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Case Examples of
Open Pit Mine Drainage

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ABSTRACT

The methods of optimizing slope angles of open pit mines
are limited. Reduction in the natural groundwater pressures
is perhaps the most significant method available to the mine
designer. For similar modest values of risk of failure of
large slopes overall savings on the order of five to ten
degrees are possible. This paper cites two cases with
widely different properties where the effect of underground
galleries have been measured. The difference between de-
pressurization and drainage is demonstrated in materials
which have overall permeability of 10^{-6} cm/sec and 10^{-2} cm/
sec, respectively.

DRAINAGE AND DEPRESSURIZATION IN OPEN PITS

Introduction
     This paper is intended to draw upon experience gained in
two predominantly copper deposits to illustrate the differ-
ence between drainage and depressurization of rock masses
forming the slopes of open pits. The importance of deter-
mining the hydraulic characteristics of a rock mass before
embarking on large-scale engineering programs will be em-
phasized.

     The concept of effective stress in materials forming

the earth's crust has been well established in both practice and in the laboratory and is an important factor in the practice of soil mechanics, rock mechanics, and reservoir engineering. Reduction in effective stress will decrease the available strength of the rock mass subjected to shear forces.

We may demonstrate deterministically (Refs.1,2 and 3) that significant increases in either slope angle and/or slope height can be achieved by reduction in water pressures present in a slope. If we wish to be more rigorous, we can express such changes probablistically in the form of risk/uncertainty analyses. In one of the cases to be briefly discussed here, as an example, some reference is made to this approach.

In the mining industry we are primarily concerned with extracting minerals with the maximum economy. In the case of open pits, we must mine the mineralized rock such that the total waste rock, which is necessary to remove, is kept to a minimum. The slopes of an open pit should be cut at as steep angles as possible consistent with efficient mine operating considerations.

If for a moment we ignore the complex issue of cost of failures and financial risk analyses in optimizing a decision process (i.e., a mine design), we can usefully turn our attention to how we may improve the strength of a slope. Since modern day soil mechanics became discernible parts of civil and mining engineering practice, it has been demonstrated that slope angles of soil or rock slopes may be steepened substantially by reducing the pore or groundwater pressures. An increase in the effective strength may be effected by other means such as cable bolting (Ref.4). The author's opinion on this method of optimizing slopes has been stated elsewhere (Ref.5). Suffice it to say here that the geological conditions where such methods of rock reinforcement should be applied are limited, but, in any case, reduction in groundwater pressures and cable reinforcement are not mutually exclusive. The primary technical and operating advantage of groundwater pressure reduction as a mechanism for increasing strength, and thus slope angles, is that changes in operating costs or mineral prices can still be accomodated by employing significant changes in the mine schedule; without losing the capital investment in the drainage or depressurization system.

Summary of Theory

If a borehole, well, or underground opening is placed beneath the water table, a gradient is set up in the rock mass. Water commences to flow from the material immediately surrounding the opening. This loss of water is made up by so-called storage effects, and the water left behind expands due to the pressure reduction. At the same time, the formation consolidates or undergoes compaction due to the increased effective stress. As the material immediately surrounding the opening is depressurized, so the material further away is "stressed," a hydraulic gradient is set up, and flows will be initiated towards the "depressurized" zone and then subsequently into the opening or "drain." The rate at which the depressurized zone expands will depend on the ratio of the permeability to the storage coefficient of the material. The storage coefficient may be related to the stiffness of the material; thus low stiffness and low permeability will lead to an extremely low rate of expansion of the depressurized zone. An example of a material with these properties would be clay. On the other hand, a fractured andesite with high permeability and relatively high stiffness will allow the zone of depressurized rock to expand very quickly. Once the depressurized zone reaches the phreatic surface, water will begin to drain from the material at this elevation. With time, the entire volume of water which occupied the drainable porosity of the rock mass will pass into the opening. The drainage of the rock mass may thus be divided into two phases: depressurization and subsequent drainage and lowering of the phreatic surface. A simple diagrammatic representation of these processes is shown in Figure No. 1.

In the two case histories summarized in this paper, it will be demonstrated that essentially complete depressurization has occurred in one (Twin Buttes), with the phraetic surface still remaining at approximately its original position. In the other case (Bougainville-Bulk Sampling Adits), the other results demonstrated that depressurization and drainage occurred almost simulataneously.

