COST BENEFIT APPROACH TO PIT SLOPE DESIGN

by

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ABSTRACT

Cost benefit analysis is one of the areas evaluated when using a probabilistic approach to pit slope design. Costs of instability are compared to benefits gained from reduced stripping as pit slopes are steepened. Failure costs usually consist of cleanup, haulroad repairs, facility repairs, lost production, and value of lost ore. Cost of lost production has the greatest immediate economic impact when a haulroad failure affects ore availability. Costs and benefits are compared on an incremental basis. Generally, incremental costs increase and benefits decrease as slopes are steepened. The optimum slope angle is that angle where the incremental cost is equal to the incremental benefit. This economic optimum angle would not apply if it is greater than the angle required to provide minimum catch bench widths for safe operating conditions. The main reason for using this pit design approach is, ultimately, maximization of profits, not the construction of an excavation with permanently stable slopes.

INTRODUCTION

This discussion reviews, in very general terms, the cost benefit approach to pit slope design. One of the primary objectives in open pit mine planning is the optimizatin of pit slope angles. In the past, selection of an ultimate pit slope was sometimes a very arbitrary decision. Although geology and structure were considered, it was accepted practice to design pits with the same average angle for the entire pit. As additional geologic data, operating experience, and computerized mine planning techniques were developed, the designs were revised to take into account a multitude of factors, including those related to slope stability. The cost benefit approach takes advantage of probabilistic analysis to assist the mine planner in optimizing pit design.

Cost-Benefit Model

Cost benefit analysis is a probabilistic approach using geotechnical and engineering principles to determine economic optimum pit slope angles. By presenting the results of stability analysis in terms of expected failure volumes and expected number of failures, the failure costs for various slope angles can be compared to the benefits gained primarily from reduced stripping as slope angles are steepened. Cost benefit analysis compares incremental benefits with incremental costs, in terms of dollars per degree, as slope angles are increased. Generally, incremental costs increase and benefits decrease as slopes are steepened, as shown in Figure 1. The economic optimum slope angle is that angle where the incremental cost is equal to the incremental benefit.

Curves, such as those in Figure 1, are developed for each design sector into which the pit has been divided (Figure 2). Sector boundaries are based primarily on wall orientation and, where possible, they will coincide with structural domain boundaries. When more than one structural domain occurs in a sector, the sector is subdivided for design purposes, as indicated by domains a and b in Figure 2.

A typical design cross-section (Figure 3) illustrates the three major components in slope design: (1) bench configuration, (2) interramp slope angle, and (3) overall slope angle. Cost benefit deals with the economic optimization of the interramp slope angles and requires a knowledge of haulroad and facility locations for estimating costs of failure.

The basic steps in a typical engineering study to evaluate slope stability and determine optimum pit slope angles are illustrated in Figure 4. The functions shown can be categorized as data collection, testing, analysis, evaluation, and design.

Typical failure modes used in the analysis are shown in Figure 5. Numerical models, which are simplified geometric representations of the actual expected failure mechanisms, are used for the probability analysis to determine expected failure volumes and expected number of failures.

Benefits

As pit slopes are steepened, benefits accrue in the form of reduced stripping and increased ore reserves. Several preliminary ultimate pit plans are usually developed to ensure that the entire range of possible slope angles are included. Two design scenarios are shown in Figure 6. The upper designs at 35°, 40°, and 45° illustrate a case with limited ore reserves where the benefits are primarily associated with reduced stripping. In this situation, the "as-is" operating pit crest has already been mined back of the 40° and 45° pit limits. The lower designs for the 40° and 45° pit limits illustrate an increase in mineable ore reserves where ore extends in depth.

Calculation of benefits is fairly straight-forward and essentially consists of gross sales, less mining and processing costs. Benefits are calculated for each domain and sector in each plan. Net benefits are calculated by difference between each plan, and this allows incremental benefits to be developed per degree of change in slope angle over a wide range of slope angles.

Costs of Failure

Failure costs are based on probabilistic analyses for each failure mode in each design sector. Expected number of slope failures and the expected failure tonnages are developed for each sector, and these are input into the cost of failure models.

The cost of a slope failure is a combination of various factors, each of which is dependent on the type and location of the failure. Failure costs include cleaning up the failure material, re-establishing access on failed ramps and roads, repair of facilities, disruptions in operations, and value of unrecoverable ore. In most cases the actual cost of failure is difficult to estimate, and assumptions made in arriving at the costs are often open to debate. The important thing to remember in evaluating failure costs is that the results are indications of relative differences for the slope angles being evaluated. The results will often provide insight into critical areas not previously recognized. Because costs are difficult to estimate, it is generally a good idea to be conservative in estimating costs.

Cleanup Costs

A cleanup cost (mining cost) is applied to the total expected failure tonnage per sector. This is true even though it may not be necessary to remove all of the failed material. Average mining costs are generally increased by about 20 percent for removing failed material to allow for reduced productivity created by adverse operating conditions in the cleanup area.

Haulroad Repair Costs

Haulroad failures, including rail and conveyor roadways, can be slides which cover the roadway and/or cause the roadway to fail (Figure 7). The greatest total economic impact occurs when a haulroad fails and backfilling results not only in lost production but in lost or buried ore. A conservative approach is to assume that all failures affecting haulroads require backfilling (Figure 8).

In Figure 8 the average failure width can vary based on the expected failure geometry. A width of H/2 was used only for illustrative purposes.

Factors which influence haulroad repair costs include:

1) sector height,
2) average failure height,
3) total sector failures,
4) sector width,
5) haulroad length,
6) backfill cost per ton
   - mined waste
   - dump waste, and
7) rail-conveyor repair cost per foot.

Failure cost calculations based on the above factors are as follows:

a) calculate number haulroad failures

$$\text{failures} = \frac{(2)}{(1)} \times (3) \times \frac{(5)}{(4)}$$

b) calculate tons backfill per failure (see Figure 8);

c) calculate cost of backfilling cost = a x b x (6); and

d) calculate rail-conveyor repair cost cost = a x (5) x (7).

If backfill material is available from normal stripping, then only any additional costs associated with diverting this material to backfill are included; however, if other material must be used, the total cost of handling this material will be included in failure costs.

Cost of Lost Production

It is assumed that lost ore production takes place whenever an ore area access ramp or an ore haulage roadway failure occurs. Production is also lost when failures result in damage to critical mine facilities. In a large pit it may be assumed that sufficient working faces are available; so ore production is not affected by other failures.

Cost of lost production is usually determined for various shutdown periods from which an average daily shutdown cost is developed. The daily shutdown cost would be determined using a format similar to the following.

Cost per Day

Sales	$ xxx
Less: Total Costs	xx
Net Income	xx
Plus: Fixed Costs	x
Total Cost per Day	$ xx

Costs would be pro-rated for partial cutbacks in production. Fixed costs are those costs which continue when an operation is not operating.

