THE OBSERVATIONAL APPROACH APPLIED TO OPEN PIT MINE SLOPES[1]

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Abstract: Mined land reclamation permits for open pit mines and quarries often require detailed mine plans showing mine development, phasing, areas of disturbance, and reclamation activities at each stage of development. Slope angles and bench/highwall configurations are critical to the mine plan both for reclamation and for mine economics. However, detailed evaluation of slope stability prior to excavation requires an extensive exploration and testing program followed by detailed engineering analyses which can be both time consuming and expensive to the mine owner. Furthermore, basing slope configurations entirely on predictions requires a relatively high degree of conservatism in the design.

An alternative approach is to base slope design on the performance of existing slopes combined with engineering models to extrapolate the observed behavior - the "Observational Approach". A key factor in applying the observational approach is the development of different mine reclamation plans for the range of alternative slope configurations. During the process, regulatory authorities need to be satisfied that a rational approach is used to progressively open the mine without overdevelopment which could potentially compromise reclamation activities.

This paper describes the observational approach to mine development and reclamation, and presents a discussion of how the method can be implemented with the use of specific controls to satisfy regulatory requirements. An example project is presented for an open pit aggregate quarry in the foothills of the Rocky Mountains near Denver, Colorado. Details of application of the observational approach to the project are presented including alternative mine configurations, reclamation measures, and regulatory agreements.

Introduction

The growth of society increases demand for raw materials from mines. However, a dilemma is created because this growth also results in greater restrictions on mine operations and higher levels of reclamation for environmental preservation. It is in the interest of both the general public and mine owners to operate mines economically while maintaining high environmental standards. Although often overlooked, high mine operational costs are ultimately borne by the general public in higher product costs, and lost job opportunities.

Mining is actually a partnership between mine owners and the general public. The public is represented primarily by officials of federal, state, and local agencies which administer laws and regulations that govern mining and reclamation. Citizen groups and nearby residents can also play a significant roll in representing public interests. With this partnership, the goal is to economically operate mines to provide resources for public and private infrastructure while maintaining other public interests - primarily environmental preservation and reclamation. In an effort to build a solid relationship, it is of vital importance to ensure adequate highwall stability which will support the successful development of the applied reclamation plan. To follow is an example of how this partnership was achieved for quarry reclamation as it relates to slope stability for an open pit hard rock aggregate quarry near a large metropolitan area.

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[1]Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5-8, 1995.

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Proceedings America Society of Mining and Reclamation, 1995 pp 617-624

DOI: 10.21000/JASMR95010617

https://doi.org/10.21000/JASMR95010617

Reclamation Measures and Regulations

Regulations under which mines operate focus on upholding public interests in the environmental protection of the air, water, and land. Completing mined land reclamation after mining is a key provision of these regulations. In general, these regulations specify not only what reclamation must be accomplished, but also bonding requirements to ensure the reclamation is completed.

Reclamation of slopes in open pit mines and quarries is focused on enabling later non-mining beneficial uses of the land. For many open pit mines the beneficial use requires providing a stable habitat for local species with establishment of soil and vegetative cover on benches. Other requirements can include drainage control, reduction of visual impacts, and removal of safety concerns.

Mine plans must be generated which show the final buildout of the mine including bench and highwall configurations, and proposed reclamation measures. Implementation of these measures is dependent on the stability of slopes and on the final configuration of benches and highwalls. Mine owners are constrained to work within these requirements following regulatory approval of the mine plan.

Mine Owners Planning Constraints

Operation of mines, whether for construction materials, precious metals, or minerals involves a substantial investment by the owner. This investment includes the direct expenses for equipment, unrecovered operational expenses to access the saleable product, and the expense of obtaining permits and zoning approvals. Within the costs of permits are the direct labor, engineering, and other fees associated with securing the permits, as well as the cost of associated bonding, especially for reclamation.

