MONITORING PIT SLOPE BEHAVIOR

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ABSTRACT

In any open pit, some slope instability can be expected, varying from bench sloughing to large-scale slope movement. Major slope displacements are preceded by small, but measurable, displacements and by other indicators of instability, such as tension cracks, rock noise, and changes in groundwater levels. A comprehensive monitoring program, capable of measuring and assimilating displacement related data, is essential for sound pit operation.

The objectives of a pit slope monitoring program are

1) to maintain safe operational procedures for the protection of personnel and equipment;
2) to provide advance notice of instability so that mine plans can be modified to minimize the impact of slope displacement; and
3) to provide geotechnical information for analyzing the slope failure mechanism, for designing appropriate remedial measures, and for conducting future re-design of the slope.

Surface displacement measurement using conventional survey equipment and extensometers has been the most widely used method, and it is still the most cost-effective. Tiltmeters and borehole inclinometers are also useful tools, and there are promising developments in microseismic monitoring. A monitoring system should have redundancy in both type and number of measurements, and be capable of rapid and effective dissemination of displacement information to those affected.

INTRODUCTION

In any open pit, some slope instability can be expected, varying from bench sloughing to large-scale slope movement. Because of the inherent variability of rock strength and geologic structure, the uncertainties associated with sampling and measuring rock characteristics, and the mathematical and geometric approximations of the stability analysis, even a "safe" slope, designed to some customary safety factor, has a finite probability of instability.

Rather than attempting to design a permanently stable slope, the current trend in slope design is to estimate the probability of failure by quantifying the variability of the stability analysis input parameters and to utilize this probability of failure in a cost-benefit analysis in order to determine economic optimum slope angles. Analyses of this type, which compare the cost of stripping to the cost of slope instability, indicate that the economic optimum slope angle may, in some cases, have probabilities of instability as high as 30 percent.

Acknowledging that slope instability can occur leads to commitment to a monitoring program to ensure safe working conditions. The objectives of any slope monitoring program are

1) to maintain safe operational practices for the protection of personnel and equipment;
2) to provide advance notice of instability, thus allowing for the modification of mine plans to minimize the impact of slope displacement; and
3) to provide geotechnical information useful for analyzing the slope failure mechanisms, for designing appropriate remedial measures, and for conducting re-design of the slope.

SLOPE FAILURE

Defining slope failure is not as simple as it would first appear. From a theoretical standpoint, if the rock is considered to be an elastic material, any displacement beyond recoverable strain constitutes failure. This, however, is not a satisfactory definition for a mine operator who often successfully mines a pit slope that has "failed" from an elastic standpoint. Displacement of several feet, which would be failure in a mechanical sense, may or may not cause difficulties for a mine operation, depending on the rate of movement, the type of mining operations, and the relationship of the moving material to the mining operation.

In a truck and shovel operation, which has considerable operational flexibility, a displacement rate of 1 to 2 cm/day may present no major problems because material is removed from the mining area at a faster rate and any offsets in the haulroads can be smoothed over by routine maintenance. The real hazard for this type of displacement is not the existing rate of displacement but the potential of a greatly accelerated rate of movement.

On the other hand, a few cm of displacement of track in a rail pit or in the foundation of a building adjacent to the pit would require extensive realignment and repair. Thus, it is useful to distinguish between theoretical and operational "failure." When the rate of displacement is greater than the rate at which the slide material can be economically mined, or the movement produces unacceptable damage to a permanent facility, it is an operational failure.

Varnes (1) used a similar economic concept to distinguish between creep and landslides. He restricted the lower limit of the rate of movement of landslide material "...to that actual or potential rate of movement which provokes correction or maintenance."

Most techniques used to calculate slope stability are static, rigid block, limiting equilibrium analysis. If the driving forces exceed the resisting forces, the slope is considered unstable.

These analyses cannot be used to predict post-failure deformation because the dynamic energy relationships of a moving block are not considered in this type of analysis. Therefore, our knowledge of the behavior of unstable slopes is largely empirical. Broadbent and Ko (2) postulated a rheologic model which shows a good fit to observed displacement, particularly the cyclic displacement shown in Figure 1:

$$\mu = \frac{f}{K}\left(1 - e^{\frac{-Kt}{N}}\right) + \mu_o;$$

where

μ = displacement;
μ_o = initial displacement;
f = force difference;
K = elastic coefficient;
N = viscosity coefficient; and
t = time.

Because of the difficulty in determining the values of K and N from material properties, the model is limited to prediction of movement after sufficient displacement has occurred to obtain values of K and N by empirical curve fitting (3).

Predicting slope movement is further complicated by changes in the excess driving force, which can occur with displacement. The failure surface is rarely a smooth plane, and shearing of asperities can reduce the resisting force. Where the failure surface approximates a rotational shear, the driving force decreases as the toe heaves and the top of the slide drops.

The cyclic nature of slope displacement can also be explained by changes in pore pressure. For example, in the case of a water-filled tension crack, displacement will cause the crack to widen, and the water level will drop, reducing the driving force. As the crack fills again, the driving force will increase.