Total days of lost production for a failure is the sum of days lost for the following reasons.

1) Pre-failure road closures for safety reasons.
2) Delay between time of failure and start of repairs.
3) Cleanup and/or backfill times based on expected productivities per shift and whether these functions are scheduled only during daylight hours for safety reasons.
4) Repair time for railroad, conveyor, and other facilities.

Unrecoverable Ore

Backfilling will result in buried or unrecoverable ore when the interramp pit slope angles are greater than the angle of repose for fill material (see Figure 9). It is assumed that only backfilled failures will result in lost ore. Cost of unrecoverable ore is estimated in the following manner.

1) If failure occurs in ore, the cost is equal to the benefits attributable to the buried ore.
2) If failure occurs in waste, the cost is equal to the benefits attributable to the buried ore, less the cost of waste not mined.

Surface Facility Repairs

Failure costs include all repair costs associated with damage to structures such as crushers, conveyors, railroads, substations, concentrators, and other miscellaneous structures. This also includes costs for re-locating facilities, if required.

Engineering and Monitoring

Probabilistic analysis of slope instability is based on the premise that some slope failures will occur. Engineering and monitoring must be an on-going function to ensure that the effects of any instability are minimized; however, as areas of instability are recognized, increased engineering and monitoring costs will be incurred.

Cost of Failure Summary

Figure 10 represents a format summarizing the expected failure costs previously discussed. Each slope angle represents a final pit plan with individual and total costs. Incremental costs represent the cost per degree of change as slopes are steepened. The failure costs are compared to corresponding benefits to determine the optimum slope angles.

Cost-Benefit Comparison

An idealized set of cost-benefit curves is shown in Figure 11. From the figure, it is apparent that an increase in slope angle from 37° to 38° will result in an increase in expected failure cost of $8,000,000. The corresponding increase in benefit is $13,000,000. Thus, it is profitable to increase the slope from 37° to 38°. In contrast, increasing the slope from 44° to 45° will result in an increased failure cost of $11,000,00, but an increased benefit of only $9,000,000. Thus, it would not be profitable to increase the slope from 44° to 45°. The economic optimum slope angle would be 43°, where the two curves cross. Below the crossover point, the benefits of steepening are greater than the costs; above the crossover point the costs are greater than the benefits. The crossover point represents the optimized slope angle.

The cost-benefit approach, using probabilities of failure, provides the methodology by which the risks and costs of failures can be compared with the corresponding benefits for any design. The cost-benefit approach provides an optimized design, unlike safety factor methods where a conservative design implies that little risk, or cost, of failure is expected.

The fact that a slope is designed with some risk of failure must not be viewed as a disregard for safety concerns. Since almost any economically viable option will have some probability of failure, it is better to be aware of the level of that risk and to provide sufficient, suitable monitoring so that instability can be detected at an early, noncritical stage and remedial engineering and safety measures can be taken.

Backbreak Analysis

Economic optimum interramp pit slope angles are determined by the cost-benefit analysis; however, if these angles are steeper than the interramp slope angles determined by backbreak analysis, the flatter interramp angles are used for pit design, as illustrated in Figure 12. Backbreak analysis is based on the probability that minimum catch bench widths (Figure 13) can be maintained at reliabilities not exceeding 90 percent or less than 70 percent.

The relationship of minimum and mean bench widths is shown in plan in Figure 14. The primary purpose of a catch bench in the final pit design is to stop rocks from rolling down the slope and endangering men and equipment working on lower levels.

Catch bench design is based on work done for design of highway cuts. Double benching is generally recommended for final pit slopes because the double bench interramp angles, based on backbreak analysis, are usually several degrees steeper than single bench angles for the same degree of reliability for maintaining minimum catch bench widths.

Conclusions

A primary advantage of this optimized pit design approach in a mature pit is the possibility of an almost immediate decrease in waste mining. The nearer a pit approaches its final limit, the more critical is the timing in making a decision regarding pit design optimization. It is also possible that a pit, or areas within a pit, are already mined beyond what are considered to be optimum pit slopes as determined by cost-benefit and backbreak analysis. In addition, current mine plans might also call for mining beyond the area noted as being already mined beyond an optimized pit limit.

Cost-benefit analysis is applicable not only for presently operating pits but also in the evaluation and design of proposed pits.

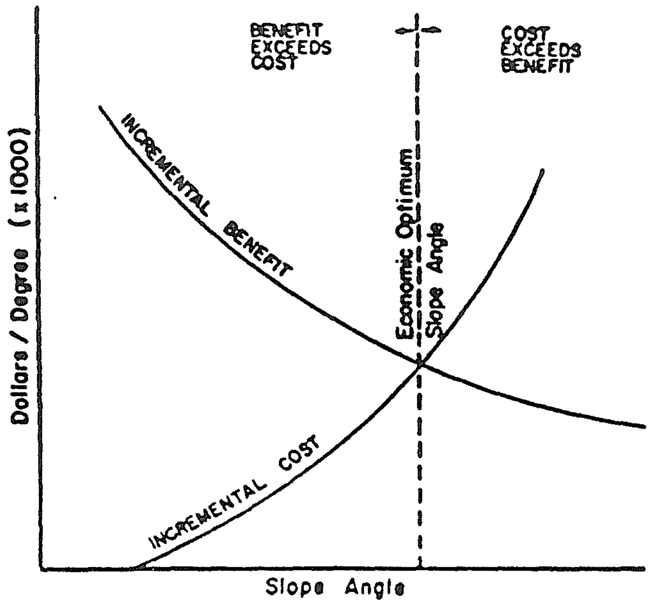


Figure 1: Cost-Benefit Curves.

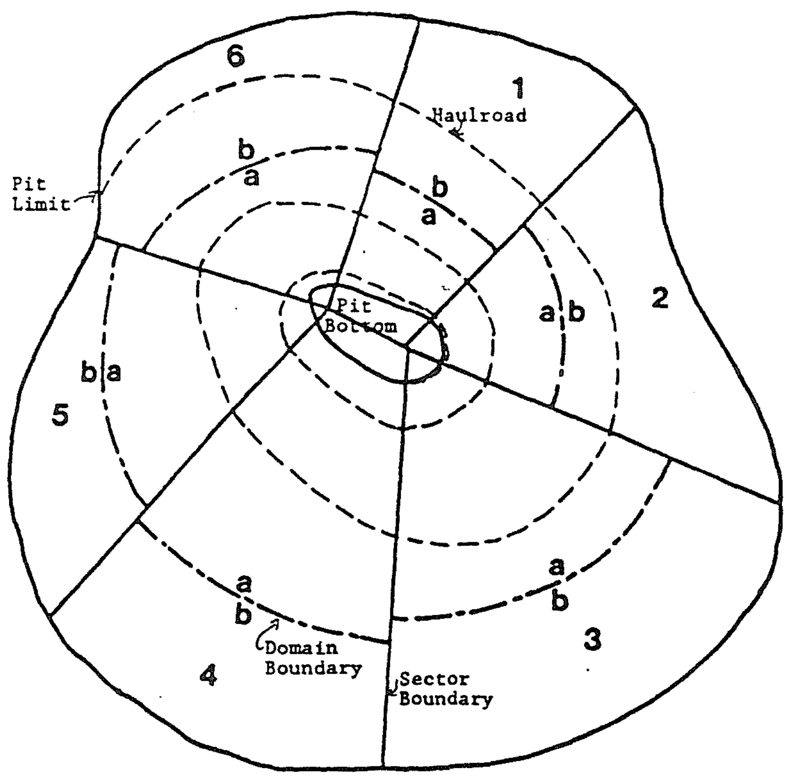


Figure 2: Final Pit Plan.

