Highway Earthworks and Mass Haul Diagram

In this lecture;
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A- Roadwork equipments

B- Earthworks quantities

C- Mass Haul Diagram

The information listed in this lecture is mainly taken from; the Iraqi General Specifications for Roads and Bridge (SCRB, 2007), Traffic and Highway Engineering (Garber and Hoel, 2009) and Highways (O’Flaherty, 2007).

A- Highway Grades and Terrain Criteria

Land topography has significant effects on the selection of a highway location and hence the laying of the grade line. The primary factor that the designer considers on laying the grade line is the amount of earthwork that will be necessary for the selected grade line. The ultimate purpose is to minimise this amount.

One method to reduce the amount of earthwork is to set the grade line as closely as possible to the natural ground level (ground line). Another method to reduce the cost is by setting the grade line such that there is a balance between the excavated volume (cut) and the volume of embankment (fill).
B- Roadwork excavation and hauling equipments

Depending on the function and suitability, there is wide range of heavy equipment used in road construction, mainly in earthworks and paving. The majority of these equipments are used in road excavation and earthmoving (hauling). Some of them have specific use while others have multiple functions. Among of these functions are; excavation, loading, hauling, placing (dumping & spreading), boring or tunnelling, compacting, grading and finishing.

Following are the most common heavy equipment used in road excavation and hauling; Backacters (Backhoes), Bulldozers, Dragline crane, Face shovels, Front-end loaders, Graders, Scrapers and finally Trucks and wagons. The following Table lists some common types of equipment and typical uses to which they are put.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backacters (Backhoes)</td>
<td>Excavating below ground level in confined spaces in firm soil, e.g. when digging drainage trenches; as small ‘handling cranes’, e.g. when laying drainage pipes.</td>
</tr>
<tr>
<td>Bulldozers</td>
<td>Opening up access roads; clearing vegetation; stripping top soil; shallow excavating; moving earth over short distances (e.g. &lt;100 m); spreading and rough-grading earth previously moved by scrapers, trucks or wagons.</td>
</tr>
<tr>
<td>Dragline crane</td>
<td>Excavating below ground level in non-confined spaces in soft or loose soils, e.g. digging large trenches or large foundations; dredging underwater deposits of gravel.</td>
</tr>
<tr>
<td><strong>Face shovels:</strong> Excavating firm material above ground level, e.g. in cuttings, and previously-blasted rock in quarries.</td>
<td></td>
</tr>
<tr>
<td><strong>Loader shovel:</strong> Several localized earthworks operations, e.g. digging/filling shallow trenches, excavating for manholes, loading loose materials onto trucks and wagons, stockpiling.</td>
<td></td>
</tr>
<tr>
<td><strong>Graders:</strong> Accurate finishing work, e.g. trimming the subgrade and establishing the formation, and shaping shoulders, ditches and backslopes; maintaining haul roads. Also, for blending materials, including water.</td>
<td></td>
</tr>
<tr>
<td><strong>Scrapers:</strong> Earthmoving operations which involve self-loading, hauling over various distances (e.g. &lt;3 km), dumping and spreading of materials.</td>
<td></td>
</tr>
<tr>
<td><strong>Trucks and wagons:</strong> General haulage operations over long distances (typically 1–10 km).</td>
<td></td>
</tr>
</tbody>
</table>
C- Earthworks quantities (Excavation and Embankment)

The final element in the highway location process is to establish the horizontal (layout) and vertical (profile) alignments. Land terrain influences the cost of earthworks involved in constructing the roadbed. The determination of earthworks quantities is based on cross-section data. These data normally indicate the extent of the excavation (i.e. cut) from cuttings, and filling (i.e. fill) for embankments, at regular intervals – say every 15–30m – and where major ground irregularities and changes occur along the selected alignment.