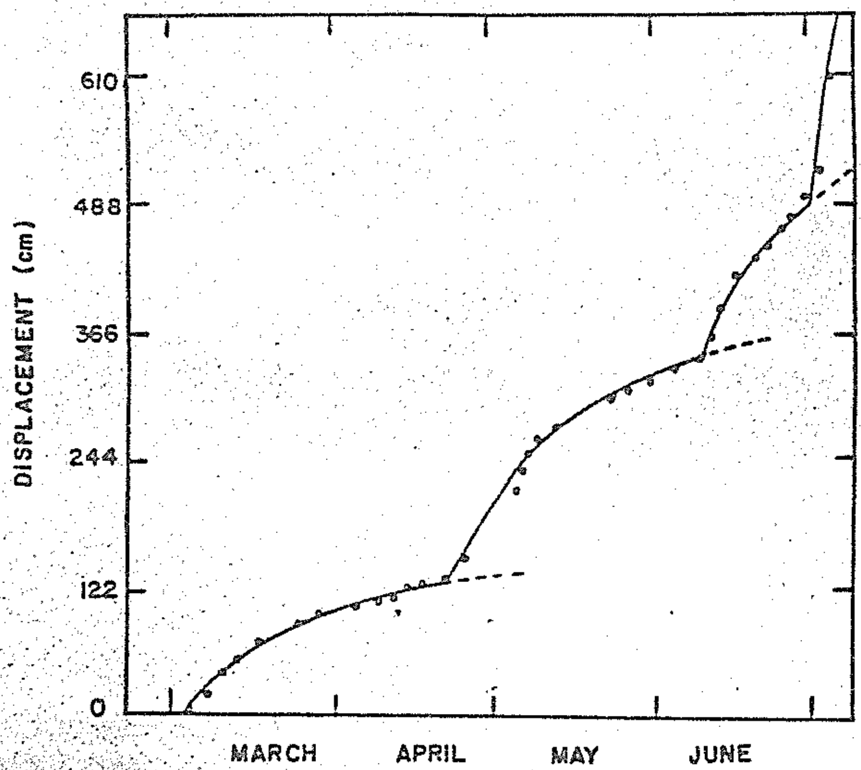


Fig. 1. Cyclic Slope Displacement (from Broadbent & Ko, 1971).

Given the complexity of slope displacement, no single mathematical relationship is sufficient for predicting slope behavior. This does not mean, however, that safe working conditions cannot be maintained or that rapid slope movement will occur without warning. Major displacements are preceded by small but measurable displacement and other indications of instability, such as tension cracks, rock noise, and changes in pore pressure. As stated by Terzaghi (4) "...if a landslide comes as a surprise to the eyewitnesses, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide."

The Lavender Pit in Bisbee, Arizona, offers a good example of the need for and benefits of monitoring (5). Through the use of simple displacement monitoring, it was possible to anticipate impending failures, with sufficient accuracy to move men and equipment from the areas three days to sixteen hours prior to major displacement.

SURFACE DISPLACEMENT MEASUREMENT

Surface displacement measurement using conventional survey equipment and extensometers has been the most widely used method of monitoring. It is still the most cost-effective.

Survey Network

A survey network consists of targets on the pit slope and instrument stations from which angles and distances to the targets are measured (Figure 2). Either triangulation with a theodolite or trilateration with an EDM can be used.

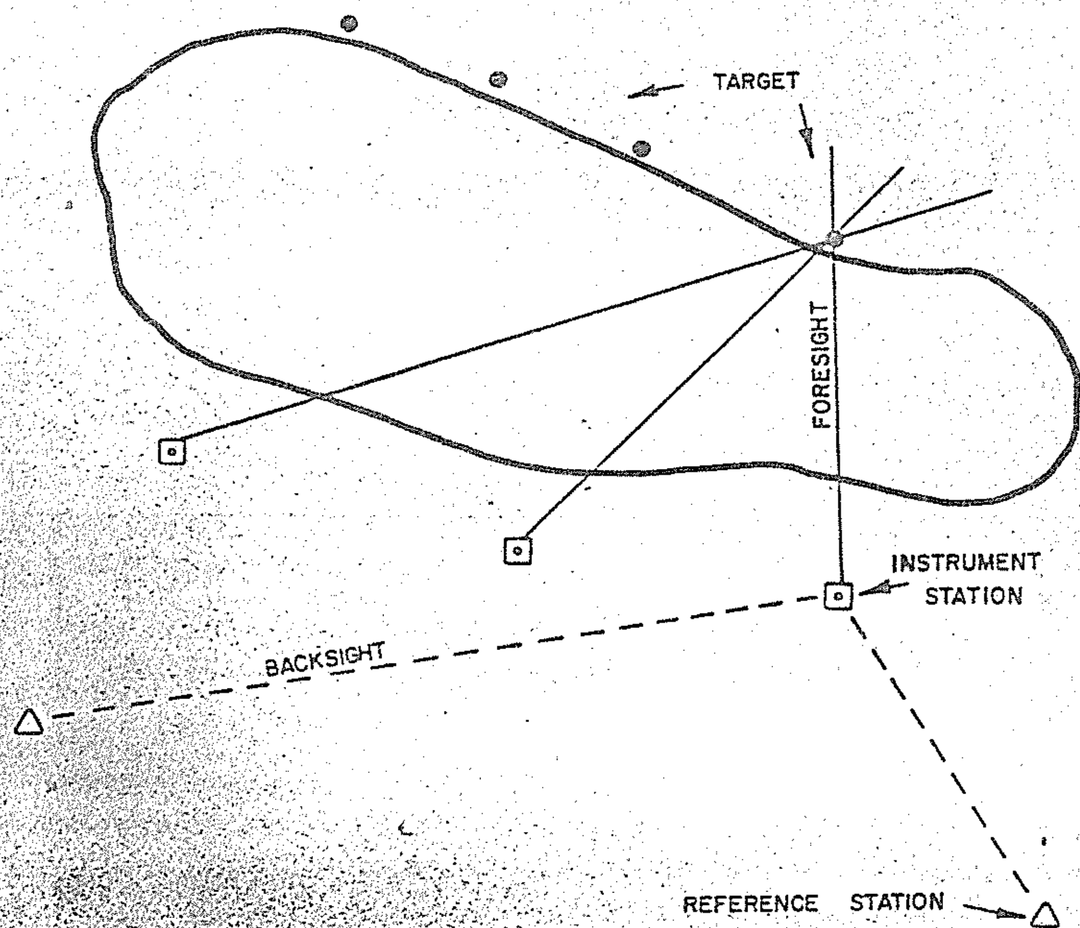


Fig. 2. Illustration of Survey Net for Monitoring.