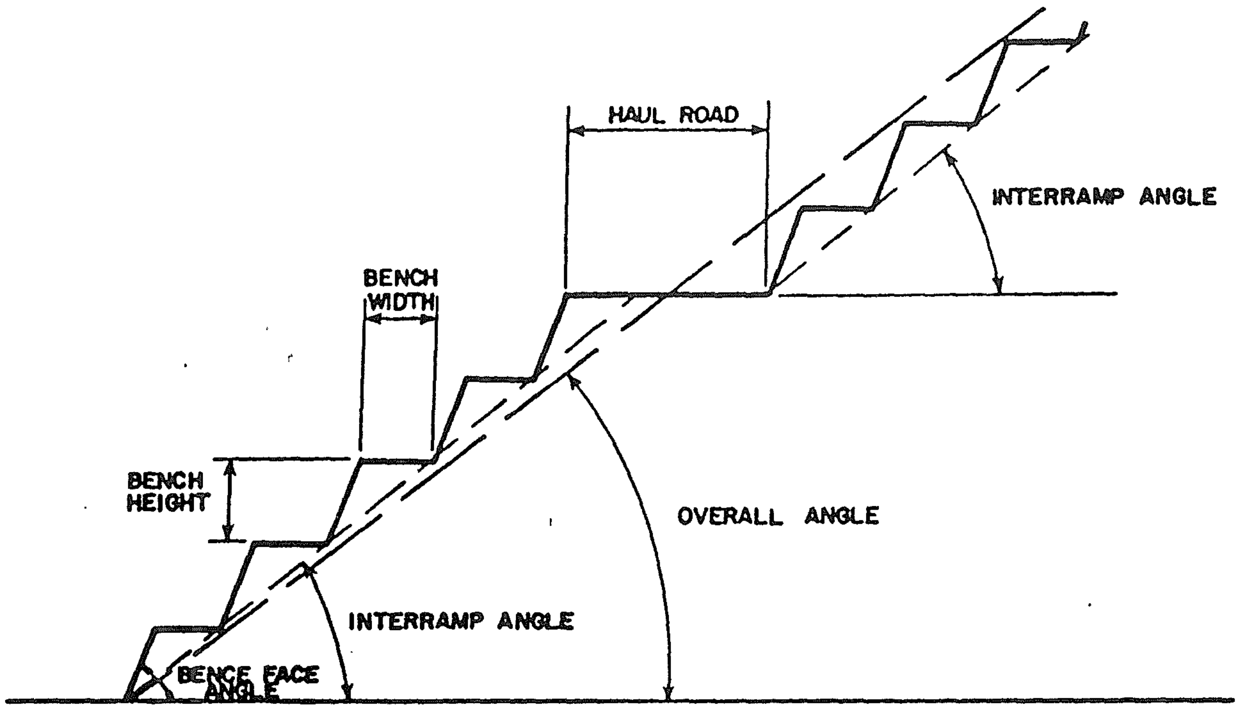


Figure 3: Typical Design Cross-Section.

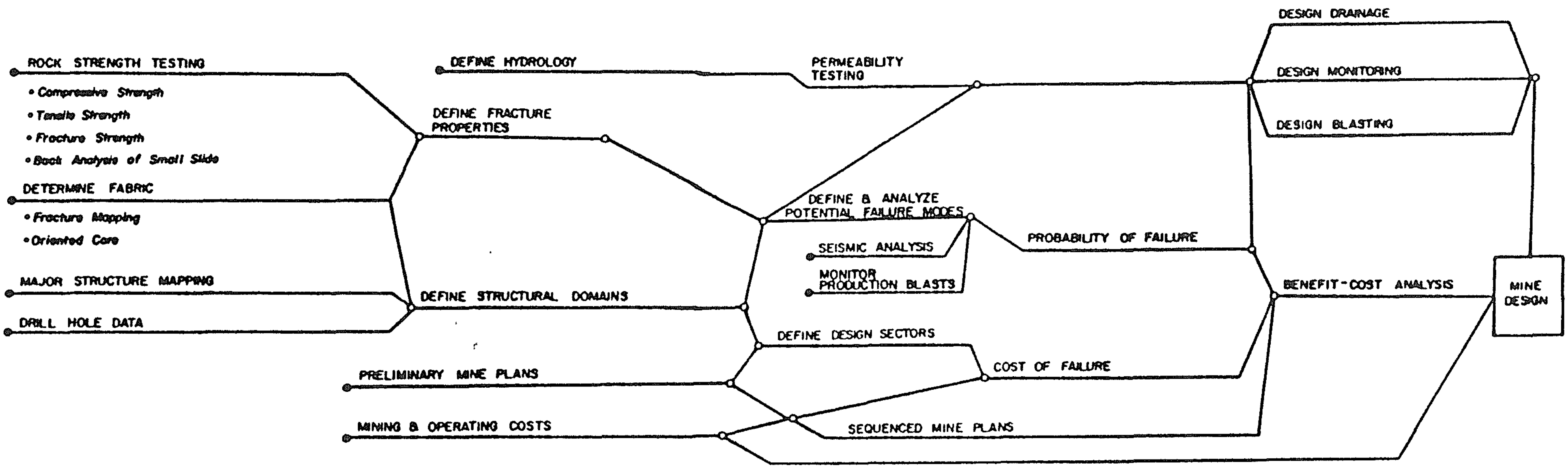


Figure 4: Slope Optimization Planning Schedule.

