next section of coal. Since the bridge is built using material from the previous cycle, its removal involves *rehandling* the overburden. The highwall bench block is removed to prepare the operating bench level for the dragline to use during the next cycle.

Some of the material removed during the excavation is used to build a new bridge and the rest is dumped onto the spoil pile.

At the end of the cycle the situation will be as in figure 1 but shifted back by the excavation length along the strip.

The general sequence of operations during the cycle for the excavation of the highwall, overburden and bridge blocks is as follows:

1. Starting at position 1, the dragline removes material from the highwall bench.

   The material from the highwall bench block is used to start building the new bridge.

   Once the new bench region is excavated the dragline begins to remove the overburden adjacent to the highwall. As this cut deepens the dragline steps forward to reach the lower material, ending at position 2.

   During the initial cut into the overburden the dragline moves in line with the highwall and digs a narrow trench down to the coal. This initial excavation gives a clean highwall face and is called the *keycut*.

   At some stage the new bridge will be finished. The material is then dumped to extend the spoil pile.

2. Once the keycut is complete the dragline moves to position 3 and begins to remove the next section of overburden, stepping forward towards position 4 as the depth of the dig increases. When the coal seam is reached and exposed the dragline moves to position 5 and repeats this process for the next section of overburden.

3. This process is repeated until all the material in the overburden and bridge blocks has been excavated and dumped onto the spoil pile.

   The dragline will move out onto the new bridge during the final excavation of the old bridge.

4. Once all the material has been excavated the dragline moves off the new bridge and takes up position ready for the next cycle. This final position is at a distance equal to the length of the excavation along the strip behind the starting position.

Statement of the problem

> Given the depth of the coal below the surface and the thickness of the coal seam, and the overburden geology, examine what methods are available to optimise overall performance or aspects of the performance.

2. Factors affecting the excavation time

In order to formulate the problem satisfactorily, we need to look in more detail at the particular operations involved in excavating the overburden.

As a first step we need to split the blocks that are to be excavated into sub-blocks of suitable size. The material excavated from each of these sub-blocks will be dumped onto a corresponding sub-block on either the new bridge or the spoil pile.

We will use the notation *O-D* to denote the Origin-Destination pairs of sub-blocks that will be excavated and filled during the cycle.

The basic operations in the excavation of a given sub-block are to *fill* the bucket, to *hoist* it vertically upwards and to *swing over* to a position above the associated destination sub-block. Once the contents of the bucket are dumped, the return operations are to *swing back* and *lower* the bucket onto the origin sub-block and repeat the process.

For the present study we assume that the bucket filling time and the quantity of material picked up by the bucket are independent of the sub-block location except for the fact that the dragline operates at 70% efficiency when digging material above the operating level.

For a given *O-D* pair, the time required to hoist, swing over, swing back and lower the bucket depends on:

a) The vertical distance through which the bucket must be moved to allow a clear swing from above the *O* sub-block to above the *D* sub-block. This distance will depend on the relative heights of the *O* and *D* sub-blocks and on the operating level if it is necessary to lift the bucket clear of unexcavated sections of the overburden and bridge blocks.

b) The angle through which the bucket is moved. This will depend on the relative horizontal co-ordinates of the *O-D* pair and the dragline position.

The final factor affecting excavation time is the time needed to move the dragline between the dig positions associated with successive *O-D* pairs.

3. General mathematical formulation of the problem

Parameters

We use the following parameter values.

$D_{down} = 45$ m	Maximum dragline digging depth
$D_{up} = 45.7$ m	Maximum dragline dump height
$D_{reach} = 82$ m	Effective dragline reach
$Y_{ob} = 40$ m	Overburden depth
$Y_{coal} = 10$ m	Depth of coal seam
$\alpha = 76°$	Highwall bench angle
$\beta = 38°$	Spoil repose angle
$\gamma = 60°$	Keycut and working face angles
$V_b = 46\ m^3$	Volume of material in the bucket
$v = 200\ m\,h^{-1}$	Walking speed of the dragline
$s_1 = 1.25$	Swell factor after blasting the overburden
$s_2 = 1.30$	Swell factor after dumping material to the spoil pile
$t_d = 15$ sec	Time to fill the dragline bucket

Table 1: Parameter values

Variables

We use the following variables to describe the system.

Let N be the total number of O sub-blocks.
There are N corresponding D sub-blocks.

An O sub-block is represented by j.
- $j = 1, \ldots, M$ are the O sub-blocks in the highwall bench blocks.
- $j = M + 1, \ldots, P$ are the O sub-blocks in the overburden block.
- $j = P + 1, \ldots, N$ are the O sub-blocks in the bridge.

V_j is the volume of the jth O sub-block.

d_j is the distance from dragline position j to position $(j + 1)$.

The digging efficiency is $e = 1$ when digging below the operating level and $e = 0.7$ when digging above the operating level.

For a vertical distance h metres, the hoist and lowering times are given by the dragline manufacturer as:

hoist time	$t_h = 0.3715h + 2.9923\ sec$	(1)
lowering time	$t_l = 0.2474h - 0.0264\ sec$	(2)

For a horizontal swing angle θ degrees, the swing forward and swing back times are given by

swing forward time	$t_f = 0.1188\theta + 7.4764\ sec$	(3)
swing back time	$t_b = 0.1177\theta + 6.4036\ sec$	(4)

The basic problem in optimising the excavation process is to find a one to one map between the O and D sub-blocks where the 3–d geometry of the mapping incorporates a dragline position for each O-D pair. For the moment let the map be defined in terms of h and θ. These values can be defined in terms of a suitably chosen co-ordinate system such as that in figure 5.