Briefly, earthwork computations involve taking consecutive cross-sections (typically 25 m) and plotting both the natural ground level and the proposed grade profile. Thereafter, determining areas of cut and fill in order to calculate earthwork volumes between the cross-sections. Finally, balancing of cuts and fills and hence planning of the most economical material hauls.
C-1 Determining cross-section areas

Roads cross sections can be either fill, cut or side-hill sections as shown below.

When the ground surface is level or regular, the area of a cross-section is easily determined by dividing the enclosed space into triangles and trapezoids and using standard formulae in the calculations, see the next example.
Or, if the ground surface is irregular, the area of a cross-section can be determined using the coordinate method. By geometry, it can be shown that the enclosed area in the Figure below is given by:

\[
A = 0.5[y_1(x_4 - x_2) + y_2(x_1 - x_3) + y_3(x_2 - x_4) + y_4(x_3 - x_1)]
\]

Generally,

\[
A = \frac{1}{2} \sum_{i=1}^{n} X_i (Y_{i+1} - Y_{i-1})
\]

where \(n + 1 = 1; 1 - 1 = n\)

* Area of trapezoidal with depth \(d\) (cut or fill) and side slope \(s\) is:

\[
\text{Area} = bd + s \ d^2 = (b+sd) \ d
\]
C-2 Determining earthwork volumes

The simplest way of measuring volume is by means of the trapezoidal or average end-area method. Thus, if the areas delineated by points A, B, C and D, and I, J, K and L, in Figure are denoted by A1 and A2, respectively, then

\[ V = 0.5D(A_1 + A_2) \]

V = volume (m³),
D = distance between end areas (m),
A1, A2 = end areas (m²) of embankment.

When greater accuracy is required, such as in situations where the grade line moves from a cut to a fill section, the volume may be considered as a pyramid or other geometric shape.

\[ V = \frac{A \cdot D}{3} \]
Balancing earthworks quantities

Ideally, the selection of the optimum horizontal and vertical alignment for a road should result in the volume of material excavated being equal to the amount of fill required in embankment, so that there is no need to waste good excavation soil or to borrow expensive material from elsewhere. In engineering practice, however, the ideal does not always happen, and good excavation material may have to be wasted because it is uneconomical to do otherwise, whilst material that is unsuitable for use in embankments may have to be discarded.

Shrinkage and swelling: On the other hand, soil usually experiences volumetric changes (during excavation, hauling and compacting. Corrected earthwork volumes should be computed by considering shrinkage and swelling factors.

The Figure below shows that when hauled material is laid in an embankment and made dense by compaction, the net result for most soils is a shrinkage whereas in the case of rocks is swelling.
EXAMPLE PROBLEM 5.2. Given the end areas below, calculate the volumes of cut and fill between stations 351 + 00 and 352 + 50. If the material shrinks 12 percent, how much excess cut or fill is there? Express excess cut in cut yards, and excess fill in fill yards.

<table>
<thead>
<tr>
<th>Station</th>
<th>End areas, m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>351 + 00</td>
<td>57.93</td>
</tr>
<tr>
<td>351 + 50</td>
<td>52.28</td>
</tr>
<tr>
<td>351 + 75</td>
<td>0</td>
</tr>
<tr>
<td>352 + 00</td>
<td>8.40</td>
</tr>
<tr>
<td>352 + 14</td>
<td>13.80</td>
</tr>
<tr>
<td>352 + 50</td>
<td>33.34</td>
</tr>
</tbody>
</table>

*Calculate earthwork volumes*

351 + 00 to 351 + 50

\[
\text{Fill} = \frac{57.93 + 52.28}{2}(50) = 2,755.3 \text{ m}^3 \quad \text{(Average end area)}
\]

351 + 50 to 351 + 75

\[
\text{Fill} = \frac{52.28 + 23.58}{2}(25) = 948.3 \text{ m}^3 \quad \text{(Average end area)}
\]