ALTERNATIVE METHODS OF OPEN PIT DRAINAGE OR DEPRESSURIZATION

The mining engineer or geologist is faced with essentially three alternative methods:
1. Toe drains
2. Perimeter and in-pit wells
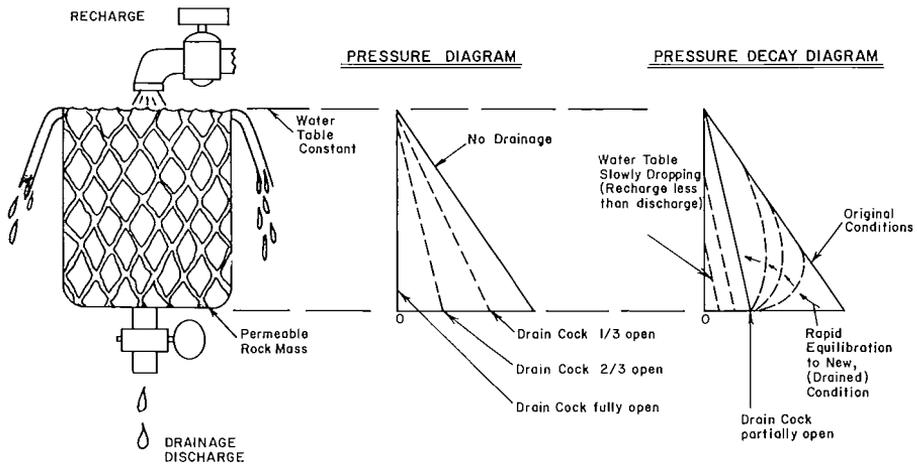3. Underground galleries.

PRESSURE DIAGRAM

PRESSURE DECAY DIAGRAM

RECHARGE

Water Table Constant

No Drainage

Water Table Slowly Dropping (Recharge less than discharge)

Original Conditions

Permeable Rock Mass

Drain Cock 1/3 open

Drain Cock 2/3 open

Drain Cock fully open

Rapid Equilibration to New, (Drained) Condition

Drain Cock partially open

DRAINAGE DISCHARGE

Figure No. 1, DRAINAGE AND DEPRESSURIZATION MODEL

TEST AREAS

Karoona Cr.

Baropinang Cr.

2500

2000

Kaverong R.

Panguna Cr.

2500

2500

3000

Biravan Cr.

Figure No. 2, PLAN SKETCH OF BOUGAINVILLE DEPOSIT AREA

The first and last categories have the advantage of being effectively passive, that is, gravity driven and thus after construction require minimal maintenance. If the rock mass is highly permeable and the hydraulic barriers such as faults are say hundreds of feet apart, then perimeter wells may present a practical solution. However, both toe drains and in-pit wells suffer the disadvantage of interfering with mining operations and require replacement as the pit expands. The toe drains also suffer from a further disadvantage that they cannot be constructed prior to mining the pit slope.

Underground galleries have often been favored for use in high slopes by the author even though the initial capital cost is relatively high because of the efficiency of the system. The possibility also exists to couple an underground gallery system with a surface run-off sump collection system.

The example of the Twin Buttes Mine quoted below indicates that where a real commitment and case is made for optimizing pit slopes, then a drainage gallery system will ensure that an effective depressurization program can be carried out.

Finally, it should be pointed out that while a drainage gallery has many advantages, this does not preclude the use of toe drains and wells in addition. Also, for local potential instability, toe drains have proved to be very successful in halting slides along highways and in some open pits (Ref. 1).

CASE HISTORY A - BOUGAINVILLE FEASIBILITY STUDY

Prior to making a decision on the investment associated with the Bougainville Copper Deposit in Papua and New Guinea, a large scale diamond drilling and bulk sampling program was carried out to determine the nature and limits of the grade distribution (Ref. 6). Associated with this study a large geotechnical program was carried out to evaluate a variety of factors including slope angles. The geotechnical study utilized diamond drillholes for mineral evaluation purposes and some additional special purpose engineering holes. Simple probe tests (inflow) were performed to evaluate permeability in a variety of holes over specified lengths (1 to 2 meters). The majority of the groundwater information was, however, obtained from instrumentation of two bulk sampling adits; the Pan Adit and the Western Adit (see Figure No. 2). The effect of driving these

adits on the preexisting groundwater conditions
was monitored by measuring the discharge at the
portal and several additional points within the
adits and by also measuring the response of open
holes and sealed piezometers. The piezometers
were set in the line of the adits and on either
side of centerline of the adits prior to construct-
ion.