Time to excavate a sub-block

Once the bucket is filled, the 'hoist, swing over, swing back, lower' operation begins. During this cycle different motors are used to hoist and swing the bucket. The vertical and horizontal movements are independent so that for a given 'hoist, swing forward' operation the time to move from an initial position I to a final position F, separated by a height h and angle θ is given by

$$t_{IF} = max\{t_h, t_f\} = max\{(0.3715h + 2.9923), (0.1188\theta + 7.4764)\} \quad (5)$$

This time is said to be 'hoist dependent' or 'swing dependent' based on which of t_h and t_f is greater.

Similarly, the time to return from the final position to the original position is

$$t_{FI} = max\{t_l, t_b\} = max\{(0.2474h - 0.0264), (0.1177\theta + 6.4036)\} \quad (6)$$

For a given O-D pair, there may be a number of 'hoist, swing forward' and 'swing back, lower' steps. For example, in the excavation of the keycut (region 1 in figure 3) the bucket must clear the outer corner of the keycut pit before it can be moved to the dumping position.

If there are K such steps needed to move the bucket from the origin to the destination of a given O-D pair then the total time required for the 'hoist swing forward' and 'swing back, lower' cycle is

$$t_{OD} = \sum_{k=1}^{K}(t_{IF_k} + t_{FI_k}) \quad (7)$$

The time needed to excavate the jth O sub-block, and hence the jth O-D pair, is given by

$$T_j = \frac{s_1 V_j}{V_b}(t_d/e + t_{OD_j}) \tag{8}$$

where $e = \begin{cases} 0.7, & j = 1 \dots M \\ 1.0, & j = M+1 \dots N \end{cases}$, $s_1 = \begin{cases} 1.25, & j = 1 \dots P \\ 1.00, & j = P+1 \dots N \end{cases}$

and V_j/V_b is the number of cycles of the "fill, hoist, swing forward, swing back, lower" bucket movement sequence for volume V_j.

Total excavation time

The total excavation time T is

$$T = \sum_{j=1}^{N} T_j + \sum_{j=1}^{N} \frac{d_j}{v} \tag{9}$$

Note that at this stage we still have to set up a method for calculating h_j, θ and d_j. We can do this by choosing a suitable set of axes and then linking the centres of the O and D sub-blocks via an arbitrary (dragline) position on the operating bench.

During this process we need to consider a way of stating the combinatorial problem arising from the mapping between the O and D sub-blocks that will allow us to minimise the value of T.

Constraints

There are constraints associated with the sequencing of the O-D pairs, with the dragline dimensions and with the volumes of overburden excavated.

When setting up the sequence of O-D mapped pairs we need to consider the following points:

- The horizontal distance between O sub-blocks and possible D sub-blocks cannot exceed twice the dragline reach.
- When excavating the overburden and bridge we cannot excavate an O sub-block until the one above it has been removed.
- When building the spoil pile we cannot fill a D sub-block until the one below it has been completed.

These points relate obviously to the general digging sequence in which, if the dragline starts in position 1 as in figure 1 and moves out onto the bridge, the spoil dump locations move further out from the (old) highwall.

The second set of constraints relates to the strip geometry and the dragline geometry. To write these constraints we need to refer to figure 2.

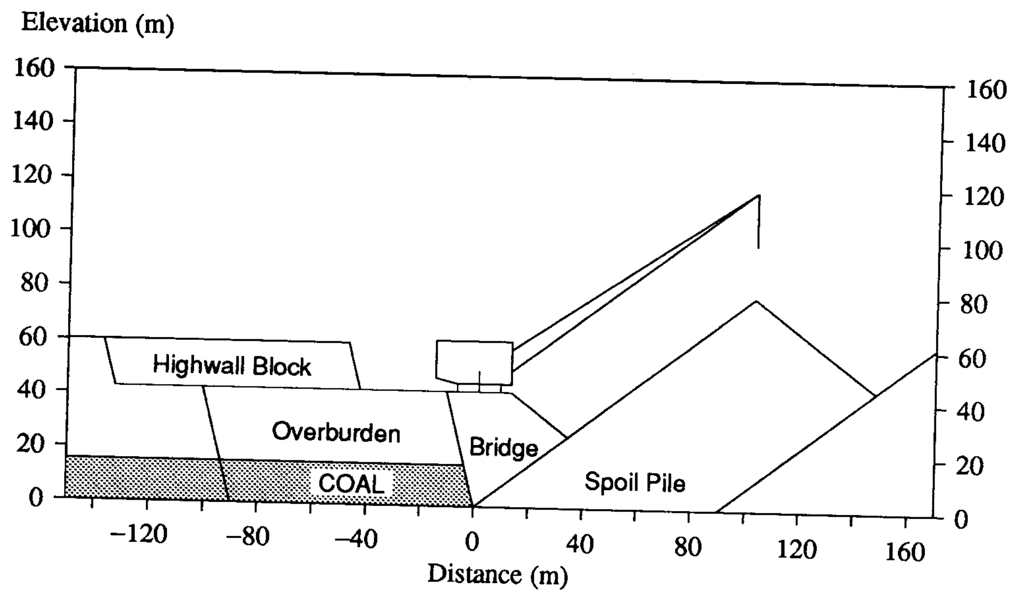


Figure 2: Dragline Range Diagram

We have a volume constraint which, assuming that the volume of material used to build the new bridge is equal to the volume removed in excavating the old bridge, we can write as

$$s_2(V_H + V_O) = V_S \tag{10}$$

where V_H is the volume of the highwall bench, V_O is the volume of the overburden, V_S is the volume of the spoil pile and s_2 is the swell factor relating the prime volumes to the volume in the spoil pile.

The remaining constraints relate to the dragline dimensions:

- The horizontal distance from 5 metres before the edge of the bridge to the spoil pile peak cannot exceed the dragline reach. The 5 metres is a safety factor, the dragline cannot be moved any closer to the edge of the bridge than this distance.
- The vertical distance from the operating level to the spoil pile peak cannot exceed the dragline maximum dump height.

- The vertical distance from the operating level to the top of the highwall bench block cannot exceed typically 30 metres.
- The vertical distance from the operating level to the bottom of the coal seam cannot exceed the dragline maximum digging depth. Here we are assuming that the coal seam is horizontal.