In planning the network, care should be taken to ensure that a sufficient number of targets are established for collecting the necessary data, as long as periodic readings can still be taken with a minimum number of instrument set-ups. If a total station EDM instrument is used, approximately three minutes will be required for each reading; thus, about 30 to 40 prism targets can usually be surveyed in a half day. If a distance-meter EDM and a theodolite are used in combination, each reading would take about five minutes.

The survey network has several primary functions:

1) it establishes a surveillance system to detect initial stages of slope instability;

2) it provides a detailed movement history in terms of displacement directions and rates in unstable areas; and

3) it defines the extent of the failure areas.

The observation (instrument) stations should have stable bases because deviations in survey data can result from the inability to repeatedly set up exactly in the same position at the stations. Stable bases are best established with concrete or metal monuments. An instrument base plate is affixed to the top of the monument to serve as an instrument platform.

Primary survey points, used to tie the observation stations to the mine grid baseline, should be located on stable ground, beyond the influence of pit excavation. These relatively permanent stations (solid monuments) are needed to determine whether movement of the observation stations has occurred as a result of slope instability.

Prism targets should be attached to bench faces, if possible. A location 6 to 8 ft above the bench toe is usually preferred. Minor raveling may dislodge the prism if it is located near the crest. If the target is near the toe, it could be covered relatively quickly by raveled rock debris. In some areas, the prism reflectors will have to be mounted on sturdy tripods at selected monitoring points. It is best to allow newly installed targets to stabilize for one week before readings begin. Initially, the readings may be somewhat erratic, but an overall trend should soon become apparent.

An adjustment capability is usually needed for each target on a moving slope because it may be necessary to adjust the prism for proper instrument alignment if significant slope displacement occurs or if the instrument station is relocated. The prism can tolerate a misalignment up to 14° and still return the signal to the EDM.

The accuracy of survey measurements is a function of the precision of the instruments and the distance measured, as shown in Figure 3.

Tension Crack Mapping

One early, obvious indication of slope instability is the development of tension cracks. By systematic mapping of these cracks, the extent of the unstable area can be established (Figure 4). The ends of the cracks should be flagged so that on subsequent visits new cracks or extensions of existing cracks can be identified.

Wire Extensometers

Portable wire extensometers can be used to provide monitoring in areas of active instability and to provide backup for the survey system. These monitors can be quickly positioned and easily moved. A simple extensometer, which can be fabricated in the mine shop, is shown in Figure 5.

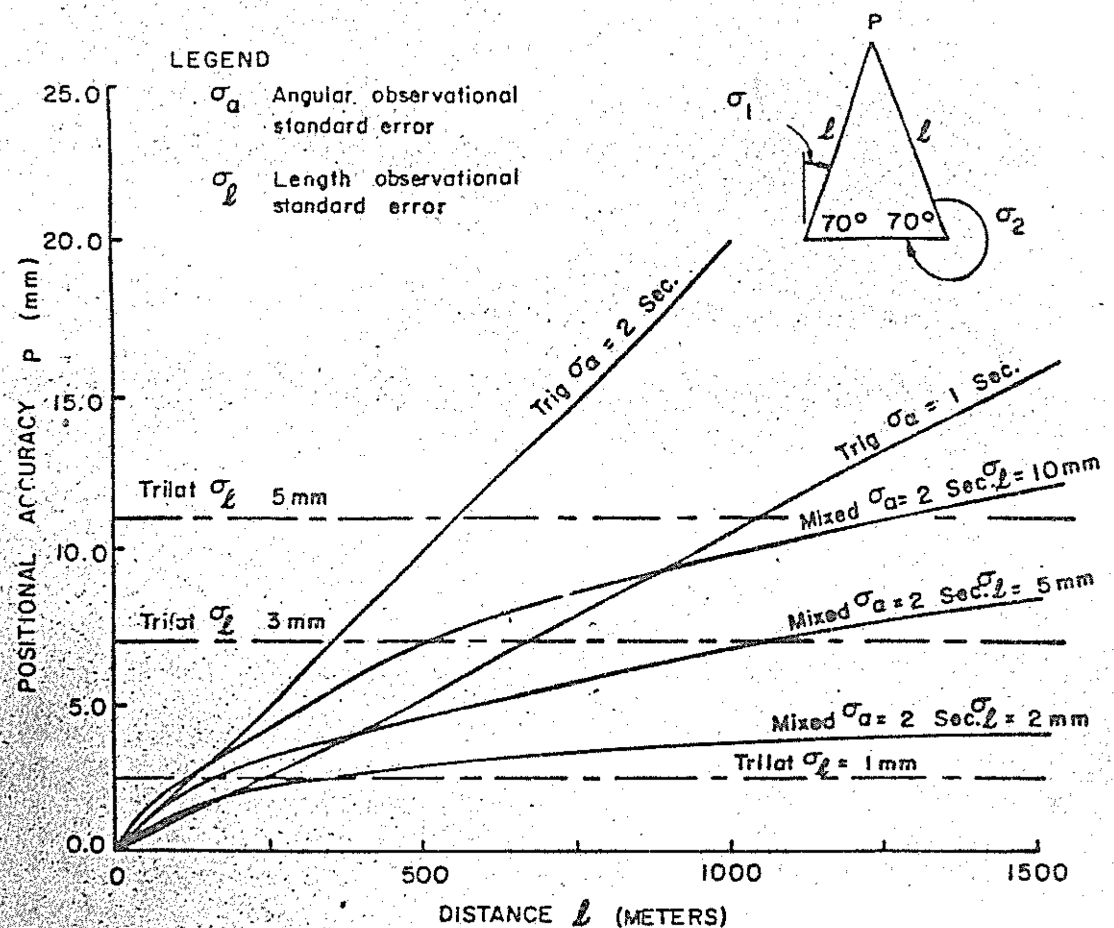


Fig. 3. Positional Accuracy of P by Triangulation, Trilateration, and Triangulateration (after V. Ashkenazi).[7]

