11 EARTHWORK QUANTITIES AND MASS HAUL DIAGRAM

11.1 Introduction

The topic of geometric design would be incomplete without a chapter devoted to the issue of earthwork quantities and a mass haul diagram. The careful attentions to limiting earthwork quantities through the preparation of a mass haul diagram are essential elements in providing the best-combined horizontal, vertical, and cross-sectional design. This is especially true when the design includes consideration of the least cost in relation to earthworks.

Key terms associated with this process, as listed in Definitions, include:

- Borrow- material not obtained from roadway excavation but secured by widening cuts, flattening back slopes, excavating from sources adjacent to the road within the right-of-way, or from selected borrow pits as may be noted on the plans
- Waste- material excavated from roadway cuts but not required for making the embankment
- Free Haul- the maximum distance through which excavated material may be transported without the added cost above the unit bid price
- Overhaul- excavated material transported to a distance beyond the free haul distance
- Economic Limit of Haul- distance through which it is more economical to haul excavated material than to waste and borrow

The steps involved in the computation of earthwork quantities and the development of the optimal mass haul diagram are:

- End area calculations
- Earthwork calculations
- Preparation of mass haul diagram
- Balancing earthworks using the mass haul diagram

These steps are presented in the following text. Of note is the fact that most current highway design computer programs, including MX (MOSS), will produce the mass haul diagram as part of the output when typical sections and horizontal and vertical alignments are inputs. A final stage of geometric design is then usually to make adjustments to the alignments in the interests of balancing or minimizing the earthwork quantities.

11.2 End Area Calculations

End area calculations are usually made by one of the following methods:

1. Planimeter Method - The original ground line and template section (cross section) must be plotted on grid paper. Centerline profile grade must first be calculated for each cross section station to determine the centerline reference of each template plot. Areas of cut and fill quantities are calculated using a planimeter, converted to square meters, and tabulated for each section.
2. Electronic Computer Method - This method is widely used due to its versatility and speed of calculations. The end area calculation on modern computer programs is an integral part of the alignment design program and shown on output listings along with the geometric of each section.

11.3 Calculating Earthwork

There are several ways of calculating earthwork but the most common is the "average end area" method. This method consists of averaging the cut and fill quantities of adjacent stations and multiplying by the distance between stations to produce cubic meters of excavation and embankment between the two stations. This procedure is followed when manual methods are used. Projects designed by computer will be tabulated on the mass plot listing and these calculations are integral parts of the alignment design program.

Compaction factors of excavated material must be determined or estimated in order to determine earthwork quantities of excavation and embankment. When common material is excavated from natural ground and compacted in an embankment, it loses volume. When solid rock is broken up and compacted in an embankment, it usually swells. Although adjustment factors can be applied to either embankment or excavation quantities, it is general practice to apply the compaction factor to the excavation so that a compaction factor of –25 percent would result in 100 cubic meters of excavation required for an embankment of 75 cubic meters. Likewise, a 10 percent swell factor would result in 100 cubic meters of rock excavation required for an embankment of 110 cubic meters.

Compaction factors should be determined or estimated for each project taking into consideration the various types of soils and depth of proposed cuts and fills.

The designer should avoid using one factor for the entire project as these results in incorrect distribution of earthwork quantities. Cuts through rock should be classified using parameters, such as swell, associated with the particular rock, and not as a common value for all types of excavation.

Sometimes the use of stripping factors or pre-rolling factors of the natural ground prior to placing embankments are employed. This is done by assuming that the natural ground will be stripped or compacted a certain depth, such as 75 – 100 millimeters, thus increasing the volume of the required embankment to be placed on the natural ground. This assumption may prove satisfactory on projects following virgin country having fairly uniform type of soil, however, problems develop on projects that follow an existing road as only those areas beyond the toe of slopes of the existing roadway will compact the estimated depth. This manual does not recommend the use of natural ground or stripping factors on ERA projects. Instead it is recommended that if the designer considers this volume to be significant, it is recommended to increase the compaction factors from say –20 percent to –25 percent. Accumulation totals of cut and fill can now be calculated as follows:

- Total accumulated cut is the total of adjusted cuts (excavation volume x adjustment factor) added from station to station.
- Total accumulated fill is the sum of the embankments from station to station (no adjustment).
The mass ordinate can now be calculated by taking the algebraic sum of adjusted excavation and unadjusted embankment from station to station, using "+" for excavation and "-" for embankment.