The Bougainville deposit is characterized by a
high frequency of jointing in intrusive and ex-
trusive rocks (andeoite and diorites, granodior-
ites are the predominant rock types). Typically,
the rock fractures have a frequency from 10 to 70
fractures per meter and associated high porosity
(see Figure No. 3, Ref. 7). The fracturing shows
some directional concentrations but this did not
preclude joints being measured in exposures in
any orientation. The majority of joints were
however, measured at angles of greater than 60
degrees. The joints exposed in the test regions
of the two adits were open and fresh for the most
part. In addition to the joints, the rock mass
at Bougainville was found to be interspersed by
some predominantly steeply dipping clay filled
faults. The results from the two adits may be
summarized as follows:

Pan Adit

1. Full drainage occurred almost instantan-
   eously, i.e., there was no discernable de-
   pressurization phase. Steady state was
   reached within 2 to 3 weeks at any point
   which was monitored.

2. The zone of rock which was drained to ap-
   proximately the elevation of the adit ex-
   tended beyond the immediate confines of
   the underground openings (see Figure No. 4).

3. When clay filled structures were penetrated
   as mining progressed, sudden responses in
   piezometric head (see Figure No. 5) were
   measured accompanied by sudden increases
   in inflow in the adit.

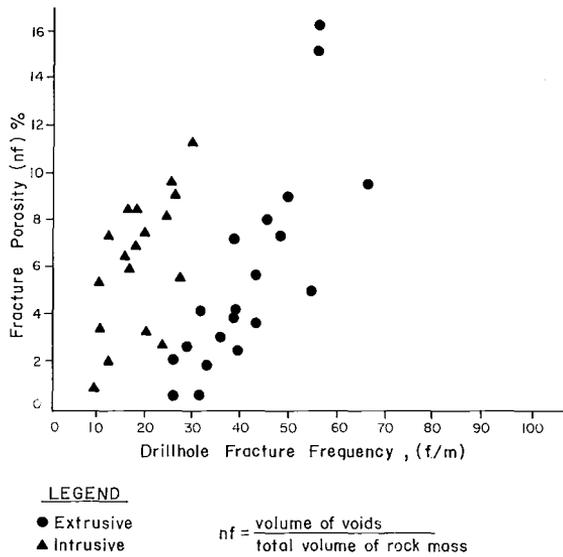4. A maximum rate of some 100,000 gallons per