The formulation of these constraints is straightforward once we have chosen a co-ordinate system to suitably describe the dragline and sub-block locations. They are given as equations 14 and 15.

4. Excavating sub-blocks

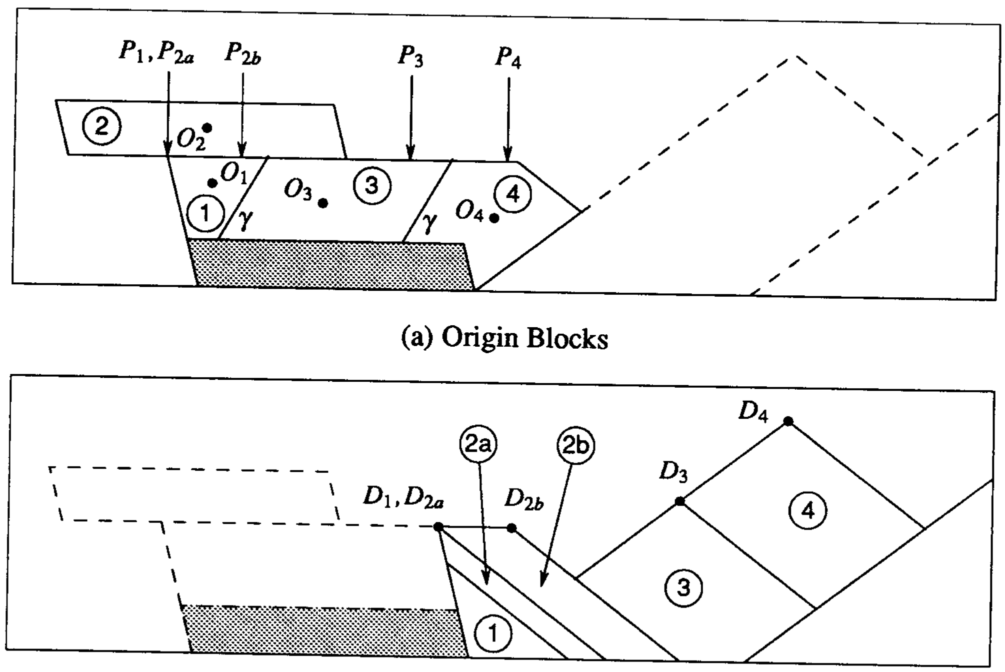
Figure 3 shows the division of the overburden material into typical sub-blocks. The O sub-blocks are shown in figure 3 (a) and the D sub-blocks in figure 3 (b). A view from above is given in figure 4.

The blocks are excavated in order from 1 to 4. The origin of the jth sub-block is given by O_j which is taken as the centre of mass of the origin sub-block. The corresponding destination is given by D_j. The locations of the D_j are the points at which the material is released so that the spoil pile sub-blocks will build naturally at the repose angle β. The location of the dragline for the jth O-D pair is given by P_j.

Note that, for demonstration purposes, we have assumed that the bridge is built from the keycut (region 1) and from the material above the operating level (region 2). We also assume that region 2 is excavated from two dragline positions. The first position is the same as that for the keycut, in this position we have only to move spoil material to the edge of the highwall. The rest of region 2 must be excavated from a new position so that we can reach position D_{2b} at the edge of the bridge.

Referring to figure 4, we can see that there is no point in moving the dragline position P_j closer to the destination location D_j than the length given by the effective dragline reach, since this will only increase the swing angle for a given O-D pair.

This means that we can fix the position of P_j, in the direction perpendicular to the strip, from the location of the corresponding destination D_j. Further, we can calculate the location of a particular destination from the geometry shown in figures 3 and 4, together with the parameter values given in Table 1.



(a) Origin Blocks

(b) Destination Blocks

Figure 3: Origin and destination sub-blocks

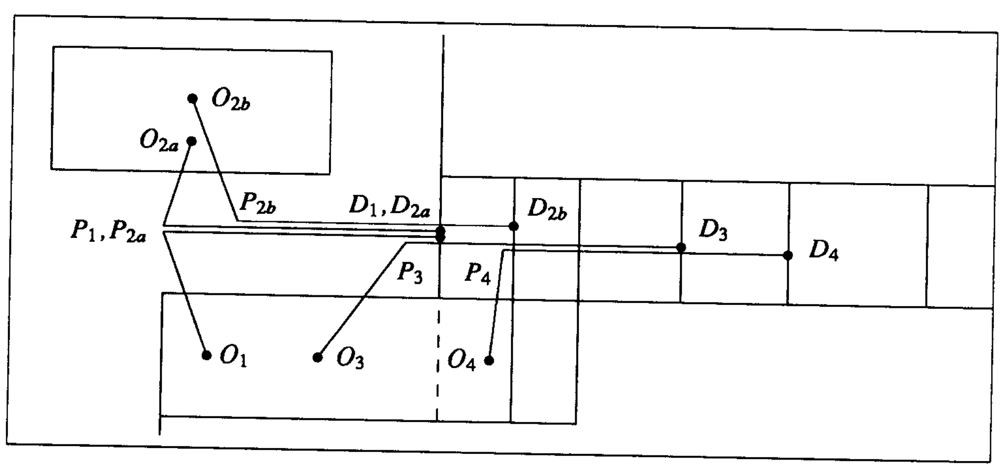


Figure 4: The layout of figure 3 shown from above

5. Simulating dragline operation

Given a set of parameters as in Table 1, the *O-D* geometry shown in figures 3 and 4, and equations 5 to 9, we can develop a simulation model of the dragline operation. We need to specify in addition, the width at the bottom of region 1 (the keycut) and the width of region 3.

Using this data we can calculate the origin positions, the size of the bridge and the locations of the sub-block destination positions. We can then calculate the excavation times needed for the different *O-D* pairs.