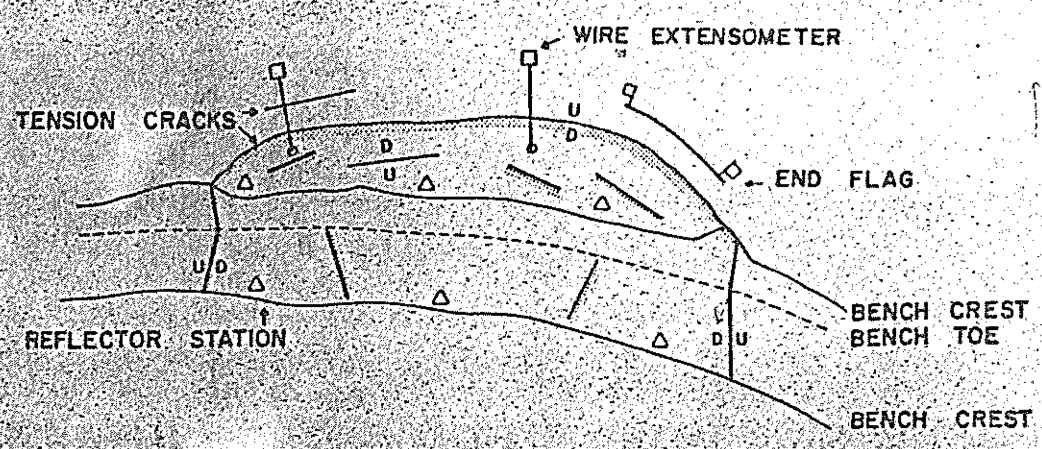


Fig. 4. Tension Crack Map.

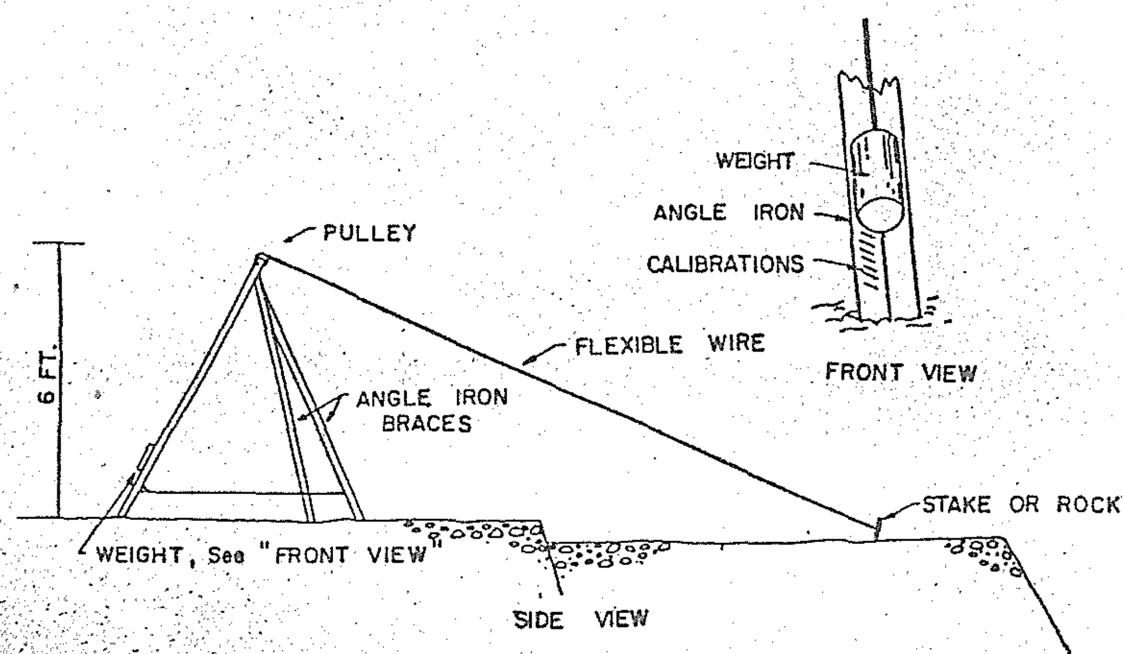


Fig. 5. Wire Extensometer.

For backup to the survey system, an extensometer should be positioned on stable ground behind the last visible tension crack, and the wire should extend out to the unstable area (Figure 4). For warning devices, or for information on deformation within the sliding mass, wire extensometers can also be placed at any strategic location. Anyone working in the area can make an immediate check on slope movement by inspecting the instruments.

A wire extensometer can be set up as a warning device by affixing a switch several cm above the displacement weight; significant displacement will trip the switch. Lights or sirens powered with a 6-volt dry cell battery wired to the switch will warn of slope activity. A continuous drum-type recorder adapted to an extensometer can provide a continuous record of slope movement (Figure 6). It will provide excellent data regarding the sensitivity of the slope to blasting, production, and rainfall.

The length of the extensometer wire should be limited to approximately 200 ft because sag can produce inaccurate readings. Usually 35 to 50 lbs of counterweight are needed for such a length, but this depends on the tensile strength of the wire. Aircraft control cable, or similar wire, which is manufactured to have very little tensile stretch, is recommended for this type of monitoring device. The flexibility and durability of steel cable, compared to the rigidity and brittleness of INVAR wire, outweigh the benefits of the thermal properties of INVAR wire. Temperature fluctuations can be measured, and corrections can be made, if necessary.