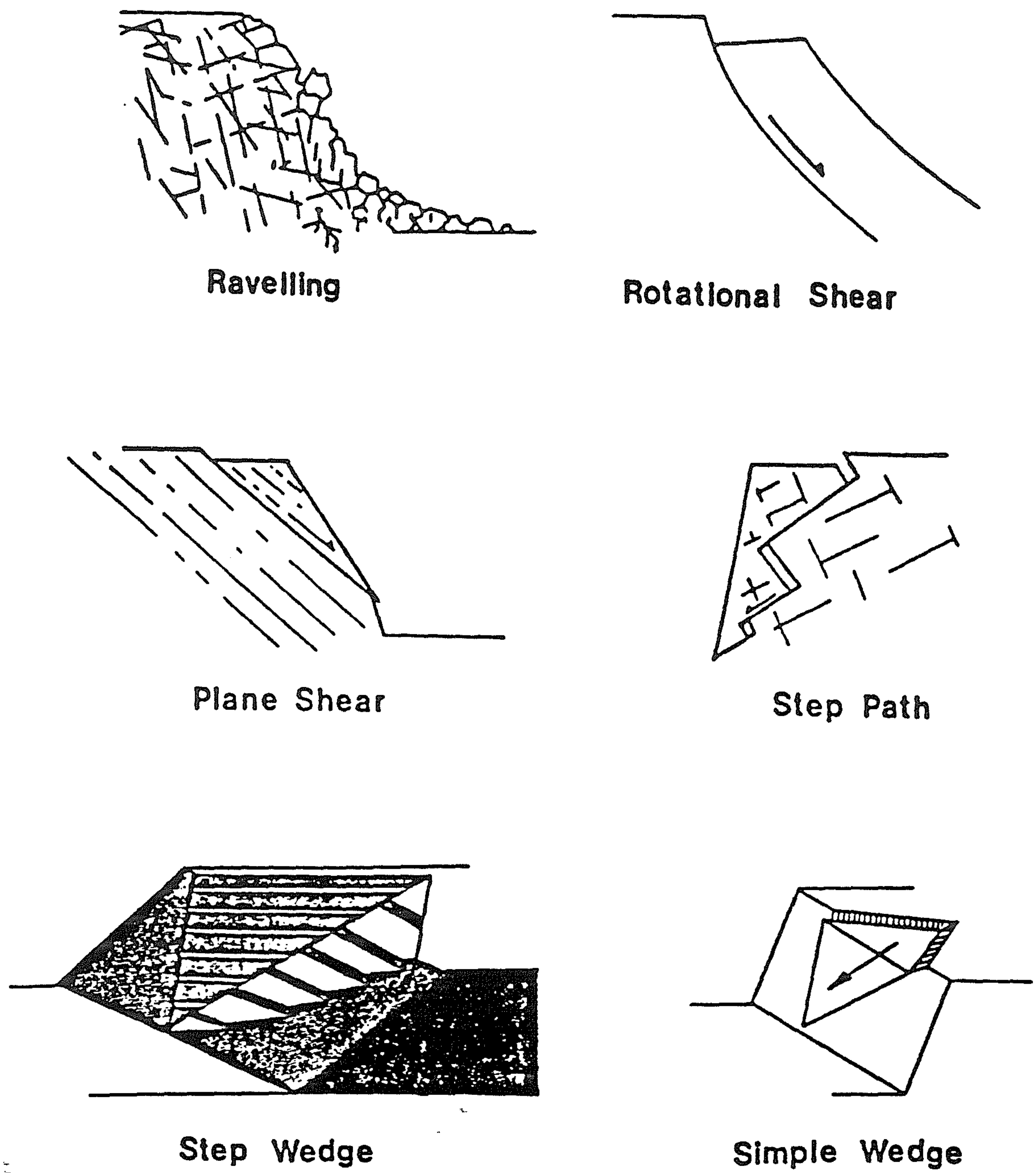


Figure 5: Typical Failure Modes.

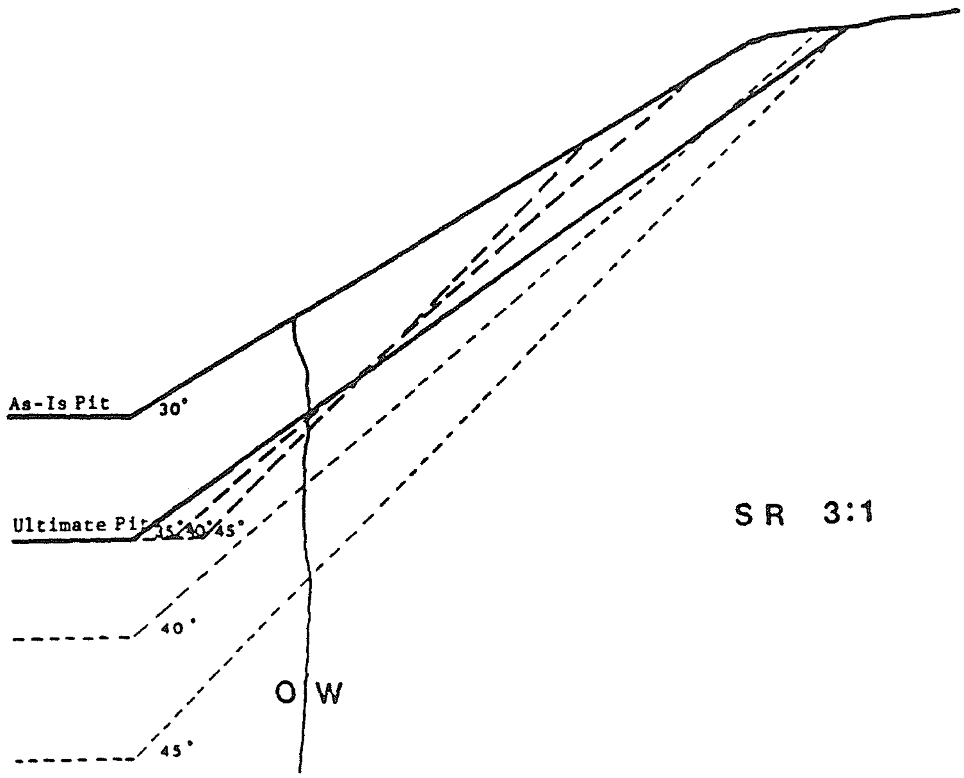


Figure 6: Alternative Pit Designs.