It is possible to specify the system completely except for the dragline position co-ordinates in the direction along the strip. Consequently, a useful simulation model can be developed in which a user could study a series of 'what if' scenarios in which the dragline positions can be specified with a single variable.

Such a simulation model can be made more accurate by dividing the overburden into smaller regions.

At present a prototype model, in which the regions 1–4 have each been divided into three horizontal layers, is under development. This prototype model is giving realistic output results at the current stage of verification.

6. Optimising overall productivity

In this section we develop formulae to find the optimum operating level y_b and pit width X_{pit} for the dragline. We use figure 5 as reference.

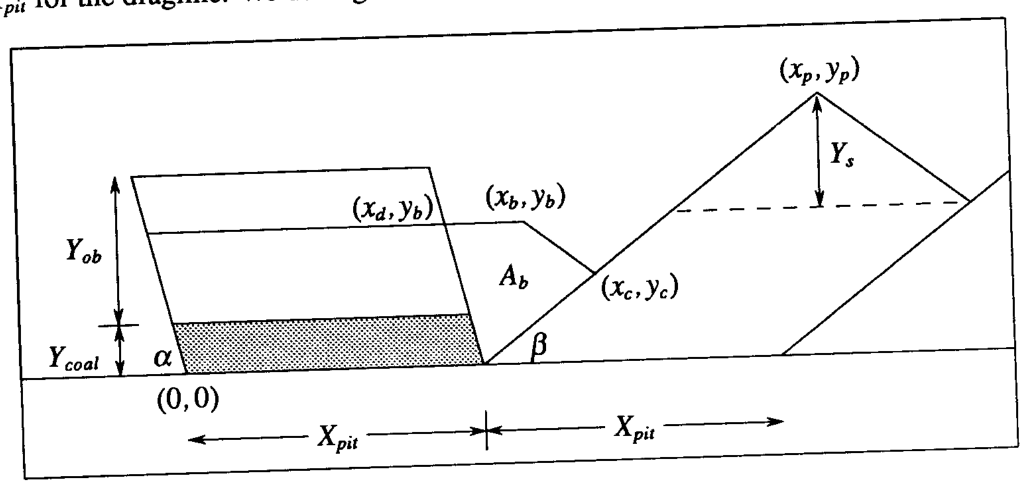


Figure 5: Dragline operation geometry

The co-ordinates (x_p, y_p) of the top of the spoil pile

From figure 5 we have $Y_s = 0.5 X_{pit} \tan\beta$ and substituting for Y_s in the volume balance equation: (expanded overburden volume) = (spoil pile volume) which can be written

$$s_2 X_{pit} Y_{ob} = X_{pit}(y_p - Y_s) + \frac{1}{2} X_{pit} Y_s$$

gives

$$y_p = s_2 Y_{ob} + \frac{1}{4} X_{pit} \tan\beta \qquad (11)$$

then from $x_p = X_{pit} + y_p / \tan\beta$ we have

$$x_p = 1.25 X_{pit} + \frac{s_2 Y_{ob}}{\tan\beta} \qquad (12)$$

The co-ordinates (x_b, y_b) of the top right corner of the bridge

The values of x_p and y_p depend on the dragline dimensions and the location (x_p, y_p) of the spoil pile peak. We have from $x_b = x_p - D_{reach}$ (where D_{reach} includes a safety factor representing the distance that the dragline must remain from the edge of the bridge)

$$x_b = 1.25 X_{pit} + \frac{s_2 Y_{ob}}{\tan\beta} - D_{reach} \qquad (13)$$

Note that if $x_b \le x_d = X_{pit} - \dfrac{y_b}{\tan\alpha}$ then we do not need a bridge.

The operating level y_b is one of the variables we wish to find, it is constrained by the dragline dimensions so that:

$$y_p - D_{up} \le y_b \le D_{down} \qquad (14)$$

$$Y_{coal} \le y_b \le Y_{coal} + Y_{ob} \qquad (15)$$

The co-ordinates (x_c, y_c) of the outer corner of the bridge

From $y_c = (x_c - X_{pit}) \tan\beta$ and $(x_c - x_b) \tan\beta = (y_b - y_c)$:

$$x_c = \frac{1}{2}\left(x_b + X_{pit} + \frac{y_b}{\tan\beta}\right) \qquad (16)$$

$$y_c = \frac{1}{2}\left(y_b + (x_b - X_{pit}) \tan\beta\right) \qquad (17)$$

The effect of operating level and bridge area on excavation time

For the particular model under consideration, the total excavation time will be influenced by:

a) the cross sectional area A_b of the bridge, if one is built,
b) the fact that digging efficiency is reduced to $e = 70\%$ when removing overburden from above the operating level y_b.

Assuming that for an efficient digging operation, excavation times will depend on the volumes (and here, on cross sectional areas) of material shifted, we can write an equation for the excavation time T. The equation for T will contain a term related to excavating the bridge and a term related to operating below the surface level.

For purposes of comparison we are interested in a normalised measure of excavation time. We will use T/X_{pit}, the excavation time per unit (pit) width. This is proportional to the excavation time to uncover a fixed amount of coal and hence maximum productivity is obtained by minimising T/X_{pit}.

From

$$T \propto A_b + X_{pit}\{(y_b - Y_{coal}) + \frac{1}{e}(Y_{coal} + Y_{ob} - y_b)\}$$

we have

$$\frac{T}{X_{pit}} \propto \frac{A_b}{X_{pit}} + (y_b - Y_{coal}) + \frac{1}{e}(Y_{coal} + Y_{ob} - y_b) \tag{18}$$

where the bridge area A_b is given by

$$A_b = y_b(x_c - x_d) - \frac{y_b^2}{2\tan\alpha} - \frac{1}{2}(x_c - x_b)^2 \tan\beta - \frac{1}{2}(x_c - X_{pit})^2 \tan\beta$$

and our aim is to minimise the right hand side of equation 18 with respect to X_{pit} and y_b.