351 + 75 to 352 + 00

\[
\text{Fill} = \frac{23.58 + 3.73}{2}(25) = 341.4 \text{ m}^3 \quad \text{(Average end area)}
\]

\[
\text{Cut} = \frac{(8.40)(25)}{3} = 70.0 \text{ m}^3 \quad \text{(Pyramid)}
\]

352 + 00 to 352 + 14

\[
\text{Fill} = \frac{(3.73)(14)}{3} = 17.4 \text{ m}^3 \quad \text{(Pyramid)}
\]

\[
\text{Cut} = \frac{8.40 + 13.80}{2}(14) = 155.4 \text{ m}^3 \quad \text{(Average end area)}
\]

352 + 14 to 352 + 50

\[
\text{Cut} = \frac{13.80 + 33.34}{2}(36) = 848.5 \text{ m}^3 \quad \text{(Average end area)}
\]
Summary;

\[
\text{Excess fill (in fill yards) } = 4,062.4 - \\
1,073.9(1.00 - 0.12) \\
= 3,117.4 \text{ m}^3
\]

---

**Example** Computing Fill and Cut Volumes Using the Average End-Area Method

A roadway section is 2000 ft long (20 stations). The cut and fill volumes are to be computed between each station. Table on page lists the station numbers (column 1) and lists the end area values (ft²) between each station that are in cut (column 2) and that are in fill (column 3). Material in a fill section will consolidate (known as shrinkage), and for this road section, is 10 percent. (For example, if 100 yd³ of net fill is required, the total amount of fill material that is supplied by a cut section is 100 + (0.10 × 100) = 100 + 10 = 110 ft³.)

Determine the net volume of cut and fill that is required between station 0 and station 1.

Solution:

\[
V_{\text{cut}} = \frac{100(A_{0c} + A_{1c})}{54} = \frac{100(3 + 2)}{54} = 9.25 \text{ yd}^3
\]

\[
V_{\text{fill}} = \frac{100(A_{0f} + A_{1f})}{54} = \frac{100(18 + 50)}{54} = 125.9 \text{ yd}^3
\]

Shrinkage = 125.9 (0.10) = 13 yd³

Total fill volume = 126 + 13 = 139 yd³

The cut and fill volume between station 0 + 00 and 1 + 00 is shown in columns 4 and 7.

Cut: 9 yd³ (column 4)
Fill: 126 yd³ (column 5)
Shrinkage: 13 yd³ (column 6)
Total fill required: 139 yd³ (column 7)
### Computation of Fill and Cut Volumes and Mass Diagram Ordinate

<table>
<thead>
<tr>
<th>Station</th>
<th>End Area (ft²)</th>
<th>Cut</th>
<th>Fill</th>
<th>Total Cut</th>
<th>Fill</th>
<th>Shrinkage 10 percent</th>
<th>Total Fill (5 + 6)</th>
<th>Net Volume (4 to 7)</th>
<th>Mass Diagram Ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>18</td>
<td></td>
<td>9</td>
<td>126</td>
<td></td>
<td>139</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>50</td>
<td></td>
<td>7</td>
<td>272</td>
<td></td>
<td>27</td>
<td>299</td>
<td>-130</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>97</td>
<td></td>
<td>11</td>
<td>420</td>
<td></td>
<td>42</td>
<td>462</td>
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<td>3</td>
<td>4</td>
<td>130</td>
<td></td>
<td>22</td>
<td>335</td>
<td></td>
<td>34</td>
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<td>4</td>
<td>8</td>
<td>51</td>
<td></td>
<td>89</td>
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<td></td>
<td>18</td>
<td>196</td>
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<td>5</td>
<td>40</td>
<td>45</td>
<td></td>
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<td>12</td>
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<td>45</td>
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<td></td>
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<td>5</td>
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<td>14</td>
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<td>50</td>
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<td>24</td>
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<td>1177</td>
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<td>33</td>
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<td>1042</td>
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<td>100</td>
<td></td>
<td>19</td>
<td>407</td>
<td></td>
<td>41</td>
<td>448</td>
<td>732</td>
</tr>
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<td>6</td>
<td>444</td>
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<td>44</td>
<td>488</td>
<td>303</td>
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<td>3</td>
<td>120</td>
<td></td>
<td>80</td>
<td>315</td>
<td></td>
<td>31</td>
<td>346</td>
<td>-179</td>
</tr>
<tr>
<td>19</td>
<td>40</td>
<td>50</td>
<td></td>
<td>130</td>
<td>148</td>
<td></td>
<td>15</td>
<td>163</td>
<td>-445</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-478</td>
</tr>
</tbody>
</table>