Figure No. 3, RELATIONSHIP BETWEEN FRACTURE FRE-
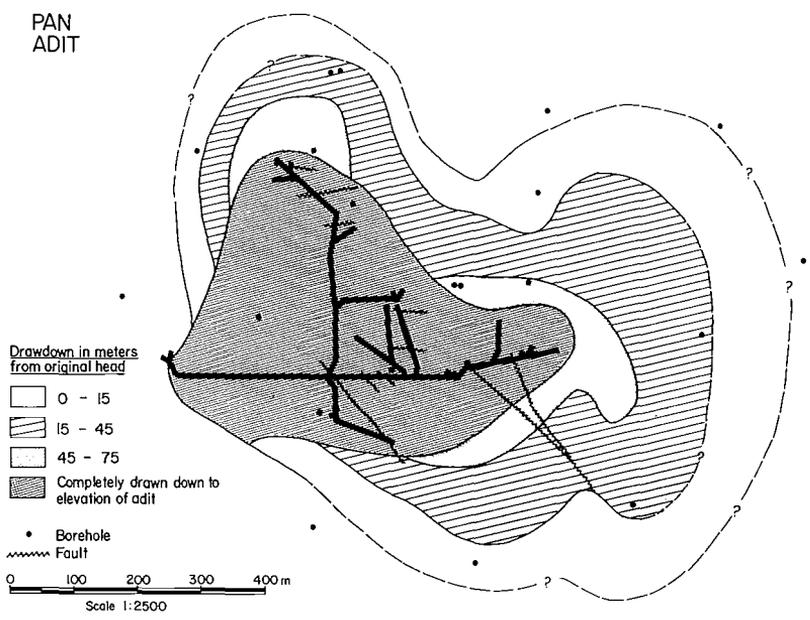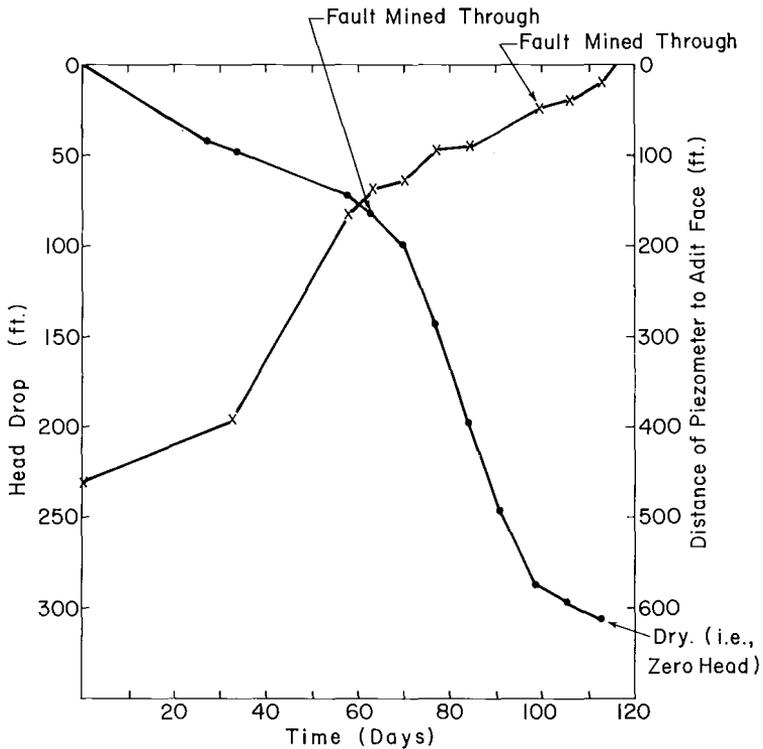QUENCY AND FRACTURE POROSITY AT
BOUGAINVILLE MINE

Figure No. 4, PLAN VIEW OF PRESSURE DROPS AS
RESULT OF PAN ADIT

hour was measured at the portal (this is equivalent to 22 gallons per foot of adit).

Figure No. 5, TYPICAL PAN ADIT PIEZOMETER RESPONSE

Western Adit

1. The Western Adit showed similar general response to that of the Pan Adit except there was more marked response to semi-impermeable structures (see Figure No. 6).

2. The significant lateral influence of the adit in one type section (see Figure No. 7 and No. 8) was restricted to some 150 meters on either side where R_U* values (Ref. 8) dropped in excess of 75 percent. Beyond this distance the response was restricted to less than 16 percent.
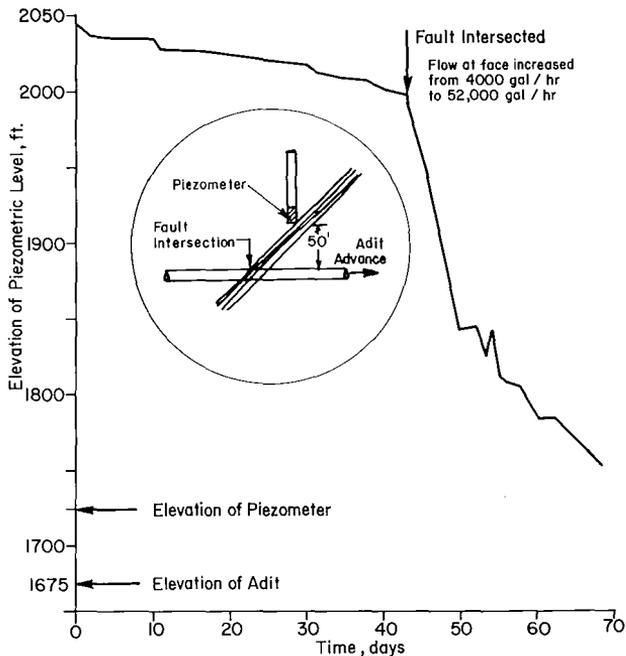
Figure No. 6,   WESTERN ADIT - EFFECT ÒF INTERSECT-
ION OF FAULT ON PIEZOMETRIC HEAD

3. The maximum flow rate which was recorded
    over the test section was some 45,000
    gallons per hour immediately after traver-
    sing the fault referred to in Figure No. 6.