The effect of operating level on excavation productivity

Figure 6 shows the relationship between excavation productivity and operating level for a number of different pit widths.

The curves for $X_{pit} = 60$–100 represent cases where we need to build a bridge. For the curve $X_{pit} = 20$ no bridge is needed. We will look at this factor in more detail in the next section.

The diagram shows that, for a given pit width it is, in general, possible to find an operating level that maximises the productivity (minimises the excavation time per unit width) and that the optimal productivity is greater for larger pit widths.

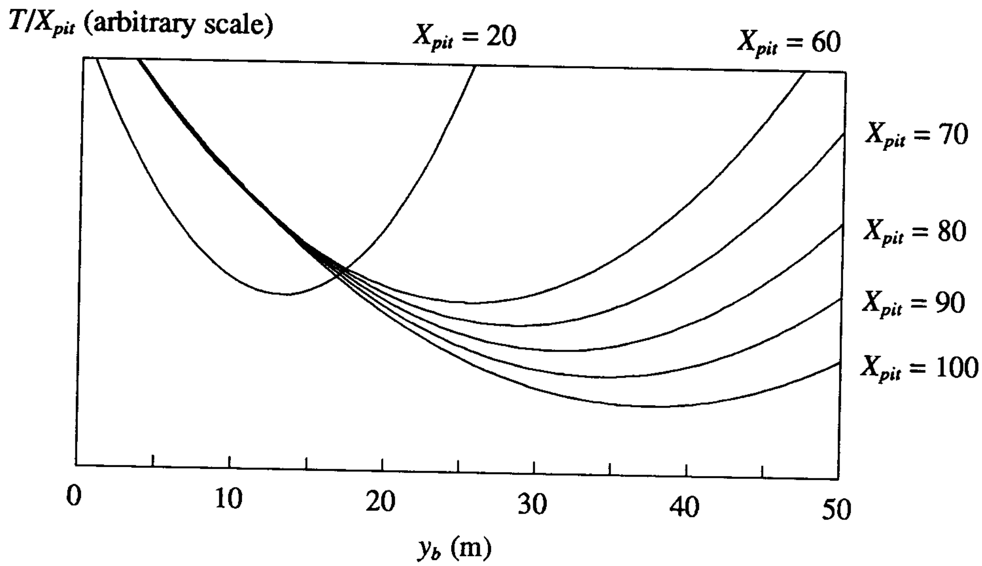


Figure 6: Dig time per unit width *vs* operating level

We find the value $y_b^\star$ for which this optimum occurs by using (11)–(17) to write the equation for T/X_{pit} in terms of y_b, X_{pit} and known parameters. Then, differentiating (18) with respect to y_b gives:

$$\frac{\partial(T/X_{pit})}{\partial y_b} = \frac{1}{8} + \left[1 - \frac{1}{e}\right] + \frac{1}{X_{pit}}\left[\frac{s_2 Y_{ob}}{2\tan\beta} - \frac{1}{2}D_{reach} + \frac{y_b}{\tan\alpha} + \frac{y_b}{2\tan\beta}\right] \qquad (19)$$

and

$$\frac{\partial^2(T/X_{pit})}{\partial {y_b}^2} = \frac{1}{X_{pit}}\left[\frac{1}{\tan\alpha} + \frac{1}{2\tan\beta}\right] > 0 \quad \text{so we have a minimum.}$$

Setting the RHS of (19) to zero and writing

$$k_1 = D_{reach} - \frac{s_2 Y_{ob}}{\tan\beta}, \quad k_2 = \frac{1}{\tan\alpha} + \frac{1}{2\tan\beta}, \quad k_3 = \frac{1}{8} + (1 - \frac{1}{e})$$

gives

$$y_b^\star = -\frac{1}{k_1}(k_3 X_{pit} - \frac{k_2}{2}) \qquad (20)$$

The effect of pit width on excavation productivity

Figure 7 shows the relationship between excavation productivity and pit width for a number of different operating levels.

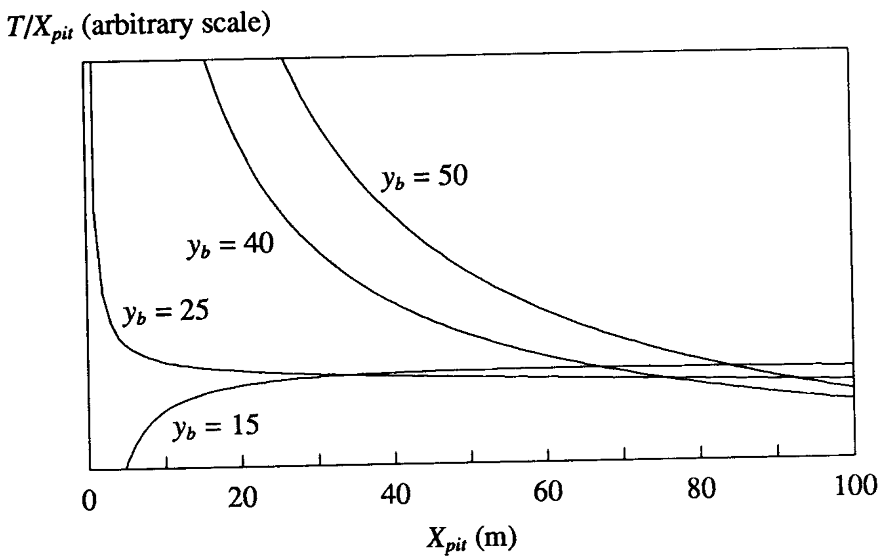


Figure 7: Dig time per unit width *vs* pit width

For fixed values of y_b, (18) shows some interesting properties.

If $y_b > k_1(1+\sqrt{1+2k_2\tan\beta})/2k_2$, which we calculate below and which corresponds to $x_b > x_d$, then the function behaves as shown by the curves for y_b = 25–50. Physically these values of y_b correspond to situations where we need to build a bridge in order to reach the horizontal peak of the spoil pile. The productivity increases with pit width but with a law of diminishing return as the width increases. We should use the maximum pit width possible.