Net volume between stations 0-1 = total cut - total fill = 9 - 139

= -130 yd³ (column 8)

**Note:** Net fill volumes are negative (−) (column 8) and net cut volumes are positive (+) (column 9).

Similar calculations are performed between all other stations, from station 1 + 00 to 20 + 00, to obtain the remaining cut or fill values shown in columns 2 through 9.
D- Mass Haul Diagram

It aids in identifying the following; selecting adequate types of equipment, where quantities of material are required, average haul distance, and haul grades.

To construct the mass-haul diagram the following definitions are necessary:

1- **Haul**: the distance over which material is moved; also represents the volume-distance of material moved.

2- **Free-haul distance (F.H.D)**: the distance within which a fixed price is paid for excavating, hauling, and dumping of material regardless of its length (usually 150 – 350)m. The cost in, say, ID/m³.

3- **Overhaul distance (O.H.D)**: the haulage distance beyond free-haul distance for which extra charge are required for each cubic meter. The cost in, say, ID/m³/sta.

4- **Max. overhaul distance**: when the haul distance is great (larger than max. overhaul distance), it may be more economical to waste (cut) good excavation material and import (barrow) fill from a more convenient source rather than pay for overhauling.

5- **Limit of economic haul distance (L.E.H.D)**: the maximum overhaul distance plus free-haul distance beyond which it is more economical to waste and borrow rather than to pay for overhauling,

\[ L.E.H.D = F.H.D + \text{Max. O.H.D} \]

Now, max. O.H.D can be mathematically computed as follows;

\[ \text{F.H.Cost} + \text{Max. O.H.D} \times \text{O.H. Cost} = \text{F.H.Cost} + \text{borrow cost} \quad ------ > \]

\[ \text{Max. O.H.D} = \frac{\text{Borrow cost}}{\text{O.H. cost}} \]
Fig. An example of a mass-haul diagram: (a) a longitudinal section showing the ground contour, the proposed formation, and areas of cut and fill, and (b) the volume accumulations for mass haul.
Some characteristics of the mass-haul diagram at the Figure above (b) are:

1- The y-coordinate at any station represents the earthworks accumulation to that point. The maximum ordinate (+) indicates a change from cut to fill, whilst the minimum ordinate (-) represents a change from fill to cut.

2- A rising curve at any point indicates an excess of excavation over embankment material, whilst a falling curve indicates the reverse. Steeply rising (or falling) curves indicate major cuts (or fills), whereas flat curves show that the earthworks quantities are small.

3- The curve starts with zero-accumulated earthworks and the baseline is the zero balance line, i.e. when the curve intersects this line again the total cut and fill will balance. A line that is drawn parallel to the baseline so as to cut a loop is called a ‘balancing line’, and the two intersection points on the curve are called ‘balancing points’ as the volumes of cut and fill are balanced between them.

4- The area between a balance line and the mass-haul curve is a measure of the haul (in station-m$^3$) between the balance points. If this area is divided by the maximum ordinate between the balance line and the curve, the value obtained is the average distance that the cut material needs to be hauled in order to make the fill.

5- Balance lines need not be continuous, i.e. a vertical break between two balance lines merely indicates unbalanced earthworks between the adjacent termination points of the two lines.