General

The results from the adit tests at Bougain-
ville indicated variable permeabilities. The
values ranged from 10^{-2} to 10^{-5} centimeters per
second.

CASE HISTORY B - TWIN BUTTES, EAST PIT

At a recent meeting of AIME (Refs. 9, 10, 11,
12) a series of papers was presented describing
an extensive program of depressurization of a
clay rich rock slope and subsequent slope stab-
ility analyses. These presentations are being
prepared for publication elsewhere and thus it is
not intended to duplicate that description but
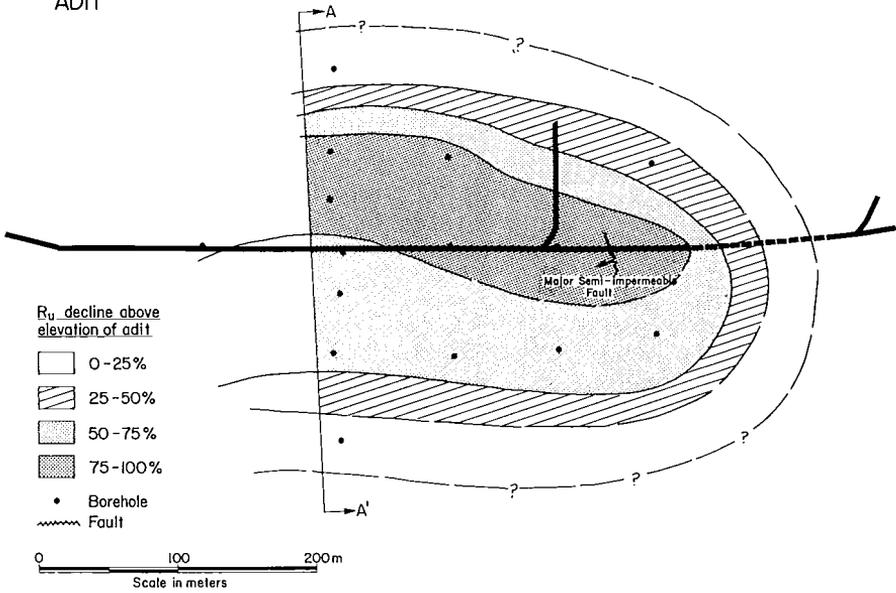rather to provide only a brief overview of the

WESTERN
ADIT

R$_u$ decline above
elevation of adit

☐ 0-25%
▨ 25-50%
▦ 50-75%
▩ 75-100%
• Borehole
〰 Fault

0   100   200m
Scale in meters

Figure No. 7, PLAN VIEW OF R$_u$ DECLINE IN TEST
SECTION OF WESTERN ADIT
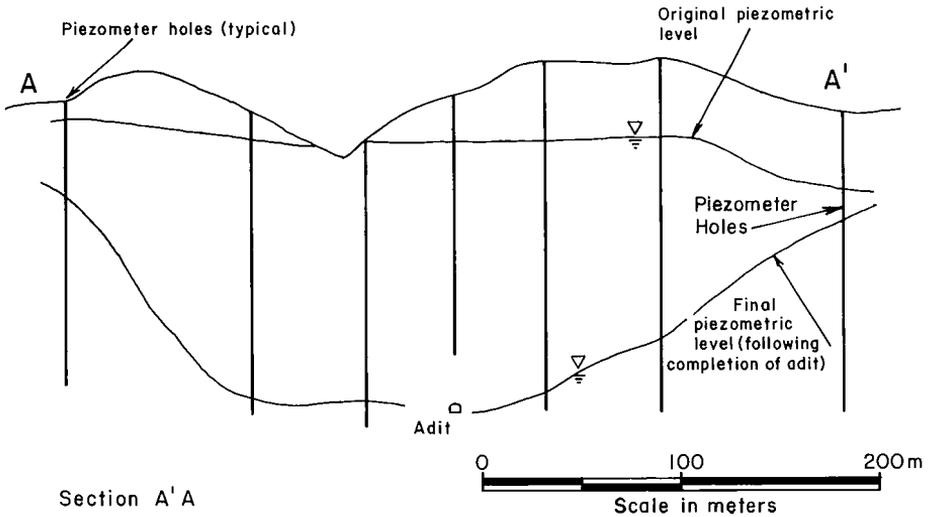

Section A'A

Figure No. 8, SECTION THROUGH TEST SECTION OF THE
WESTERN ADIT

salient characteristics of the project.