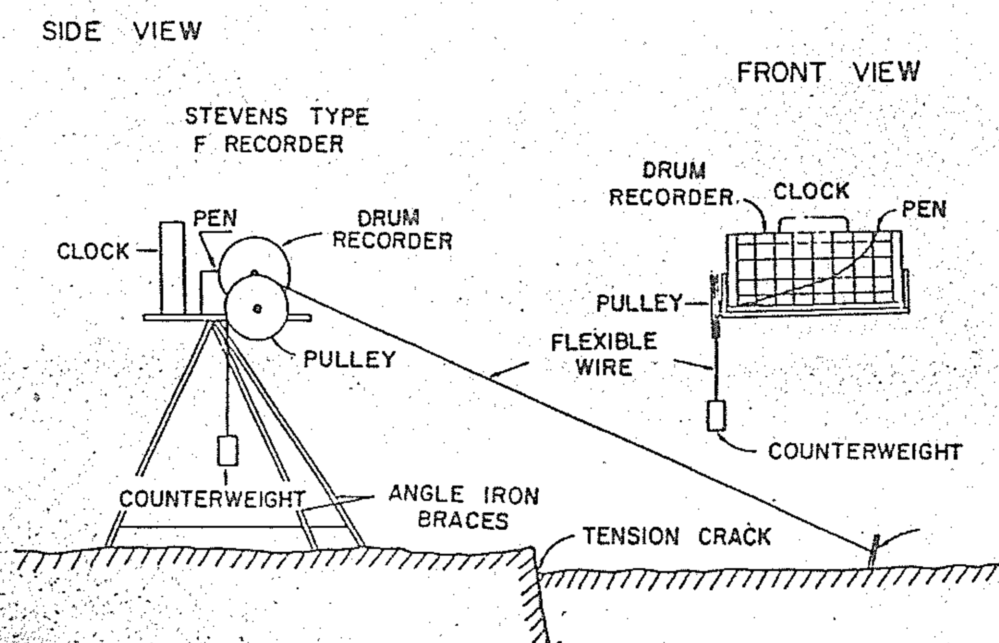


Fig. 6. Wire Extensometer with Continuous Recorder.

Other Surface Displacement Devices

When tension crack displacement is predominantly vertical, a tiltmeter, consisting of a bar across the crack with a protractor and pendulum, can be used to measure displacement. A mercury switch on the bar can be attached to a warning light. Conversely, tiltmeters can also be used to monitor angular displacement.

Manometers can also be used to monitor vertical displacement across tension cracks.

SUBSURFACE DISPLACEMENT

Surface displacement measurements do not determine the subsurface extent of instability, although it is possible to make inferences from displacement vectors. There are situations, though, where subsurface data is needed.

Shear Strips

Shear strips in a borehole will help to locate the position where the hole is cut off. Either commercial segmented strips or a coaxial cable with a fault finder can be used. These systems have the limitation of being go/no go devices.

Borehole Inclinometers

A borehole inclinometer that measures the angular deflection of the hole will give the deformation normal to the hole.

Borehole Extensometers

Borehole extensometers will give the deformation parallel to the borehole. But, because they are costly and difficult to use in locating the hole to effectively measure displacement, borehole extensometers are usually special application devices.

Piezometers

The correlation between pore pressure and slope stability is well established, both in theory and in practice. Measuring groundwater levels is an important part of monitoring, and simple standpipe piezometers are usually sufficient. There are situations, however, where low permeability or confined aquifers require pneumatic or electric devices.

Rock Noise

Experiments with microseismic recordings have established that there is a correlation between rock noise and slope movement. The cost and complexity of rock noise monitoring, though, has made it noncompetitive with direct displacement measurements. However, the lessening cost of electronic equipment and its increased reliability make its potential effectiveness greater.

PRECISION, RELIABILITY AND COST

The number of different devices that can be used for monitoring, as well as the precision and sophistication of the devices, are a function of the ingenuity, time, and budget of the engineer in charge of monitoring. Since none of these factors is infinite, hard choices must be made. Some general guidelines for decision-making follow:

1) Measure the obvious things first. Surface displacement is the most direct and most critical aspect of slope instability.

2) Simpler is better. The reliability of a series system is the product of the reliability of the individual components. A complex electronic or mechanical device with a telemetered output to a computer has significantly less chance of being in operation when needed than do two stakes and a tape measure.

3) Precision costs money. The cost of a measuring device is often a power function of the level of precision. Measuring to ±1 cm is inexpensive compared to measuring to ±.0001 cm. A micrometer is unnecessary for monitoring slope movement that has a velocity of 5 cm per

day.

4) Redundancy is required. No single device or technique tells the complete story. A single extensometer or survey point cannot indicate the area involved in the instability, and, if it is destroyed, the continuity of the record is lost.

5) Timely reporting is essential. The data collection and analysis must be rapid enough to provide information in time to make decisions. Reducing last week's survey data and telling the mine superintendent that the slope was moving Thursday when a shovel was buried Sunday does not lead to pay raises.

MONITORING SCHEDULE

A definite monitoring schedule should be established. If shooting in the monitoring points is left up to the mine surveyor to do when he gets the time, chances are nothing will be done.

The frequency of monitoring is a function of the precision of the system, the rate of movement, and how critical the area is. Table 1 shows a suggested schedule. If there is a heavy rain or a large blast in the area, additional measurements should be made.

TABLE 1. Suggested Monitoring Schedule

	Velocity						
Mining	Ft/Day	Cm/Day	Visual Inspection	Extension	Crack Map	Survey[3]	Piezometers
Active	0	0	Daily[1]	---	Monthly	Monthly	Monthly
	<0.05	<1.5	Daily[1]	Daily[2]	Weekly	Monthly	Weekly
	0.05 - 0.17	1.5 - 5.0	Each Shift[1]	Each Shift[2]	Daily	Weekly	Daily
	0.17 - 0.30	5.0 - 10.0	2 x Shift	2 x Shift	Daily	Daily	Daily
Inactive	0	0	Monthly	---	Monthly	Quarterly	Monthly
	<0.05	<1.5	Monthly	Monthly	Monthly	Monthly	Monthly
	0.05 - 0.17	1.5 - 5.0	Daily	Daily[2]	Weekly	Weekly	Weekly
	0.17 - 0.30	5.0 - 10.0	Daily	Daily[2]	Daily	2 x Week	Daily
	<0.30	<10	2 x Day	2 x Day[2]	Daily	2 x Day	Daily

1. Some mining codes require inspection of working face at beginning of each shift.
2. Extensometers should have warning lights.
3. If extensometers are not installed, survey observations should be on extensometer schedule.