### 11.4 Mass Haul Diagram

The mass haul diagram is a curve in which the abscissas represent the stations of the survey and the ordinates represent the algebraic sum of excavation and embankment quantities from some point of beginning on the profile. The plot can be to any scale, depending on the quantities involved. Project designed by computer will list, tabulate, and plot all of the data shown above including a mass haul diagram and balance points.

The mass haul diagram shows excavation (adjusted) and embankment quantities from some point of beginning on the profile, considering cut volumes positive and fill volumes negative. At the beginning of the curve the ordinate is zero, and ordinates are calculated continuously from the initial station to the end of the project.

The mass haul diagram can be used to determine:

- Proper distribution of excavated material
- Amount and location of waste
- Amount and location of borrow
- Amount of overhaul in kilometer-cubic meters
- Direction of haul.

Figure 11-1 shows a mass haul diagram curve with an accompanying profile of existing ground line and grade line.

The double line in the profile and the mass haul diagram indicate areas of excavation. Arrows indicate direction of haul. Note in the mass haul diagram that the material moves from the rising line to the falling line. The steeper the slope of the mass curve, the greater the cubic meters of excavation or embankment.

**a)** An upward slope on the mass curve indicates excavation, and conversely, a downward slope indicates embankment. The steeper the slope of the mass curve, the greater the cubic meters of excavation or embankment.

**b)** The maximum ordinate of the mass curve occurs at the point where excavation ends and embankment starts. Similarly, the minimum ordinate occurs at the point where embankment ends and excavation starts.

**c)** Cut and fill quantities between the points at which any horizontal line cuts off a loop of the mass curve will exactly balance. Such horizontal lines are called balance lines and the points at which these lines intersect the mass curve are called balance points.

**d)** Areas below the balance line indicate that hauling of excavation to embankment is from right to left, whereas areas above the balance line indicate that the haul is from left to right.
e) The area between a balance line and its corresponding loop of the mass curve is a measure of haul (product of the volume and distance in station-meters).

f) The ordinate at any station represents the accumulated amount of surplus or deficit of material at the station. It does not indicate the amount of cut or fill volume at that station.

![Diagram of Mass Haul Diagram](image)

**Figure 11-1: Relationship of Profile Grade and Haul to Mass Haul Diagram**

### 11.5 Balancing Earthwork Using the Mass Haul Diagram

The designer should carefully assess the project before start of design and set certain guidelines for balancing the earthwork. A determination should be made as to the maximum haul distance or distance between balance points, whether tight balances will be used or whether it will be more economical to excavate to spoil in some areas and obtain borrow material in others.

Listed below are a few considerations in determining the best earthwork design:

a) Right-of-way restrictions may necessitate importing borrow material for the required embankments.

b) Where large quantities of inferior or deleterious material are encountered in the excavation, it will be necessary to waste this material, which is unsuitable for use as embankment.
c) Special conditions through deep cuts, such as sloughing, sight distance requirements, or sand drift conditions may require very flat back slopes resulting in large amounts of excavation and no large embankments within a reasonable haul distance. This situation will require that some excavated material will be wasted.

d) The need to carry the road level considerably above the existing ground for extended distances through flood plain areas will generally require borrow excavation.

After the designer has analyzed all of the above factors and determined how he proposes to balance the earthwork, he is ready to start calculations as previously outlined.

In order to obtain a better perspective of the work the project should be broken down to sections not to exceed 5 kilometers in length. This allows the designer to work with smaller sections, solving the individual problems of each section involving drainage, grades, erosion control, and earthwork distribution. Figure 11-2 shows three situations where the balance line can be at the top, bottom or at the center of the mass curve. Note that Case 3 where the balance line is located at the center of the mass curve is not necessarily the ideal situation in all cases. The profile grade should be studied along with the mass haul diagram to determine where it will be more economical to haul towards back stations (Case 1), towards forward stations (Case 2), or to haul equally towards back and forward stations (Case 3).