In the previous Figure (b) the limits of economic haul distance (L.E.H.D) are drawn as the balance lines bd, fh, and km. The direction of haulage is shown by the arrows in part (a) of the Figure. Note that the haulage is downhill to the embankments so that the emptied vehicles can travel uphill to the excavation sites.
The limits of free-haul distance are indicated by the balance lines 1–2, 3–4, and 5–6. The free-haul station-$m^3$ is indicated by the dotted areas 1c2, 3g4, and 5l6. In this case, by chance, the balance line d–f is equal to the free-haul distance and, hence, the area def is also free-haul station-$m^3$.

The overhaul volume for section BCD is given by the difference between the ordinates from c to b–d and from c to 1–2. The average length of overhaul is estimated by drawing the balance line 7–8 through the median of the overhaul ordinate. Since the free-haul distance is given by 1–2, the average overhaul is the distance 7–8 minus the distance 1–2.

In practice, selection of the optimum horizontal and vertical alignment rarely results in the earthworks being exactly balanced from beginning to end of the project. In the previous Figure the earthworks are not fully balanced, and it can be seen that borrow material will have to be imported for the embankments between A and B and between M and P, and that the required quantities are given by the ordinates at b and m, respectively. Between H and K the excavated material will have to be wasted to a spoil tip as it is uneconomical to overhaul it for use in the embankment.

**Borrow:** It is the location away from the Right of Way (R.O.W.) and it is chosen by the Engineer.

**Waste:** It is the unwanted excavation material which should be disposed out of R.O.W.
Example   Computing Mass Diagram Ordinates

Use the data obtained in Exam_ on P.111 to determine the net accumulation of cut or fill beginning with station \(0 + 00\). Plot the results.

Solution: Columns 8 and 9 show the net cut and fill between each station. To compute the mass diagram ordinate between station \(X\) and \(X + 1\), add the net accumulation from Station \(X\) (the first station) to the net cut or fill volume (columns 8 or 9) between stations \(X\) and \(X + 1\). Enter this value in column 10.

\[
\text{Station } 0 + 00 \text{ mass diagram ordinate } = 0 \\
\text{Station } 1 + 00 \text{ mass diagram ordinate } = 0 - 130 = -130 \text{ yd}^3 \\
\text{Station } 2 + 00 \text{ mass diagram ordinate } = -130 - 292 = -422 \text{ yd}^3 \\
\text{Station } 3 + 00 \text{ mass diagram ordinate } = -422 - 451 = -873 \text{ yd}^3 \\
\text{Station } 4 + 00 \text{ mass diagram ordinate } = -873 - 347 = -1220 \text{ yd}^3 \\
\text{Station } 5 + 00 \text{ mass diagram ordinate } = -1220 - 107 = -1327 \text{ yd}^3 \\
\text{Station } 6 + 00 \text{ mass diagram ordinate } = -1327 + 25 = -1302 \text{ yd}^3 \\
\text{Station } 7 + 00 \text{ mass diagram ordinate } = -1302 + 180 = -1122 \text{ yd}^3 \\
\]

Continue the calculation process for the remaining 13 stations to obtain the values shown in column 10 of Table p.111. A plot of the results is shown in Figure on page 118.

Example   Computing Balance Point Stations

Compute the value of balance point stations for the mass diagram in Figure p.118 for the following situations:

(a) The x-axis
(b) The horizontal distance \(S-T\), which measures 500 ft

Solution:

(a) Balance points are computed by interpolation using the even stations where the ordinates change from cut to fill (or vice versa).