DATA REDUCTION AND REPORTING

The following measurements or calculations should be made for each survey reading:

1) date of reading, incremental days between readings, and total number of days the survey point has been established;
2) coordinates and elevation;
3) magnitude and direction of horizontal displacement;
4) magnitude and plunge of vertical displacement;
5) magnitude, bearing, and plunge of resultant displacement vector;

and

6) rates of horizontal, vertical, and resultant (total) displacements.

Both incremental and cumulative displacement values should be determined. Calculating the cumulative displacement from initial values rather than from summing incremental displacements minimizes the effects of occasional survey aberrations.

Slope displacements are best understood and analyzed when the monitoring data are graphically displayed. For engineering purposes, the most useful plots are

1) horizontal position (Figure 7);
2) vertical position (elevation vs. change in horizontal position, plotted on a section oriented in the mean direction of horizontal displacement, Figure 8);
3) displacement vectors (Figure 9);
4) cumulative total displacement vs. time;
5) incremental total displacement rate (velocity, usually in ft/day) vs. time; and
6) Schmidt plots of total displacement vectors.

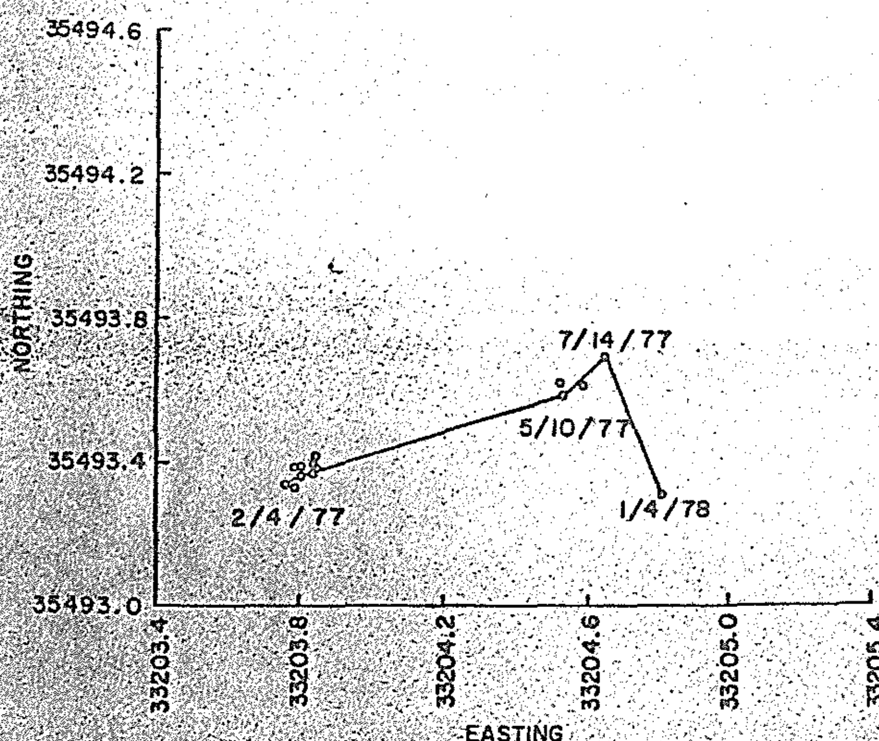


Fig. 7. Example of Horizontal Position Plot for One Monitoring Point.

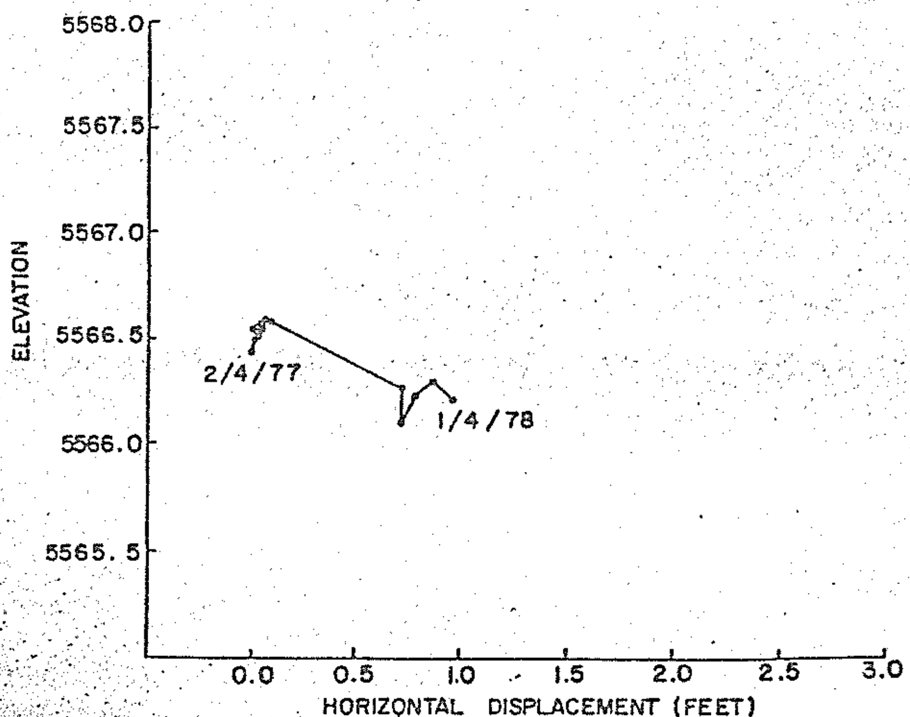


Fig. 8. Example of Vertical Position Plot for One Monitoring Point.

All graphs should be kept up-to-date and should be easily reproducible (for ease of distribution). By studying several graphs simultaneously, the movement of history of a particular slope can be determined.