The east slope of the East Pit of the Twin Buttes Mine in Arizona is geologically characterized by a paleozoic sequence (typically limestones, siltstones) containing the ore and separated by a major fault zone from the waste mesozoics (arkoses and porphyries). This fault zone contains several well defined semivertical clay filled structures and in some 200 feet wide zone. Overlying the bedrock is an alluvium cap which exceeds some 400 feet in vertical thickness.

As a result of several geotechnical and mining considerations, it was decided in 1975 to optimize the slope angles to be formed in the weak and relatively impermeable mesozoics. After several unsuccessful attempts at using toe drains, an extensive underground adit system was driven with some 72 piezometers installed in predominantly surface drilled vertical holes in a manner such that the project could be monitored from a standpoint of reduction in groundwater pressures. A system of installing pneumatic piezometers was developed (Ref. 13) such that up to 4 piezometers could be installed to depths of up to 900 feet.

A total footage of approximately 3,400 feet of underground gallery was mined specifically for this purpose with additional 25,500 feet of fan drilling (installed with slotted PVC pipe) (Figure No. 9).

The program was carried out in stages with each stage being planned based on the monitored results of the piezometers. The flow from the underground openings was also monitored which, for example, averaged some 0.13 gpm/feet through the 21-02 crosscut (see Figure No. 9). Flows from the fan holes drilled from the 21-05 crosscut showed in some cases flows as much as 25 gallons/minute which after typically two months dropped off to fractions of a gallon per minute in the majority of holes.
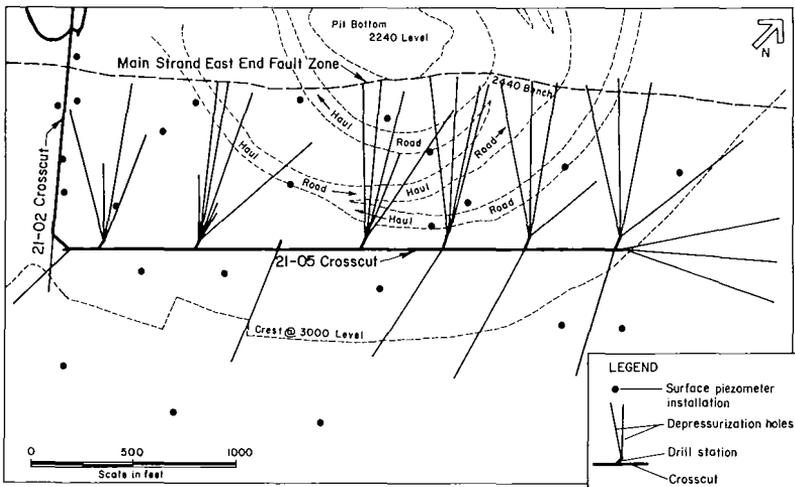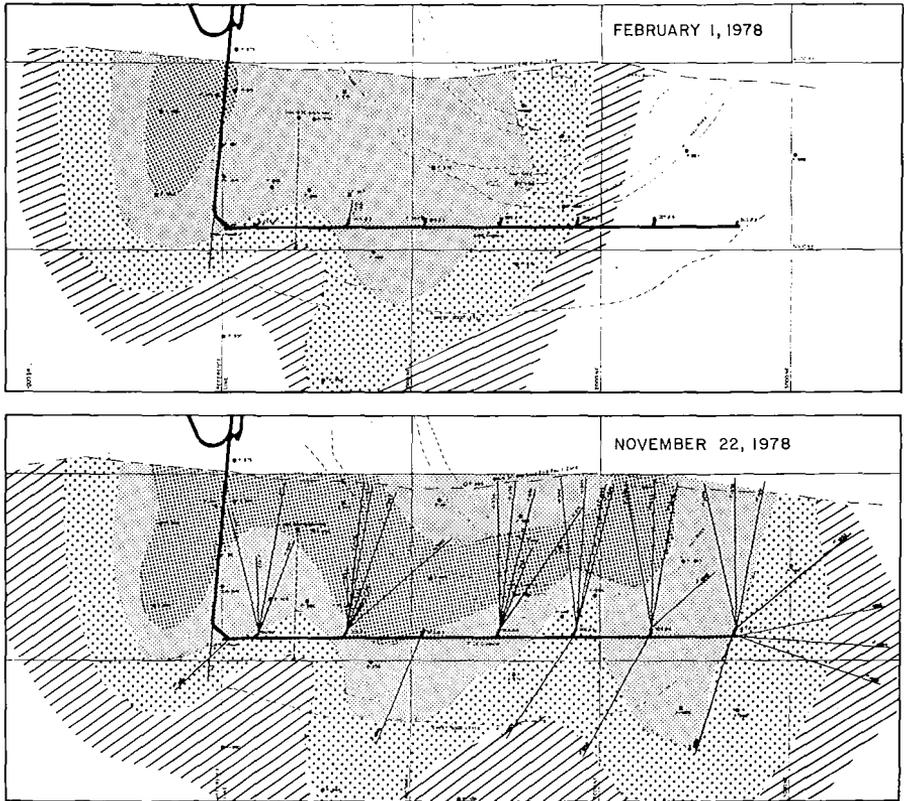
Figure No. 9,   PLAN OF DEPRESSURIZATION UNDER-
GROUND LAYOUT