A key consideration of reclamation is the final buildout configuration of the mine including mine slopes, and bench and highwall sizes and locations. Design of open pit quarries is a balance between removing as much product as possible which requires steep slopes, while maintaining slope stability which is generally better with lower angle slopes. The stability of rock slopes can be determined using any one of several stability models and data on rock mass properties. These models have been shown to accurately calculate the stability of the slopes in different conditions based on rock mass properties. However, the accuracy of the models, and therefore knowledge of the stable slope angle, is limited by the accuracy of the rock mass properties input into the models. In practice, limited data for these properties are available during initial design and mine development. More is continually learned as the life of the mine progresses and rock exposures are revealed.

Although core holes and laboratory tests on intact specimens and on discontinuities can be used as a basis for evaluating rock mass properties, these methods are only approximate, resulting in a high degree of uncertainty. These problems result from variability of the rock mass, scale effects in extrapolating from exploratory borings to the rock mass, and the impracticality of performing large scale field tests. As a result, determination of final buildout configurations early during mine planning is often difficult, expensive, and unreliable.

It is significantly more accurate and economical to determine slope configurations concurrent with mine development through direct observations of rock mass properties and behavior. Large rock exposures are revealed with the opening of a mine, allowing for observation of a large portion of the rock mass thus eliminating scale effects. Also, data on behavior of the rock mass early during mine development can be used as the basis of models to predict the behavior at later stages of development. In other words, the early stages of mining can be used as full scale tests. For these reasons it can be highly beneficial to mine owners to modify mine slopes and bench and highwall configurations concurrent with mining.

Practical Approach

There is often an impasse between regulatory requirements for reclamation, which require detailed mine planning of slopes and reclamation, and constraints on owners relative on the practicality of accurately determining stable slopes prior to mine development. However, a method can be employed whereby regulatory authorities can be assured that the final configuration and reclamation will be acceptable even though some design details remain unknown at the time of permitting. A rational approach is agreed upon whereby they are assured the opportunity to review and approve future design refinements. This can be implemented through conditional permit approval stipulating that geotechnical data be collected and evaluated, and that this together with design modifications be submitted for review annually.

The observational approach is an ideally suited vehicle for fulfilling the needs of both mine owners and regulatory authorities relative to mine configurations, slope stability, and reclamation of slopes. Following is a description of the observational approach with specific application to mine slopes, including a case example from a hard rock aggregate quarry.

The Observational Approach

Development and Definition

The observational approach was popularized by geotechnical engineers as a practical method of design and construction in dealing with facilities constructed in unpredictable subsurface conditions. In general the method is applicable where conditions upon which design must be based are not fully known, or where it is impractical to obtain sufficient design information prior to the beginning of construction. It is also a rational approach to deal with unanticipated conditions during construction. Dr. Ralph Peck is attributed with popularizing the method. According to Dr. Peck (Peck, 1969), the method embodies the following steps:

1. Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
2. Assessment of the most probable conditions and the most unfavorable conceivable deviations from these general conditions. Geology often plays a major role in this assessment.
3. Establishment of the design based on a working hypothesis of behavior anticipated under the most probable conditions.
4. Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
5. Calculation of values of the same quantities under the most unfavorable conditions compatible with the available data concerning the subsurface conditions.
6. Selection in advance of a course of action or modification of design for foreseeable significant deviations of the observational findings from those predicted on the basis of the working hypothesis.
7. Measurement of quantities to be observed and evaluation of actual conditions.
8. Modification of design to suit actual conditions.

An iterative application of the method is often used to refine design as new data becomes available.

Application to Slopes and Reclamation

Application of the observational approach to slopes begins with evaluation of the range of anticipated rock mass properties. Using this information, engineering analyses are preformed to determine the likely range of stable slopes angles. The initial cut is made with a conservative-(less steeply dipping) slope that would be stable even in the worst case conditions anticipated. Exposing the slope allows for a more detailed evaluation of the rock mass, from which more accurate rock mass properties are derived. More accurate slope stability analyses can then be performed. Based on these refined analyses, the slope is reconfigured as appropriate.