Free haul is defined as the maximum distance through which excavated material may be transported without added cost above the unit bid price. Prior to the use of high-speed pneumatic-tired earth moving equipment, free haul distances were limited to approx. 1000 meters, but distances of up to 2000 meters are not uncommon now. Special conditions on a project may require longer hauls, where restrictions do not allow excavation or borrow in the immediate area. Some ERA contracts do not provide for separate payment for haul and/or overhaul, but make this work incidental to the excavation item. Haul and overhaul figures shall be made available to prospective bidders to assist them in determining their excavation bid price. A note on the mass haul diagram, in the plans, or in the specifications shall state that the contractor may be required to haul material a specified distance, or within balance points shown on the plans, without additional compensation.

The economical limit of haul is defined as the distance through which it is more economical to haul excavated material than to waste and borrow. The following formula is presented as a guide to assist the designer in determining the economic limit of haul:

\[
E.L.H. = F.H. \text{ distance} + \frac{\text{Unit Price of Borrow}}{\text{Unit Price of Overhaul}}
\]

Where:

- \(E.L.H\) = Economic limit of haul
- \(F.H.\) = Free haul distance
Figure 11-2: Location of Balance Line on Mass Haul Diagram

CASE 1: Excavation is hauled mostly to the left or towards back stations. This is recommended for steep grades uphill to produce haul in a downhill direction.

CASE 2: Excavation is hauled mostly to the right or towards forward stations. This is not recommended for steep grades uphill but can be used on downhill grades providing balance distances are not too long.

CASE 3: Excavation is hauled equally to left and right. This is optimum situation for most road construction where grades do not exceed 5%. 

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Example: Assume F.H. Distance = 15 stations (1500 meters)

Borrow U.P. = ETB 8.00/m³
Overhaul U.P.= ETB 5.00/100/meter/m³

\[E.L.H = 15 + \frac{8}{5}\]

\[E.L.H = 15 + 16 = 31\] stations

The designer can make some quick estimates to determine whether to use long haul distances, to borrow or waste, or whether a redesign to shorten balance distances is required.

Overhaul is the product of volume times distance and is represented on the mass haul diagram as the area between the zero balance line and the curve of the mass after eliminating all free haul. When the mass is computed using adjusted cut (adjusted for swell), it is necessary to correct overhaul volume to unadjusted excavation by applying the proper correction factor.

In Figure 11-3 the shaded areas show overhaul in the mass haul diagram.

Waste and borrow should be avoided on most types of projects by hauling suitable material within economical limits of haul. These terms are defined as follows:

a) Waste is material excavated from roadway cuts but not required for making the embankments. It must be pointed out that this material is not necessarily wasted as the word implies, but can be used in widening embankments, flattening slopes or filling ditches or depressions for erosion control.

b) Borrow is material not obtained from roadway excavation but secured by widening cuts, flattening cut back slopes, excavating from sources adjacent to the road within the right-of-way, or from selected borrow pits as may be noted on the plans. Borrow areas should be carefully selected after consideration of the suitability of the material; economic haul; access to the pits, including cost of access roads; drainage problems; and impact on the environment including timber production, fish life, watershed, soil erosion and all multiple land uses present and future.
11.6 Methods of Balancing Earthwork

As stated in the previous discussion, after the mass haul diagram is plotted using the trial profile grade, a determination is made whether to borrow, waste, or adjust the grade to achieve tight balances.

The following three examples with accompanying mass haul diagrams illustrate different methods of balancing earthwork:

a) The first example, Figure 11-4, assumes that grades have been adjusted as much as the terrain will permit and the required balances have not been obtained, therefore, it will be necessary to borrow and waste to balance the earthwork.
The mass haul diagram shows that the balance line is dropped 10,000 cubic meters at the beginning of the job due to excess embankment requiring 10,000 cubic meters of borrow between stations 0+00 and 3+50. This will result in new balance points at stations 3+50, 11+00, 20+50 and 27+00.