The velocity-versus-time plot is usually constructed on log paper rather than on a linear scale (Figure 10). This allows a greater range of displacements to be plotted without losing the precision required for small measurements. Also, this type of graph is compatible with current monitoring techniques and analyses of slope failure kinematics (3).

Precipitation data should also be recorded in order to evaluate possible correlations with slope displacement. A gage located at the mine site can be used to measure occurrences and amounts of precipitation. In addition, measurement of the average daily temperatures will provide some indication of freeze and thaw periods.

The location of mining areas and the number of tons mined should also be recorded on a regular basis, because slope displacements are often associated with mining activity. One method of cataloging this information is to plot the mining area and then note the number of tons mined and the date on a plan map of the pit. A histogram can be made of tons mined versus time, and this plot can then be compared to the total displacement graphs.

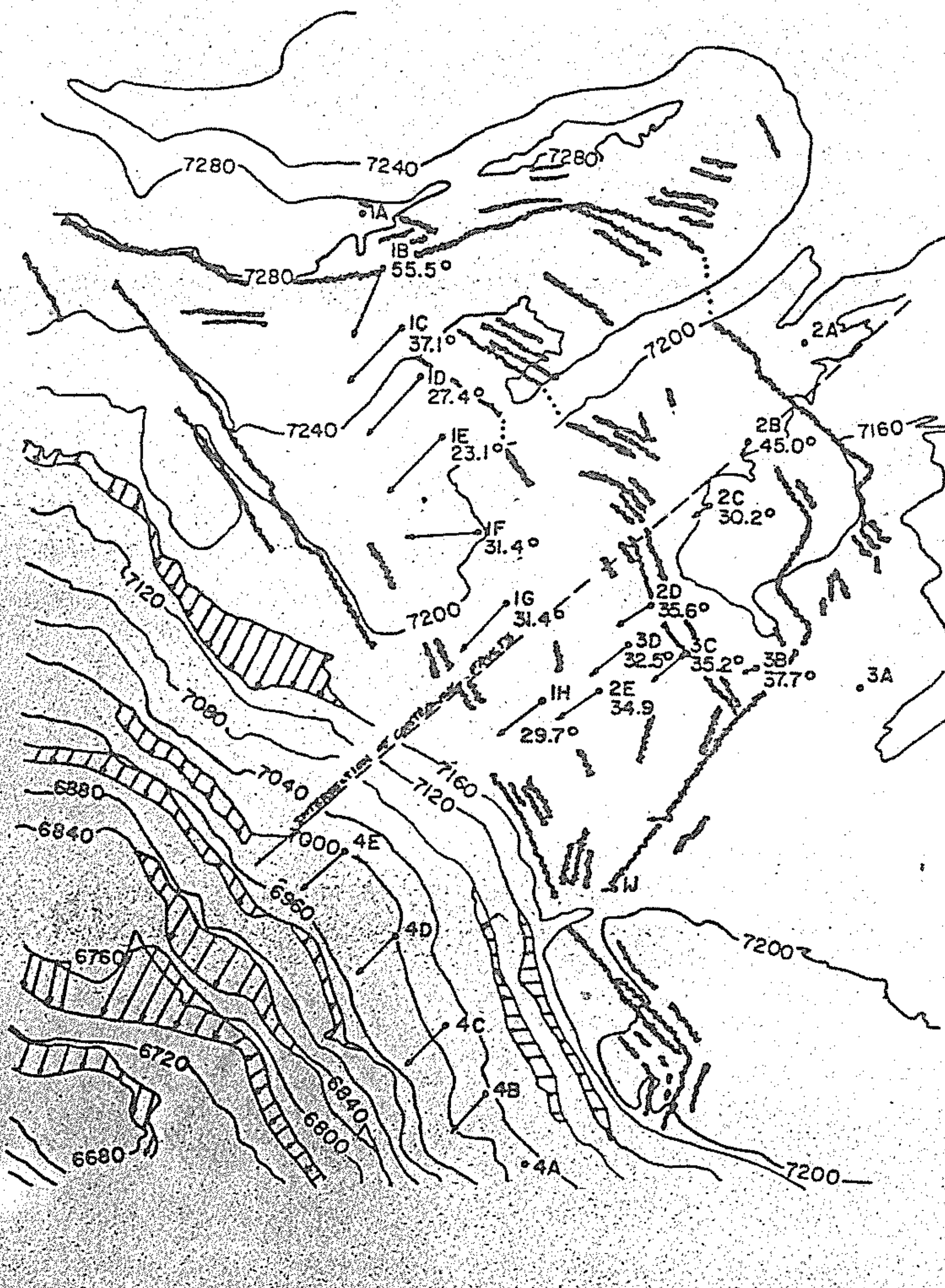


Fig. 9. Displacement Vectors (from Miller).