Example Project

Cooley Gravel Company operates the Morrison Quarry, located in the foothills of the Rocky Mountains approximately twenty miles southwest of Denver, Colorado. The quarry generates sound aggregate products and related construction materials from mining and processing granitic and metamorphic bedrock. Development, expansion and reconfiguration of the quarry required a mine plan amendment showing the proposed final buildout configuration of highwalls and benches. Although previous mining has exposed large sections of rock for observation, the new mine plan required expansion in areas not yet developed and observable. In addition, some slope instability had occurred in small portions of the existing quarry. Of special concern was a slope along one eastern highwall which experienced localized slope instability. The slope instability problem caused the Colorado Division of Minerals and Geology to impose restrictions on future mine slope angles. The slope had been backfilled with overburden prior to failure and direct observation of the rock mass was thus not possible. The available data was not adequate to define stable slopes as required for a revised mine plan.

To overcome this problem the observational approach was applied. In order to fulfill regulatory requirements, a provision for an observational approach to slope stability and mine development was incorporated into the mine plan. The approach and each step of the process are an integral part of the approved mine plan and are enforceable like the final reclamation measures and bonding requirements.

Methods of Analysis

Slope stability is commonly evaluated with models which incorporate rock mass properties and predict the safety factor against failure. The key point is that the models are dependent on rock mass properties and differences in rock mass properties used in the models directly affect the results. To follow are descriptions of the models, geologic conditions, rock mass properties, and results of the analyses for the example project.

Slope stability evaluations commonly utilize either or both of two different analytical techniques based on the size of the slope relative to the scale of rock mass discontinuities and features. The stability of relatively small slopes, including isolated benches, is controlled by the orientation and character of specific discontinuities within the rock mass. Small slopes are evaluated using a kinematic model based on the stability of discrete blocks and wedges defined by discontinuities. The stability of large slopes is controlled by the properties of the rock mass. Large slopes are evaluated using a limit equilibrium model which evaluates the stability of potential slide surfaces and large scale properties of the rock mass. Large scale rock mass properties are based on the properties of the parent rock modified to account for the frequency, orientation, and character of discontinuities. Properties are determined with a combination of knowledge of the geologic setting, observation of rock exposures, field explorations and laboratory testing.

Geologic Setting

Ground conditions at the Morrison Quarry generally consist of a relatively thin veneer of overburden soils overlying Precambrian biotite gneiss, granitic gneiss, schist, migmatitic gneiss and minor pegmatite. The rock mass is generally competent and is characterized by a strong parent rock with varying degrees of weathering. Major joints are usually widely spaced, and typically occur at a frequency of greater than five feet. Multiple joint sets are present within the rock mass, some of which are prevalent throughout the quarry and others which occur only in isolated areas. Faulting is prevalent along the Colorado Front Range and several faults and/or fault systems have been mapped or are tentatively mapped within the quarry.

Rock Mass Properties

Rock mass properties are based on a combination of the strength and characteristics of intact rock material and also the character, orientation, and frequency of discontinuities within the rock mass. These discontinuities can be bedding planes, foliations, joints, shears, faults, and any other features which affect rock mass behavior. Discontinuities often occur in one or more preferred orientations and can also occur randomly. The orientation, character and frequency of discontinuities have an overriding control on behavior of the rock mass, with the strength of the parent material having less influence.

For Cooley's Morrison Quarry, rock mass properties used during preliminary evaluations were based on 4 core borings for a 25 acre area comprising the Central Quarry, laboratory strength testing of intact rock core, and geologic mapping of rock exposed in highwalls. Based on these data and evaluations, two example conditions presented below were modeled representing a conservative range of conditions anticipated. Rock mass strength envelopes were based on correlations with the Rock Mass Rating (RMR) system (Bieniawski 1979) and on historical data (Hoek & Bray 1981).

Condition A - Good Quality Rock Mass

Most of the quarry can be modeled as a good quality rock mass that is characterized as fresh to slightly weathered and moderately to widely fractured, with intact specimens having an unconfined strength of at least 15,000 psi. Joints and other discontinuities are present at recurring intervals of at least five feet and are generally clean and rough with little or no weathering.

The rock mass for these conditions was modeled with a strength envelope defined by a cohesion of 7,000 psf and a friction angle of 40 degrees.