Balance point \(D'\) occurs between Station 9 + 00 and 10 + 00 (since ordinate values are \(-299\) and \(+201\)). Assuming that the mass diagram ordinate changes linearly between stations, by similar triangles, we can write

\[
\text{Station of the Balance Point } D' = (9 + 00) + \left[\frac{299}{(299 + 201)}\right](100) = 9 + 60
\]

Similarly,

\[
\text{Station of the Balance Point } E' = (17 + 00) + \left[\frac{303}{(303 + 179)}\right](100) = 17 + 63
\]

(b) To determine the balance point stations for line \(ST\), it is necessary to draw the mass diagram to a larger scale than depicted in the textbook, and to read the station for one of the points directly from the diagram. Using this technique, station 11 + 20 was measured for point \(S\) and from this value the station for point \(T\) is computed as

\[
(11 + 20) + (5 + 00) = \text{Station } 16 + 20
\]
Mass Diagram for Computation Shown in Table on Page 111.

Interpretation of the Mass Diagram

Inspection of Figure p118 and Table p111 reveals the following characteristics.

1. When the mass diagram slopes downward (negative), the preceding section is in fill, and when the slope is upward (positive), the preceding section is in cut.
2. The difference in mass diagram ordinates between any two stations represents the net accumulation between the two stations (cut or fill). For example, the net accumulation between station 6 + 00 and 12 + 00 is $1302 + 904 = 2206 \text{ yd}^3$.
3. A horizontal line on the mass diagram defines the locations where the net accumulation between these two points is zero. These are referred to as “balance points,” because there is a balance in cut and fill volumes between these points. In Figure 14.15, the “x” axis represents a balance between points $A'$ and $D'$ and a balance between points $D'$ and $E'$. Beyond point $E'$, the mass diagram indicates a fill condition for which there is no compensating cut. The maximum value is the ordinate at station 20 + 00 of $-478 \text{ yd}^3$. For this section, imported material (called borrow) will have to be purchased and transported from an off-site location.
4. Other horizontal lines can be drawn connecting portions of the mass diagram. For example lines $J-K$ and $S-T$, which are each five stations long, depict a balance of cut and fill between stations at points $J$ and $K$ and $S$ and $T$. 

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Example: The following table lists the cut and fill end areas along a 1 km roadway section. Calculate the earthwork volumes and draw the mass haul diagram. The fill soil would experience a 10% shrinkage. Also calculate the following:

a) Limit of economical haul distance.  

b) Free-Haul volume.  

c) Over-Haul volume.  

d) Waste and borrow volumes.

Giving that:

Cost of Over-Haul = 1500 I.D./m³.sta.  

Cost of borrow = 6000 I.D./m³

Free-Haul distance = 200 m.

<table>
<thead>
<tr>
<th>Sta.</th>
<th>A cut (m²)</th>
<th>A fill (m²)</th>
<th>V cut (m³)</th>
<th>V fill (m³)</th>
<th>V fill (corr)</th>
<th>Cum Vol (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+00</td>
<td>57</td>
<td></td>
<td>5000</td>
<td>-</td>
<td>-</td>
<td>5000</td>
</tr>
<tr>
<td>2+00</td>
<td>43</td>
<td>0</td>
<td>3900</td>
<td>-</td>
<td>-</td>
<td>8900</td>
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Highway Eng.  Earthworks & Mass Haul Diagram

\[ \text{LEHD} = \text{FHVD} + \text{Max. OHD} \]

Since \( \text{Max. OHD} = \frac{\text{Cost of borrow}}{\text{Cost of OH volume}} = 6000 \div 1500 = 4 \text{ sta.} \)

\[ \text{LEHD} = 2 + 4 = 6 \text{ sta.} \]

2. From MHD

\[ \text{FHVD} = 1100 \text{ m}^3 \]
\[ \text{OHVD} = 7000 \text{ m}^3 \]
\[ \text{Waste Vol.} = 3600 \text{ m}^3 \]
\[ \text{Borrow Vol.} = 360 \text{ m}^3 \]
Sample Mass Diagrams

Figure 8 A Sample Mass Diagram

Figure 9 A Sample Mass Diagram