If y_b is less than the value given in the previous paragraph, then the function behaves as shown by the curve for y_b = 15. In this case (18) is not physically relevant. It gives a solution corresponding to a situation in which no bridge is needed and an unnecessary volume of material is simply moved along the pit.

Differentiating (18) with respect to X_{pit} gives

$$\frac{\partial(T/X_{pit})}{\partial X_{pit}} = \frac{1}{2X_{pit}^2}\left[(k_1y_b - k_2y_b^2) + \frac{1}{2}\tan\beta(k_1^2 - (X_{pit}/4)^2)\right] \tag{21}$$

with

$$\frac{\partial^2(T/X_{pit})}{\partial X_{pit}^2} = -\frac{1}{X_{pit}^3}\left[(k_1y_b - k_2y_b^2) + \frac{1}{2}k_1^2\tan\beta\right] \tag{22}$$

The second derivative switches from negative to positive, corresponding to the change in behaviour shown by the difference between the curves for $y_b = 15$ and $y_b = 25$ in figure 7, when

$$(k_1 y_b - k_2 y_b^2) + \frac{1}{2} k_1^2 \tan\beta = 0 \quad \Rightarrow \quad y_b = \frac{k_1(1 \pm \sqrt{1 + 2k_2 \tan\beta})}{2k_2}$$

We require $y_b > 0$ which gives

$$y_b = \frac{k_1(1 + \sqrt{1 + 2k_2 \tan\beta})}{2k_2} \tag{23}$$

For this value of y_b the outer top of the bridge coincides with the edge of the highwall (*i.e.* $x_b = x_d$).

For y_b greater than this value the second derivative will be positive and we obtain the behaviour shown by the curves $y_b = 25$–50 in figure 7.

If y_b is less than this value then (18) is not physically relevant since we do not need a bridge. We remove the area term A_b from (18) and note, obviously, that the productivity increases as we increase y_b and reduce the amount of material removed from above the operating level.

Optimising productivity using non linear programming

The above results were confirmed by using the MINOS Non Linear Programming optimiser to minimise (18) subject to the constraints of (14, 15) and with the lower bound on y_b set by (23). The program was run with different upper bounds (but all less than 90 metres) on X_{pit}.

In all cases the optimisation drove the pit width to its upper bound and returned an optimum value for y_b as given by substituting the upper bound of the pit width into (20).

Conclusions

The above discussion assumes that we will not triple handle the overburden material. This means that we are restricting the maximum pit width to be less than the maximum effective reach of the dragline.

In this situation the results indicate that the most effective operation is obtained by choosing the maximum pit width possible and then calculating the operating level using

$$y_b^\star = -\frac{1}{k_1}(k_3 X_{pit} - \frac{k_2}{2})$$

7. Solving the combinatorial part of the problem with Dynamic Programming

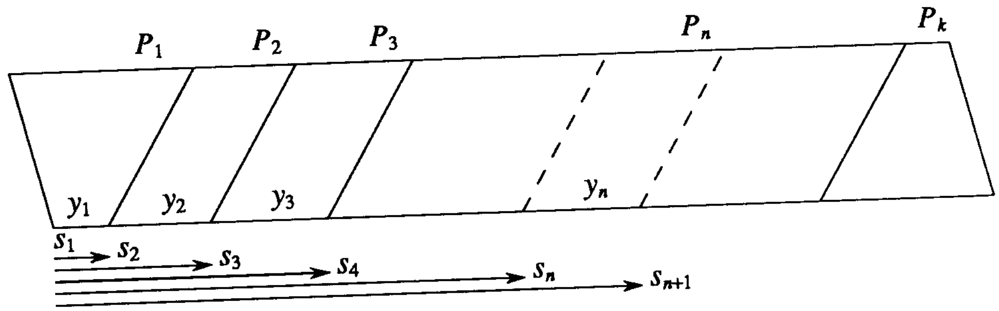


Figure 8: Geometry for Dynamic Programming model

If we know the excavation rate as a function of location across the overburden block then we can use Dynamic Programming to determine an optimal way of dividing the overburden into sub-blocks corresponding to the different dragline excavation positions.

The DP procedure is applied in the context of the geometry shown in figure 8. We divide the overburden into k excavation positions $P_1, P_2, \ldots, P_k$. With reference to figure 3 on page 9, once we have specified the width of the base of the keycut and the total width of region 3 (which we may divide into sub-blocks as here), the first and last positions are given by the overall geometry.

Let s_n be the distance to the origin (bottom left corner) of block $n-1$, then

$$s_n = \sum_{i=1}^{n-1} y_i \quad , \quad n = 2, 3, \ldots, k \tag{24}$$

with $s_1 = 0$.

Also, let $f_n(s_n)$ denote the optimal (minimal) time required to remove the remaining overburden, given that after removing $n-1$ blocks we are in position s_n. Then $f_{k+1}(s_{k+1}) = 0$, and the optimal time to move the entire cut is given by $f_1(0)$.

We can show that the following functional equation holds.

$$f_n(s_n) = \min_{y_n \in D(s_n)} \{T(s_n, y_n) + f_{n+1}(s_n + y_n)\} \, , \; 1 \le n \le k \, , \; s_n \in S_n \tag{25}$$

where $D(s_n)$ = the set of feasible values of y_n given that we are in:
S_n = the set of (discrete) feasible values of s_n.
$T(s_n, y_n)$ = the time to move the nth sub-block to the spoil pile.

(25) can be solved rapidly — assuming that the function T can be evaluated rapidly. This formulation takes advantage of the fact that the model is "separable" in a dynamic programming sense (Sniedovich, 1992).

8. Sequencing the excavation from the keycut and highwall blocks

In this section we consider that part of the excavation where the dragline operator can choose to dig from either the highwall bench block or from the keycut region. In particular, we investigate whether there is an optimal sequencing of the digging from these two regions that will minimise the excavation time.