The groundwater pressures response of the rock mass and primary conclusions may be summarized as follows:

1. The pressure drops range from 11 to 100 percent averaging 67 percent. The percentage drop in R_u values is demonstrated through time in Figure No. 10. The gallery itself caused the greatest pressure response.

2. A series of so-called "rubble zones" - - high permeability features which were found to be several hundred feet in extent. When a fan hole penetrates such zones, the effective size of the hole was increased thus enabling much larger zones to be depressurized.

3. The overall permeability of the material was found by modeling the response of piezometers and flow into the adit to be approximately 10^{-6} centimeters per second.

4. The water table is still at or near the surface since the underground system is removing water only at a slightly faster rate than it is being replenished by

FEBRUARY 1, 1978

NOVEMBER 22, 1978

R$_U$ Decline Above 2100 Level

▨	76% – 100%
▨	51% – 75%
▨	26% – 50%
▨	6% – 25%
☐	0% – 5%

Figure No. 10, R$_U$ PLOTS – FEBRUARY 11, 1978
NOVEMBER 22, 1978

rainfall and infiltration. Accordingly, very slow
pressure drops are continuing to be noted, as shown
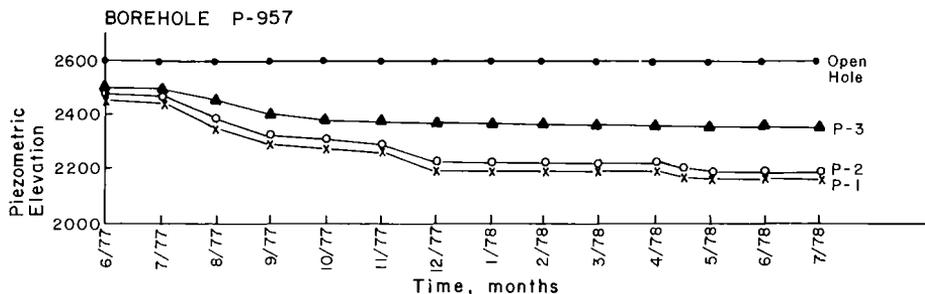typically in Figure No. 11.

BOREHOLE P-957

Figure No. 11, TYPICAL PIEZOMETER RESPONSE TO
ADIT SYSTEM

5. The results were incorporated in full risk/uncertain-
ty analysis incorporating a rigorous statement of
our uncertainty in all hydrological, geological and
strength factors. A typical result is shown on
Figure No. 12 to demonstrate the effect of a depress-
urization system on a particular slope. If in this
case a slope of 30 degrees is selected, an improve-
ment of 26 percent in reliability due to the depress-
urization program has been achieved. Alternatively,
if a risk of failure of 12 percent is accepted, then
the slope angle can be increased from 27 degrees to
to approximately 35 degrees.