Condition B - Moderate to Poor Quality Rock Mass

Shear zones and weathered zones were modeled as a moderate to poor quality rock mass characterized as moderately weathered and frequently jointed with intact specimens having an unconfined compressive strength of approximately 2,000 psi. Discontinuities are typically spaced at six-inch to one-foot intervals and are characterized as either clean and slightly open (<1mm) or closed with minor clay gouge or weathering product.

The rock mass for these conditions was modeled with a strength envelope defined by a cohesion of 3,000 psf and a friction angle of 30 degrees.

In either case, the effects of additional weathering of exposed highwalls and benches were considered to be negligible and no significant change in the rock mass properties is expected to occur during the life of the mine.

Limit Equilibrium Analyses and Results

Slopes in good quality rock (condition A) were modeled as 750 and 1000 ft high with an inclination as steep as 0.5H:1V. The calculated safety factors using a limit equilibrium analysis were 1.25 and 1.08 respectively. Slopes in moderate to poor quality rock (condition B) were modeled as 750 ft high with an inclination as steep as 1H:1V. The calculated safety factor was 1.28.

Results of the analyses showed that quarry slopes excavated in good quality rock, which represents the majority of conditions within the quarry, could safely have an inclination of 0.5H:1V. These slopes would typically be excavated in a configuration consisting of 40 ft wide benches and 80 ft highwalls. Slopes excavated in moderate to poor quality rock, which are the likely worst case condition, could safely have an inclination of 1H:1V, in a configuration of 80 ft benches and 80 ft highwalls.

These analyses set limits on quarry slope design. Slopes in the likely worst case condition and less than or equal to 750 ft high should be stable at an inclination of 1H:1V or flatter. Slopes steeper than 0.5H:1V or higher than 1,000 ft would not be stable unless the quality of the rock mass increases with depth.

Kinematic Analyses and Results

Kinematic analyses used to evaluate the stability of individual benches indicated that specific areas of the quarry were susceptible to isolated instabilities. With natural variation in the rock mass, and with slopes facing in all directions, the relative orientation of discontinuities and slope faces combined adversely. These conditions exist in approximately 25 percent of the quarry. Within these zones isolated blocks and wedges are likely to be unstable, especially near the outside edge of benches. However, it was determined that failure of these isolated blocks and wedges would not impair the operation nor the safety of the mine. Furthermore, these events would not adversely effect reclamation, and could be beneficial to break up the visual continuity of the benches creating a more random natural appearance.

Application

Based on the results presented previously, and on steps set fourth in the observational method, a preliminary slope inclination of 1H:1V was used since this condition was determined to be stable for the likely worst case condition. Following observation of actual conditions it is likely that the slopes in most areas could be steepened to a maximum inclination of 0.5H:1V. A logic diagram illustrating this approach is included as **Figure 1**, Observational Approach Decision Tree.