By making appropriate simplifications we can remove excess complexity from the problem but retain its essential elements. Here, we look at a simplification of the operations in which we reduce the number of spatial dimensions used to describe the overburden. We assume average behaviour for two dimensions and then conduct the analysis with respect to the remaining dimension.

We retain the single dimension across the pit and assume that, for each section of the overburden (averaged down and along the pit), the times to fill, hoist and lower the bucket remain relatively constant. We take the major variable part of the total excavation time to be the swing times.

Problem formulation

Figure 9 shows the simplified geometry for the sequencing problem. Side 'a' is taken to represent the overhand block and side 'b' represents the keycut.

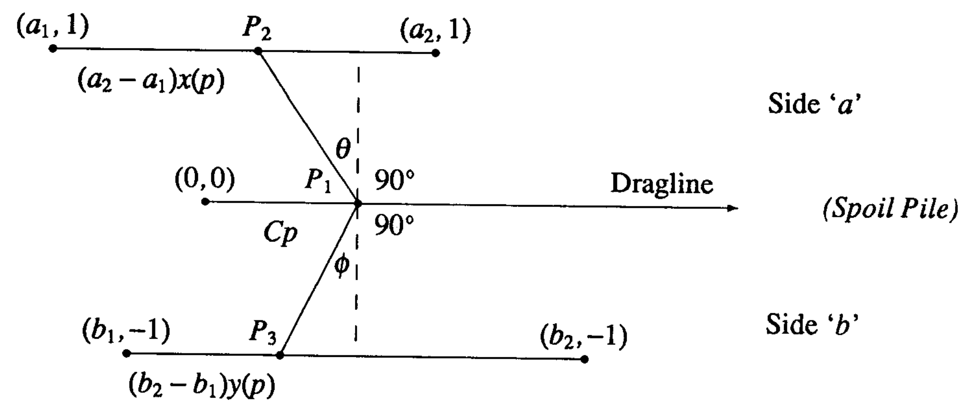


Figure 9: Normalised diagram for digging from both sides

The distances from the dragline path to the centre lines of the overburden blocks can be normalised to 1 without loss of generality.

We use the following notation in the formulation of the problem.

Parameters

a_1, a_2	the end co-ordinates of side 'a'
b_1, b_2	the end co-ordinates of side 'b'
V_a	the volume of overburden in side 'a'
V_b	the volume of overburden in side 'b'
e_a	the bucket filling efficiency when excavating from side 'a'
e_b	the bucket filling efficiency when excavating from side 'b'
A	the distance moved by the dragline in excavating all of side 'a'
B	the distance moved by the dragline in excavating all of side 'b'
C	the distance moved by the dragline after completely excavating the overburden to the spoil pile

We assume that the volumes have been corrected to allow for swelling arising from blasting the overburden prior to excavation and from dumping the overburden to the spoil pile.

In practice, bucket filling is less efficient when digging the overhand block because the excavation occurs at or above the dragline operating level and it is difficult to fill the bucket. We designate digging efficiencies $0 \le e_a \le 1$ for side 'a' and $0 \le e_b \le 1$ for side 'b' to allow for this fact. A digging efficiency of $e_a = 0.8$ indicates that the bucket is filled to 80% of its capacity when digging from above the operating bench on side 'a'.

Variables

p	the proportion of the total overburden that has been excavated so far in the current cycle
$\eta(p)$	the proportion of side 'a' excavated when a proportion p of the total overburden has been excavated
$\xi(p)$	the proportion of side 'b' excavated when a proportion p of the total overburden has been excavated
θ	the swing angle on Side 'a'.
ϕ	the swing angle on Side 'b'.

For convenience, we ignore the 90° component and take the swing angles θ and ϕ to be as shown in figure 9.

We initially locate the dragline at position $(0, 0)$ as shown in figure 9. The overhand overburden block is centred on the line $(a_1, 1)$ to $(a_2, 1)$. The keycut overburden block is centred on the line $(b_1, -1)$ to $(b_2, -1)$. The digging direction is constrained to be from $(a_1, 1)$ to $(a_2, 1)$ and from $(b_1, -1)$ to $(b_2, -1)$.

We assume that the dragline position is always a fixed distance from the spoil pile dumping point. This distance is set as the effective dragline reach so as to minimise the angle through which the dragline must turn. As the overburden is excavated the dumping point shifts outwards and the dragline moves accordingly.

The objective function

Suppose that the proportion of overburden removed at some stage is p and that we increase this to $(p + \Delta p)$ by increasing the proportion excavated from side 'a' from η to $(\eta + \Delta\eta)$ and the proportion excavated from side 'b' from ξ to $(\xi + \Delta\xi)$.

At this stage, the dragline is at position P_1 shown in figure 9. The excavation point for side 'a' is at P_2 and the excavation point for side 'b' is at P_3.

The volume of material removed from side 'a' is $V_a \Delta\eta$ and, assuming a unit bucket size, the number of bucket loads involved in this excavation is $(V_a/e_a)\Delta\eta$.

The angle turned through by the dragline in carrying out this excavation is then given by

$$\frac{V_a}{e_a}\Delta\eta\,\theta \tag{26}$$

Similarly, if we excavate a volume $V_b \Delta\xi$ from side 'b' then the angle turned through by the dragline is

$$\frac{V_b}{e_b}\Delta\xi\,\phi \tag{27}$$

The angle turned through in increasing the proportion of overburden excavated from p to $(p + \Delta p)$ is therefore

$$\frac{V_a}{e_a}\Delta\eta\,\theta + \frac{V_b}{e_b}\Delta\xi\,\phi \tag{28}$$

The angles and digging constraints associated with the problem are most conveniently expressed in terms of the positions of the dragline and excavation points on sides 'a' and 'b'. We therefore rewrite (28) in terms of the distances associated with these positions.