CONCLUSIONS

This paper is intended to emphasize the positive effect
of depressurization and drainage on rock masses forming pit
slopes. For the same degree of risk significant improve-
ments in overall slope angles are possible. Indeed, the
higher risk which a mine may be prepared to accept, so the
possible benefit of drainage or depressurization systems
will increase.

The rock mass must be investigated from a geological and
hydrological point of view prior to installing any system.
The hydrological monitoring system should be tailored for
the specific requirements and should be used to control
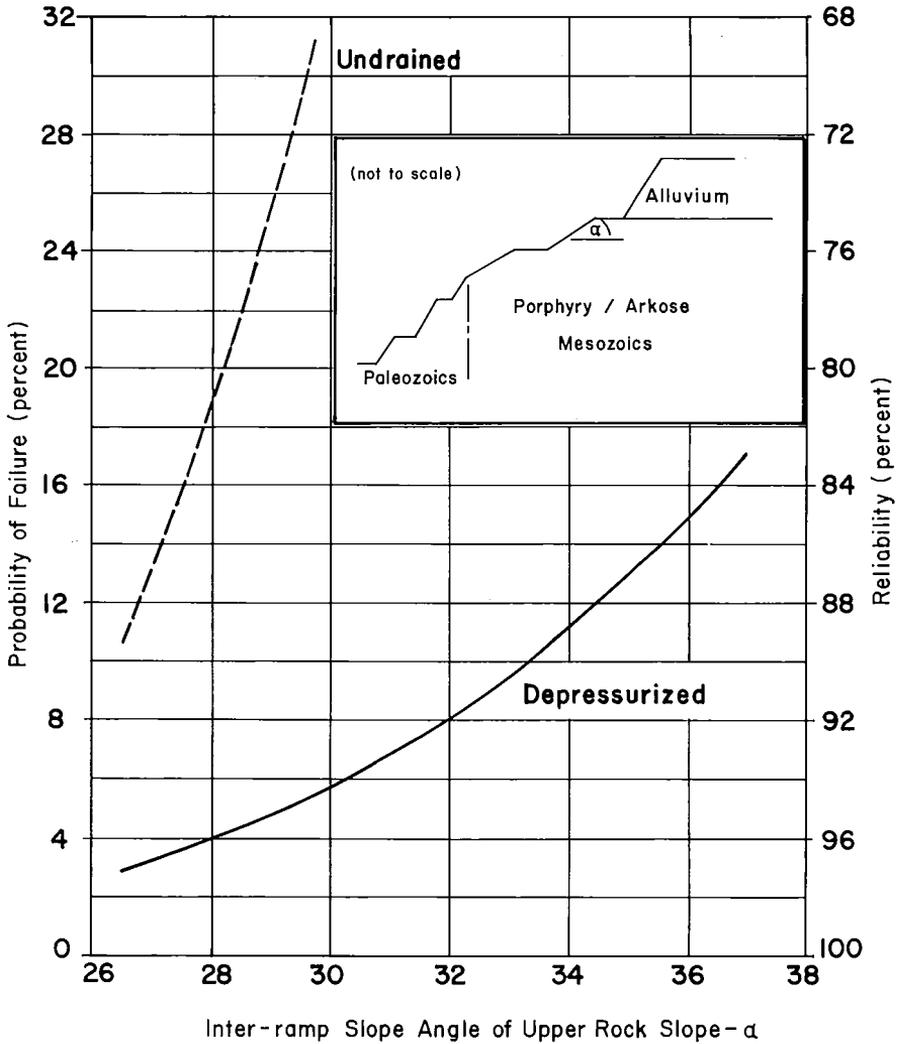the location and nature of the system.

Figure No. 12, TYPICAL RESULT OF RISK SLOPE ANALYSIS OF EAST PIT

Finally a plea is made to those geologists and engineers involved in exploration and feasibility studies of mineral deposits to maximize the information gathered from boreholes and bulk sampling adits so that substantially more reliable data may be obtained for evaluating ore as opposed to mineral reserves.

ACKNOWLEDGMENTS

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