Due to excess of excavation ahead of station 27+00, the balance line is adjusted upwards 23,000 cubic meters with balance points at 32+50, 41+00 and 50+00. Excess excavation between stations 27+00 and 32+50 must be wasted.

![Figure 11-4: Balancing Earthwork Using Borrow and Waste Determined from the Mass Haul Diagram](image)

b) The next example, Figure 11-5, considers the mass haul diagram after the trial grade results in excess excavation from station 0+00 to 72+50.

Project designed using computer programs can be easily balanced by for instance lowering vertical P.I.'s to remove excess embankment and raising vertical P.I.'s to remove excess excavation. Using the earthwork design computer program, the designer is furnished with a complete plot of the mass haul diagram, including stationing, unadjusted volume of embankment, adjusted mass ordinate and location of all balance points. The mass plot is followed by a listing, which tabulates vertical P.I. data, including stations, P.I. elevations, percent grades, middle ordinates and curve lengths.

The last column on this listing is shown as UNIT MASS and will tabulate three or four digit figures opposite each P.I. station. These figures indicate the approximate change in the mass ordinate up or down effected by raising or lowering that V.P.I. by some amount, such as 0.3 meters.

*Note in the example that Unit Mass figures of 4290, 8570, 5420, 4910 and 6410 are tabulated for V.P.I.'s at stations 8+00, 27+50, 41+00, 53+00 and 65+00 respectively.*
The designer superimposes a desired zero mass line on the diagram and scales the difference in mass ordinates between the existing and desired zero mass line at each V.P.I (tabulated as 5000, 18,000, 18,000, 23,000, 27,500 and 30,000).

Next the designer calculates the difference in mass ordinates between succeeding V.P.I's (tabulated as 5000, 13,000, 0, 5000, 4500 and 2500) as shown in Figure 11-5. Note that the desired mass ordinate change between stations 0+00 and 8+00 is 5000 cubic meters and that the unit mass at station 8+00 is 4290 cubic meters which results in an elevation change of 5000/4290 = +1.17 meters. Likewise, the P.I. elevation at station 27+50 must be raised 1.52 meters (13,000/8570). Since there is no required change in mass ordinate between station 27+50 and 41+00, no elevation change is required at station 41+00. The P.I. elevation at station 53+00 must be raised +1.02 meters (5000/4910). Note that since the last P.I. at station 72+50 will not be adjusted, the ordinate differences of 4500 and 2500 must be added and divided by the unit mass at station 65+00 (6410), resulting in an elevation change of +1.09 meters for the P.I. at station 65+00.

It must be pointed out that the unit mass figure is calculated by the computer program assuming that the roadway template is moved up or down uniformly and the results are not reliable if large elevation changes are made which result in changes in fill slopes or cut slopes. The above procedure is an approximation but will prove quite valuable in achieving the desired zero mass line in successive trial balances.

Figure 11-5: Computations of V.P.I. Elevation Changes Using Unit Mass Data
(Excess Excavation- Raise V.P.I. Elevations)
c) The third example, Figure 11-6, is very similar to the one described in paragraph B, except that the mass haul diagram starts with excess embankment and then goes into excess excavation. This will require the lowering of some V.P.I.’s and raising of others. The procedure followed in achieving the desired zero-mass line is the same as described in b. above using unit mass, ordinate for zero mass line, difference in ordinates, and elevation changes. Note the V.P.I's at stations 14+25 and 44+00 are labeled "Hold", meaning that the elevations of these V.P.I.'s will not be altered.

The mass difference used in determining the elevation change at station 22+50 must be increased by 500 since the V.P.I. at station 10+00 shows a hold. Similarly, the mass difference at station 52+00 is 7000 (4000+3000) since the V.P.I. at station 44+00 shows a hold.

Experience has shown that balancing earthworks using the unit mass figures furnished by computer listings are quite reliable and a very useful tool in balancing earthwork. Designers are encouraged to use this method.
Figure 11-6: Computation of V.P.I. Elevation Changes Using R.D.S. Unit Mass Data (Excess Embankment and Excavation- Raise V.P.I. Elevations)