For the simplified case under consideration, we specify averaged behaviour for the dimension across the strip. We assume that the dumping position is at the outer edge of the spoil material and thus depends on the proportion of total overburden excavated. The dragline moves so that it is always a fixed position from the dump position. When a proportion p of the overburden has been excavated the distance moved by the dragline is thus Cp. This distance is made up of a displacement $A\eta$ from digging side 'a' and a displacement $B\xi$ from digging side 'b'. At the completion of digging we have

$$A + B = C \tag{29}$$

We let $A = kV_a$ and $B = kV_b$, where k depends on the physical dimensions of the strip. The angle turned through in excavating a proportion Δp of the total overburden can thus be written as

$$\frac{1}{k}\left(\frac{A}{e_a}\frac{\Delta\eta}{\Delta p}\,\theta + \frac{B}{e_b}\frac{\Delta\xi}{\Delta p}\,\phi\right)\Delta p \tag{30}$$

and the total angle turned through by the dragline as

$$\frac{1}{k}\int_0^1 \left(\frac{A}{e_a}\,\eta'\,\theta + \frac{B}{e_b}\,\xi'\,\phi\right) dp \tag{31}$$

So our problem is:

$$\text{minimise} \quad \int_0^1 \left(\frac{A}{e_a}\,\eta'\tan^{-1}\mu + \frac{B}{e_b}\,\xi'\tan^{-1}\nu\right) dp \tag{32}$$

where the equations for μ and ν are given as the first two constraints below.

Constraints

From figure 9 we have that

$$\mu = (Cp - a_1) - (a_2 - a_1)\eta \tag{33}$$

$$\nu = (Cp - b_1) - (b_2 - b_1)\xi \tag{34}$$

We also require

$$\eta(0) = 0\,,\ \eta(1) = 1 \qquad \xi(0) = 0\,,\ \xi(1) = 1 \tag{35}$$

In addition we have

$$A\eta + B\xi = Cp \tag{36}$$

and differentiating (36) gives

$$A\eta' + B\xi' = C \tag{37}$$

Finally, the dragline digs only from overburden to spoil so $\eta' \geq 0$ and $\xi' \geq 0$, and from (29) and (37) we have

$$0 \leq \eta' \leq \frac{A+B}{A} \qquad 0 \leq \xi' \leq \frac{A+B}{B} \tag{38}$$

The problem given by (32)–(38) can be solved using either an optimal control approach or calculus of variations with Lagrange multipliers. Initial work indicates that the optimal solution has bang-bang control, switching between $\eta' = 0$, $\xi' = (A+B)/B$ and $\eta' = (A+B)/A$, $\xi' = 0$.

Using a discrete problem formulation, preliminary numerical analyses of the optimal schedules for digging from the two sides gave only two general excavation schedules for η' and ξ':

- Excavate all of side 'a' ($\xi' = 0$), then excavate side 'b'.
- Excavate all of side 'b' ($\eta' = 0$), then excavate side 'a'.

Which side is excavated first depends on the geometry of the problem. If the problem is symmetric both schedules are optimal.

A Dynamic Programming approach

Dynamic programming provides an alternative way of solving specific cases of this optimisation problem, and being a numerical technique will conveniently allow a more detailed description of the digging time.

The state of the problem after a proportion p of overburden has been excavated is given by $\eta(p)$ so a two dimensional table with state $\eta(p)$ and stage p can be used to implement the dynamic programming. As we have seen above, the solution is either $\eta' = 0$ or $\xi' = 0$ at each small step so the dynamic programming needs to examine only these two options at each table entry. Note that multiple local optima could exist.

We can calculate average angles through which the dragline must swing to change state by moving from p to $(p + p/n)$, with n representing the number of steps in the analysis. These angles are calculated for digging from both the 'a' and 'b' sides.

It is then possible to calculate the minimum total angle through which the dragline must turn in order to make the transition from any given state to the final condition $\eta(1) = 1$ by using the equation

$$g(s,p) = \min\{g(s+1,p+1) + \theta_s \, , \; g(s,p+1) + \phi_s\} \tag{39}$$

In (39), $g(s,p)$ represents the minimum total angle to move from state s stage p to the final condition $\eta(1) = 1$. θ_s is the angle when digging from side 'a' and ϕ_s is the angle when digging from side 'b'.

Calculations of $g(s,p)$ for different cases give results consistent with those noted above, namely that the optimal digging schedule is to either dig all of side 'a' first then side 'b', or vice versa depending on the particular geometry and excavation rates.

9. Conclusions

The Study Group identified a number of possible approaches to tackling the problem of optimising dragline operations. The techniques discussed in this report provide the first steps toward developing full 3-dimensional optimisation methods for the problem. Initial numerical work based on these methods has provided some insight into the parameters which are important in improving the dragline operating efficiency. A simulation model of the operation has been used for a preliminary investigation of the effects of different methods of walking the dragline across the operating bench.

The methods considered in the report are for the particular method of removing overburden outlined in the introduction. There are however a number of quite different operational techniques that can be employed when using a dragline to remove overburden.

Of particular importance is the blasting technique used to loosen the overburden. The charges can be set to produce a number of different possible profiles of the blasted overburden. These profiles determine the subsequent possible movements of the dragline machines.

The problem thus involves not just the optimisation of a given set of dragline operational techniques but a comparison of different operational techniques used in conjunction with the initial blasting patterns chosen for a particular type of overburden.

10. Acknowledgements

The moderator of this problem (David Sier) would like to acknowledge the contributions of the group which studied the problem. Nick Barlow from Pacific Coal provided great help in clarifying issues that arose during the discussions. Bill Whiten played a major role in developing many of the ideas presented here. Moshe Sniedovich provided the insight for the dynamic programming approach in section 7. Valuable contributions were also made by Basil Benjamin, Phil Howlett, Mohan Krishnamoorthy, Graham Mills and Kate Smith.

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