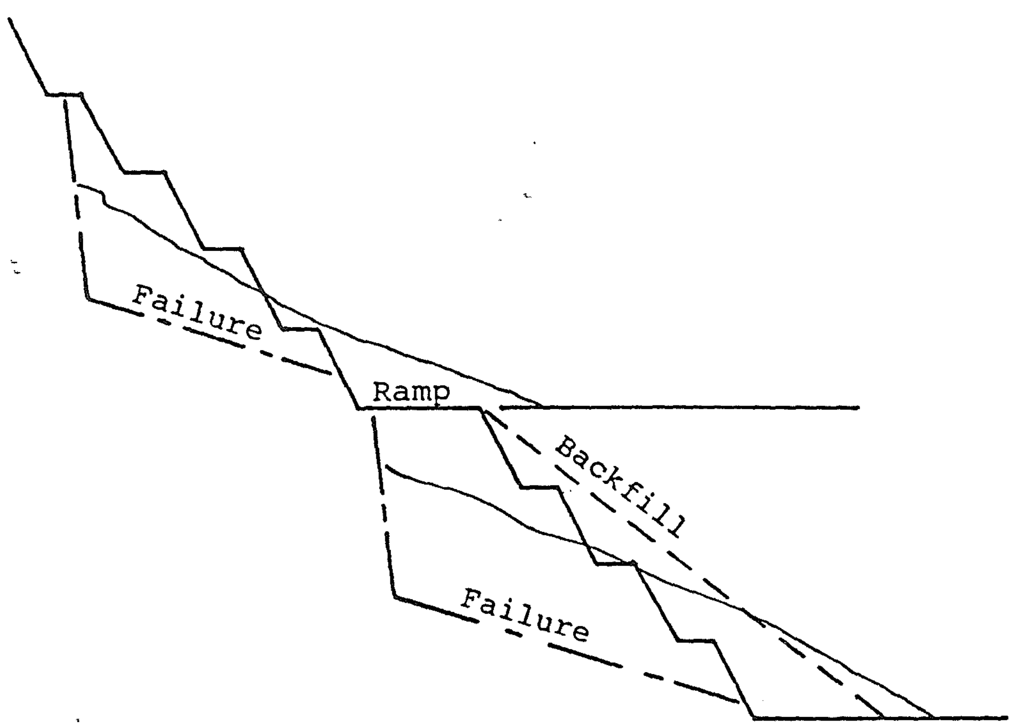
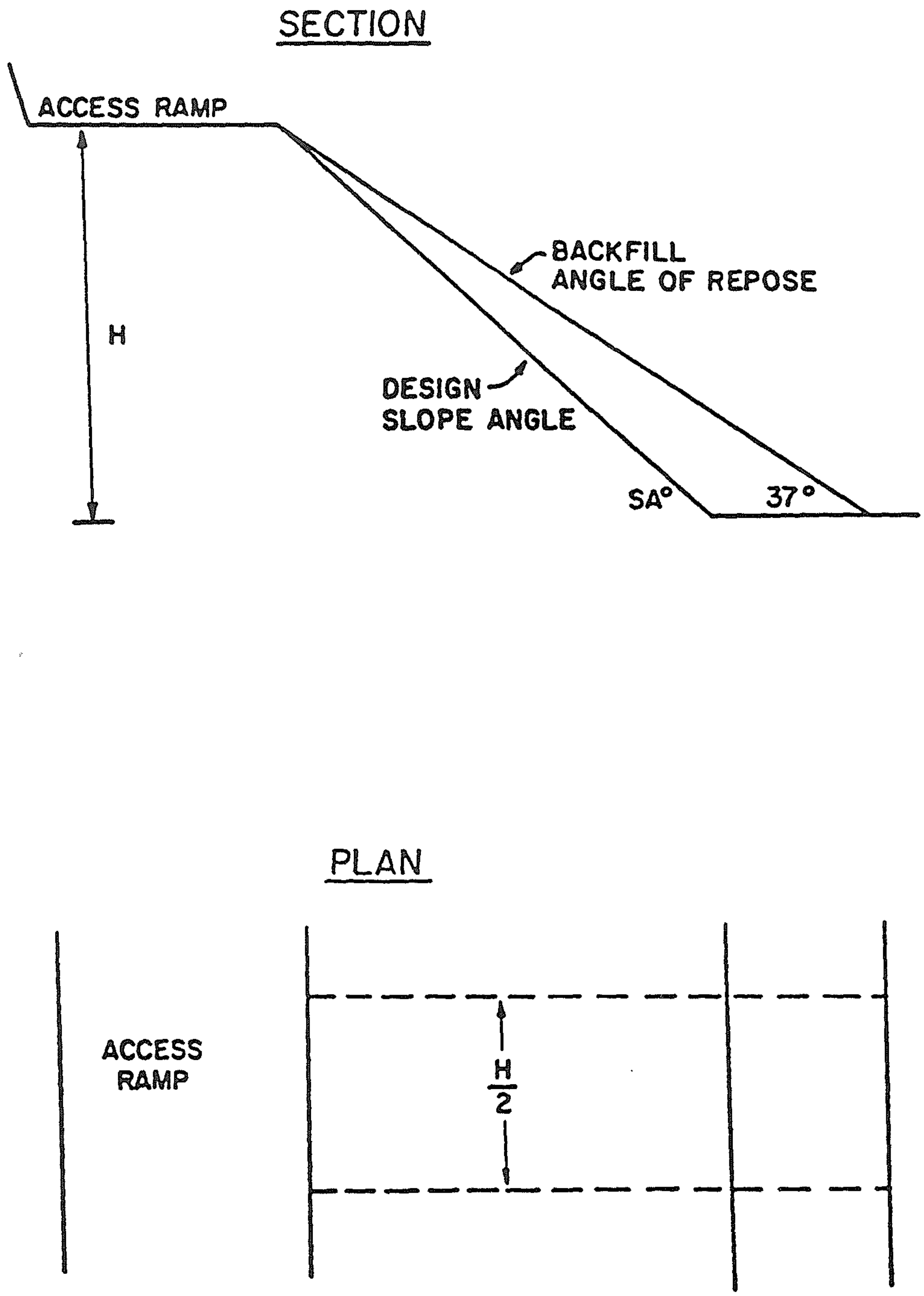


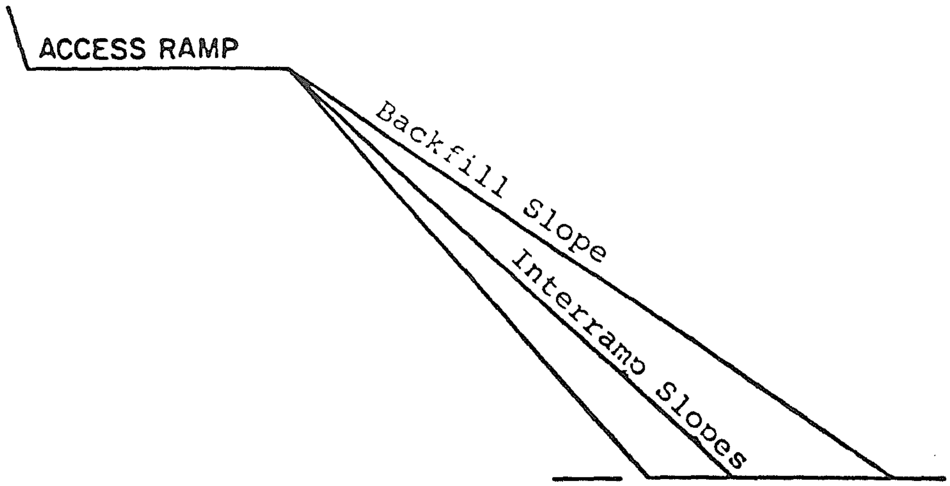
Figure 7: Haulroad Failure Modes.



$$\text{BACKFILL TONS} = D\,H^3\left(\frac{1}{\text{TAN } 37} - \frac{1}{\text{TAN SA}}\right)$$

Figure 8: Backfill Design.