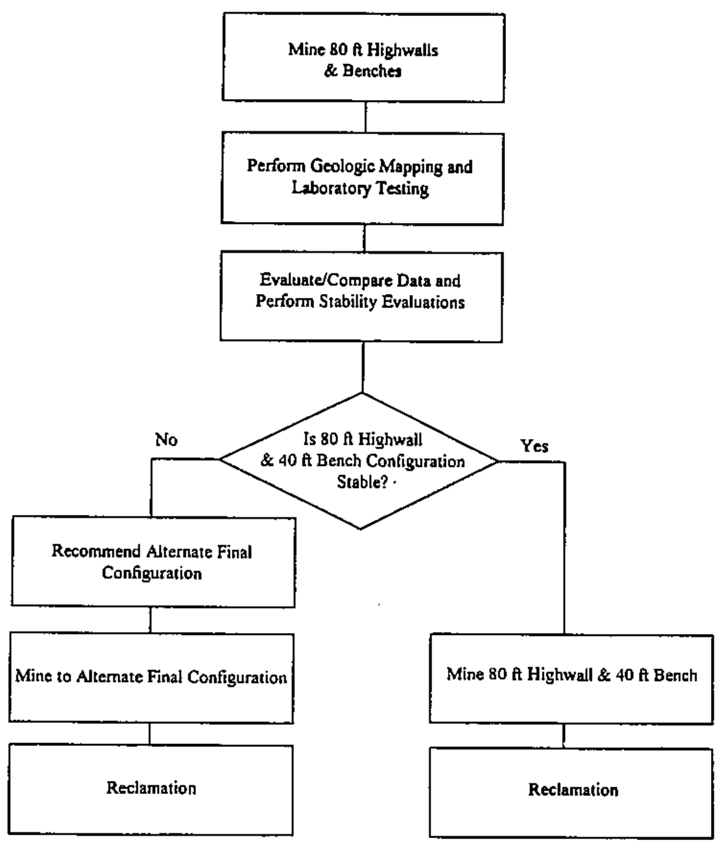

Figure 1. Observational Approach Decision Tree

Application of these alternative slope configurations to the actual mine plans uses as a step-wise excavation sequence. At each excavation level, an 80 ft highwall and 80 ft bench configuration is exposed. The engineer then performs a detailed observation and analysis of the rock exposed in the highwalls and benches. Following comparison of the observed rock mass with the prototype rock masses used in the calculations, the decision is made to either leave the benches 80 ft wide, or cut it back to less than 80 ft, but not less than 40 ft.

A key point of the approach is that reducing bench width and, therefore increasing overall slope inclination, is based on a predetermined set of conditions and a rational decision tree. Also, there is regulatory oversight of the process through annual reports submitted to the Colorado Division of Minerals and Geology.

Thus far, this approach has been successfully implemented in a portion of the quarry. After 80 ft wide by 80 ft high benches were established, geologic mapping and additional geotechnical evaluations were performed. The favorable decision to establish steeper, 40 ft wide by 80 ft high benches, was made based on the rock mass characteristics exposed.

Reclamation Measures

Reclamation measures for the quarry typically consist of the placement of a minimum of 12 inches of overburden on benches, and establishment of native vegetation. The amount of backfill placed on each bench is dependent on the bench location, orientation and on slope stability. For benches potentially within the line of sight from vantage points near the quarry, backfill generally covers as much of the highwall as practical to reduce visual impacts. Wide benches and short highwalls are planned to facilitate stable backfill wedges on the benches. Maximum top to bottom backfill can be achieved on slopes of 1.5H:1V, as long as soil erosion control techniques are implemented. For nonvisible slopes, highwall and bench configurations are based on the maximum stable slope inclination and on practical mine operational considerations. In order to achieve effective reclamation, it is necessary that the slopes be stable and the benches and highwalls essentially intact.

Discussion and Conclusions

The observational approach is more than simply making an excavation and observing the behavior. To obtain the greatest benefit, it is necessary to have a good understanding of the range of outcomes possible and have a clear plan of action for likely outcomes. Furthermore, it is vital to have a clear path between information obtained through data, and design specifics resulting from interpretation of that information and data. This pathway between data and design is usually done with technical calculations based on the range of conditions likely present. It is imperative not only to identify the range of conditions and perform calculations but also to have clear definitions of these conditions incorporating observable and testable factors so that observed conditions can be tied directly to the results. After these steps have been undertaken, direct observation of specific conditions result in a predetermined design.

The key here is that the approach is not simply design-as-you-go, but rather consists of a set of design alternatives from which following observations, the most appropriate design is chosen.

The benefit of this approach is that the design can be fine tuned to actual conditions which would be impractical to determine prior to the beginning of excavation. Furthermore, actual conditions are known more accurately with the resulting decrease in uncertainty, and less contingency built into the design.

Regulatory oversight of the process is provided with agency review of annual reports prepared by Cooley Gravel Company. These reports contain observational data, engineering evaluations, and actions undertaken over the preceding year.

References

Peck, R.B. 1969. Ninth Rankine Lecture. Geotechnique, June 1969, pp. 171-187.

Bieniawski, Z.T. 1979. The Geomechanics Classification in Rock Engineering Application. In Proc. 4th Int. Congr. Rock Mech ISRM, Montreax Vol. 2 pp 51-58. Published In Bieniawski, Z.T. 1989. Engineering Rock Mass Classifications. John Wiley & Sons, pp. 54-55.

Hoek, H. and Bray, J.W. 1981. Rock Slope Engineering, 3rd Edition. The Institute of Mining and Metallurgy. London, pp. 114-115.