NOTE: D.is function of failure width and fill density.



Backfill Slope Design.

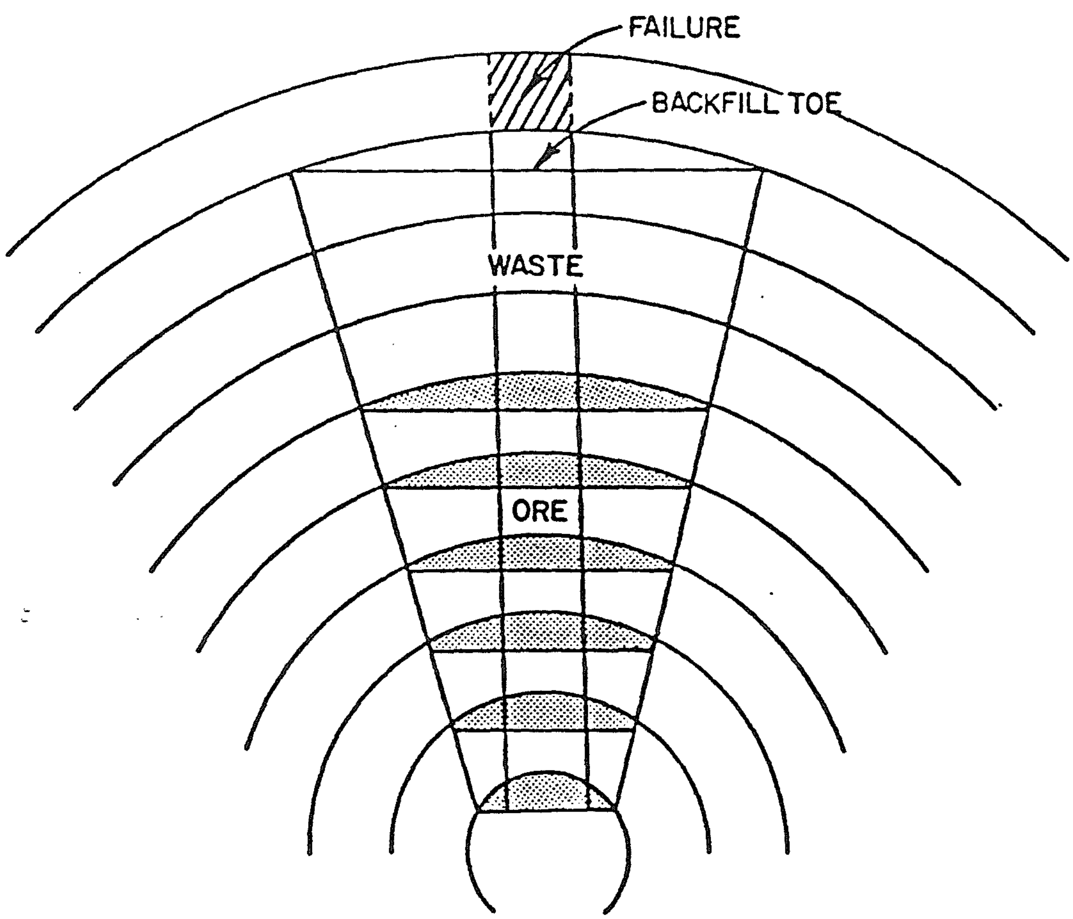


Figure 9: Ore Lost in Backfilling.

SECTOR

COST OF FAILURE

SLOPE ANGLE	CLEANUP	HAULROAD REPAIRS	SURFACE FACILITIES REPAIRS	LOST PRODUCTION	UNRECOVERABLE ORE	ENGINEERING & MONITORING	TOTAL COSTS	INCREMENTAL COST/DEGREE
36	X	X	X	X	X	X	X	
								X
40	X	X	X	X	X	X	X	
								X
44	X	X	X	X	X	X	X	
								X
48	X	X	X	X	X	X	X	
								X
52	X	X	X	X	X	X	X	
								X
56	X	X	X	X	X	X	X	

Figure 10: Failure Cost Summary.

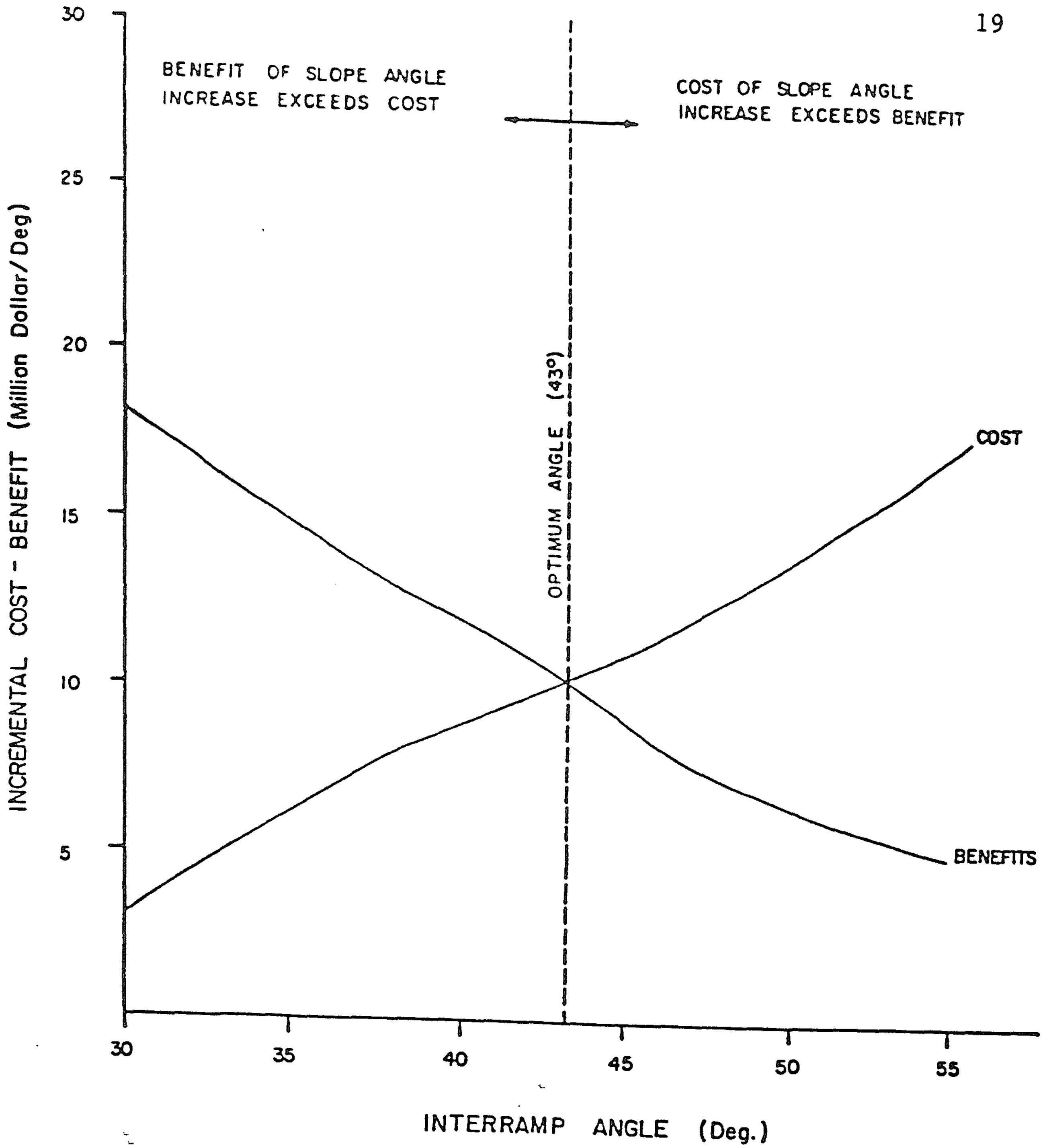


Figure 11: Idealized Incremental Cost-Benefit Curves Showing the Economic Optimum Interramp Angle.

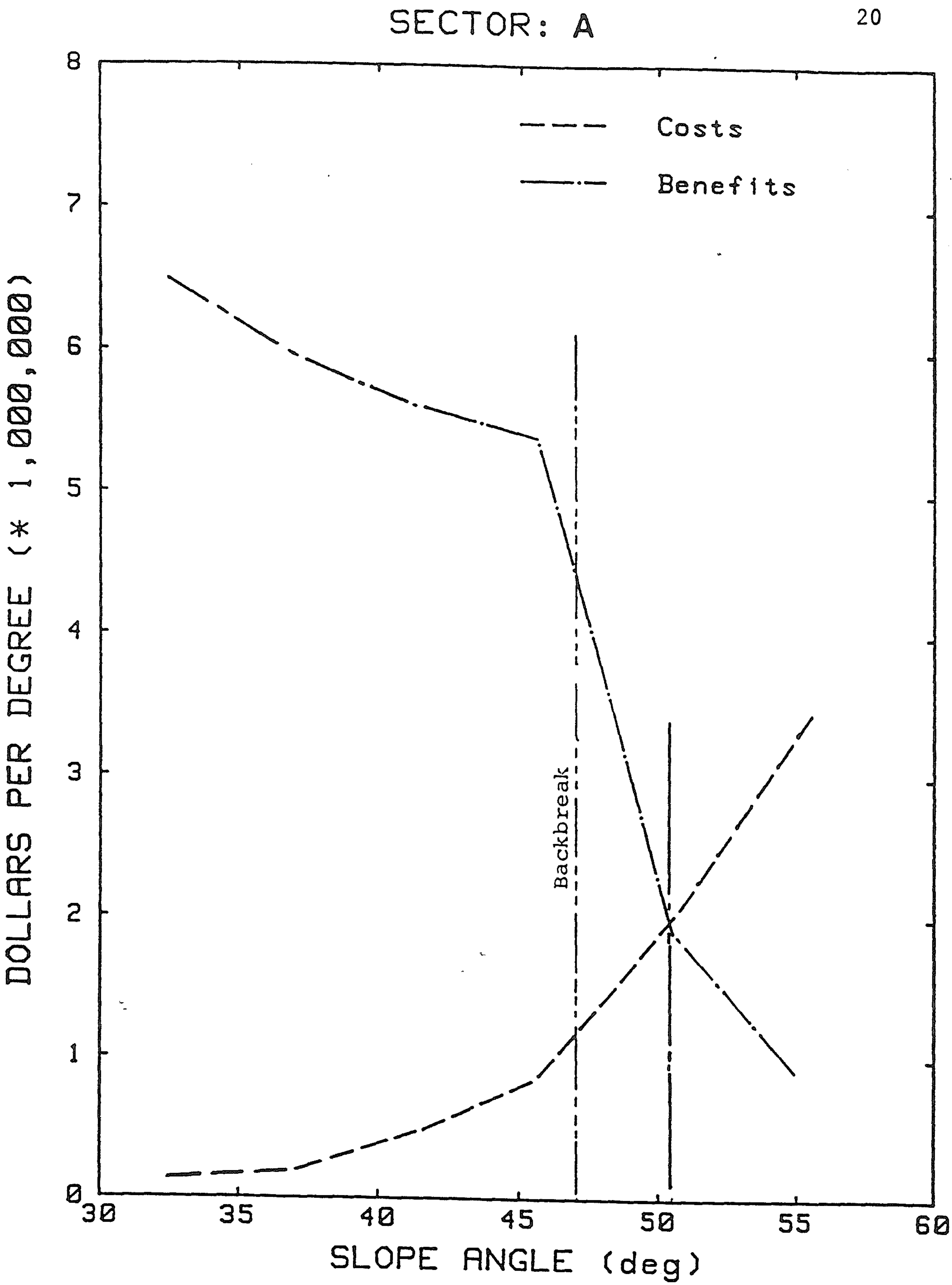
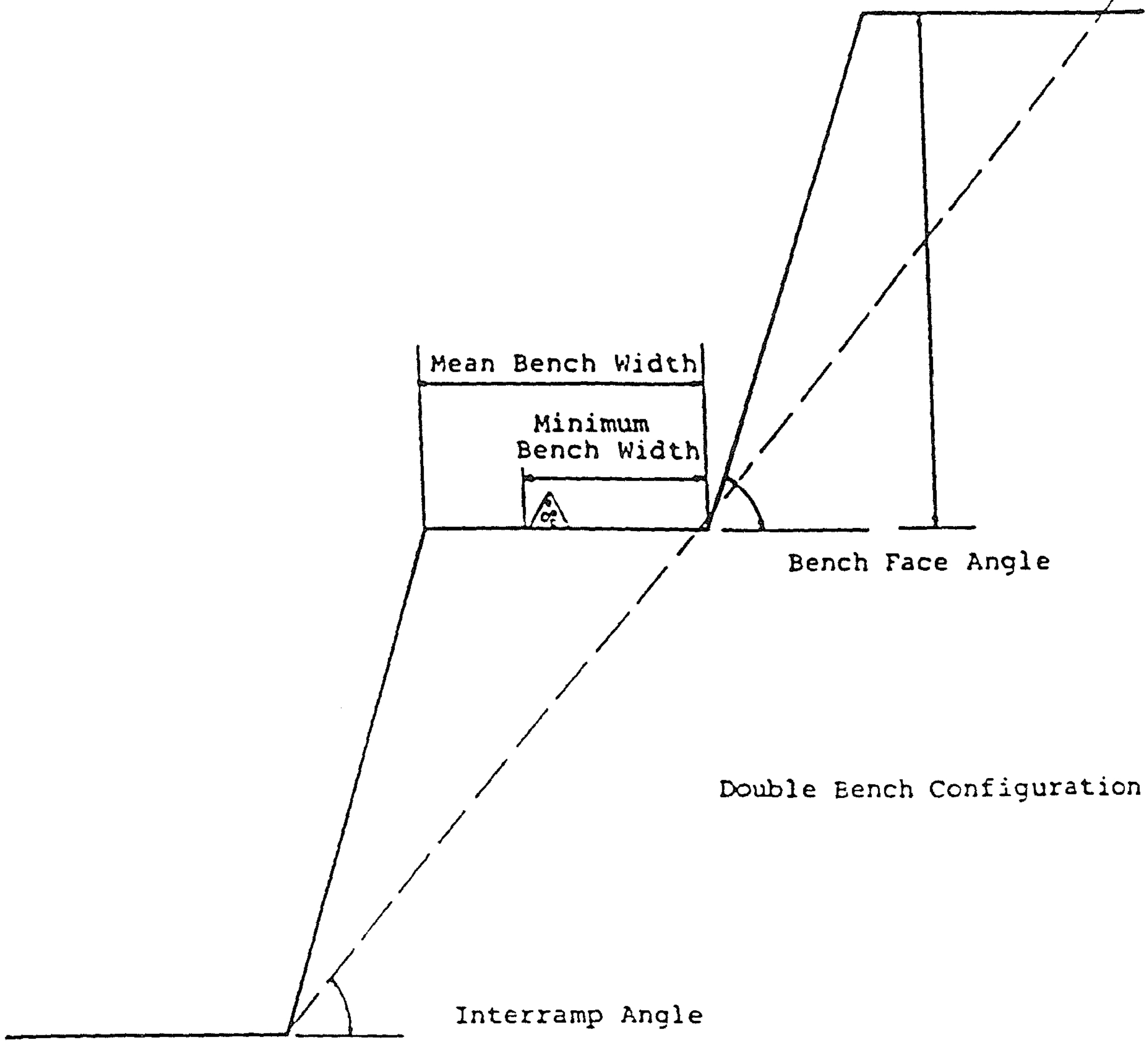


Figure 12: Cost Benefit with Backbreak.



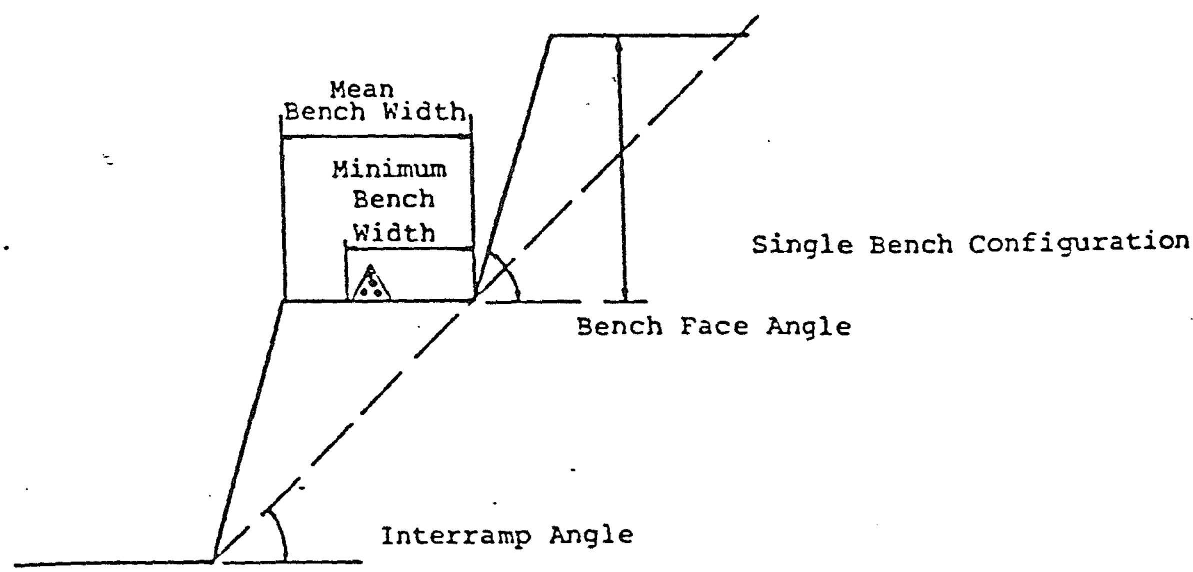


Figure 13: Catch Bench Configuration.

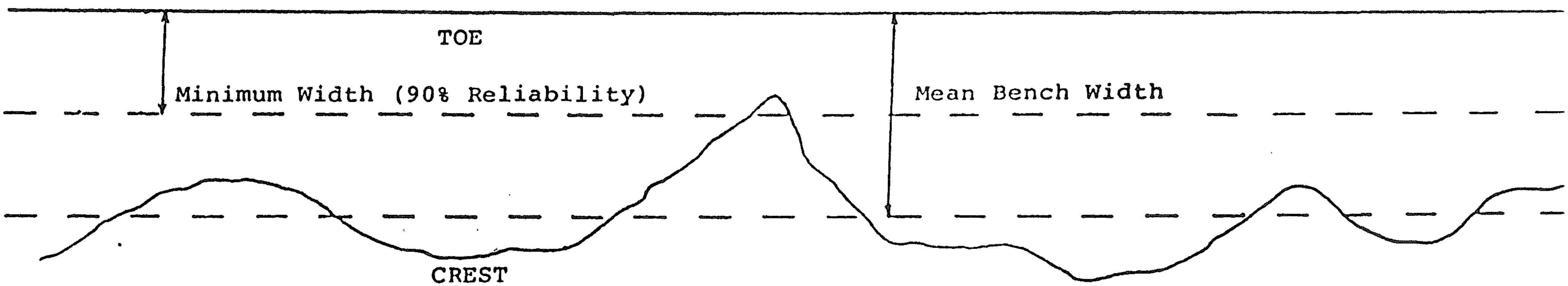


Figure 14: Plan View of Bench Width Criteria.