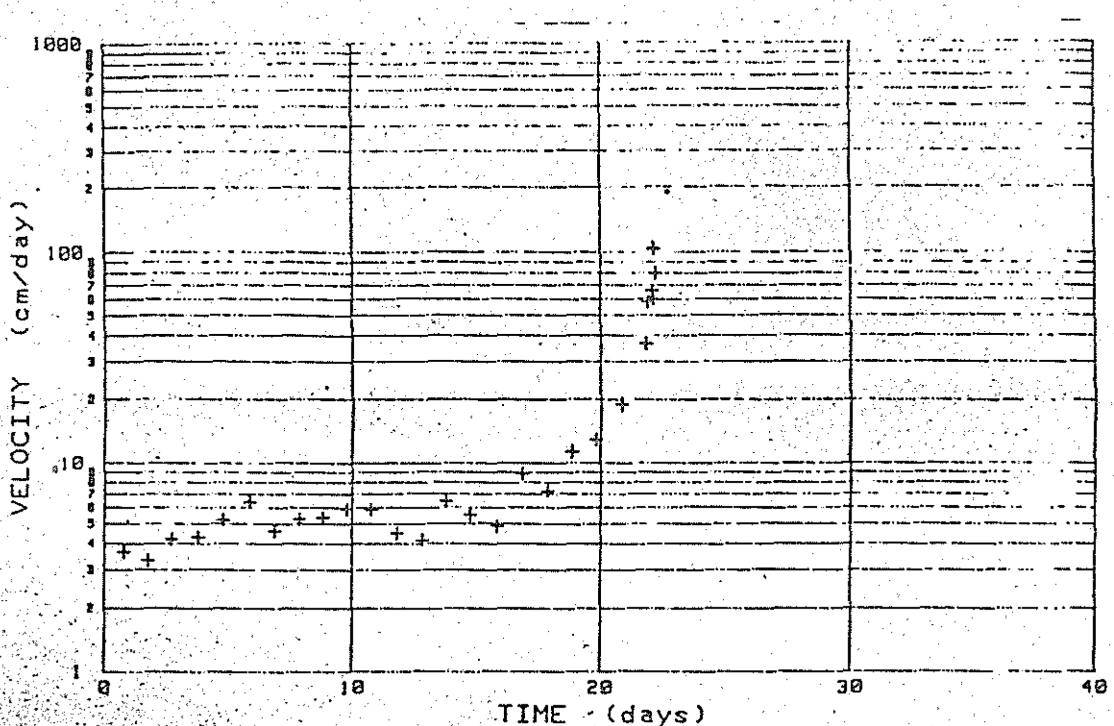


Fig. 10. Extensometer Displacement.

Monthly Slope Stability Report

A formal monthly slope stability report should be prepared, containing the data listed in Table 2. This ensures that mine management receives the appropriate information and provides the discipline to document slope behavior. Direct, informal communication should also be maintained with pit operations, on a daily basis in the case of mining in an active slide area.

Interpreting Displacement Data

Often there are several possible failure geometries for a pit slope, and it may not be clear, particularly at the onset of movement, which failure geometry is active. The displacement vectors are useful in determining the failure geometry. Figure 12 is a hypothetical example showing a possible plane shear along a fault, F_1, and a possible wedge of faults, F_2 and F_3. The difference between the two would be significant since the F_1 plane shear would affect the building while the wedge would not. By plotting the displacement vectors on a Schmidt plot, that the displacement is in the direction of the wedge, not the plane shear, can be seen.

On the basis of an examination of slope failure and displacement records, Zavodni and Broadbent have postulated two failure stages: <u>a regressive stage</u>, during which the slope will restabilize if some

TABLE 2. Monitoring Data Presentation

Graphs

Cumulative Displacement vs. Time

Velocity vs. Time (cm/day, Log Plot)

Precipitation vs. Time

Water Levels vs. Time

Mining vs. Time

Maps & Sections

Pit Map with Location of Unstable Areas (Figure 11)

Location of Monitoring Points with Displacement Vectors

Tension Crack Map

Horizontal Plot of Location with Time

Vertical Plot of Location with Time

Inclinometer Displacement

Map of Piezometric Surface

Cross-Section of Unstable Area

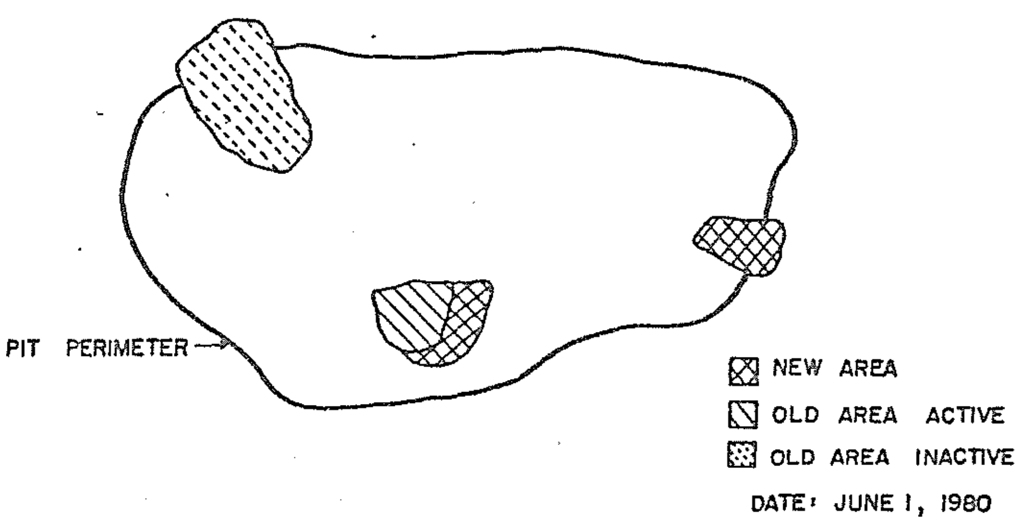
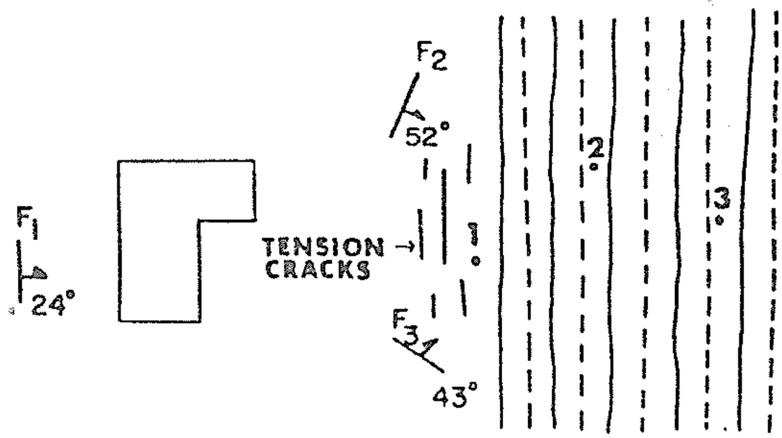
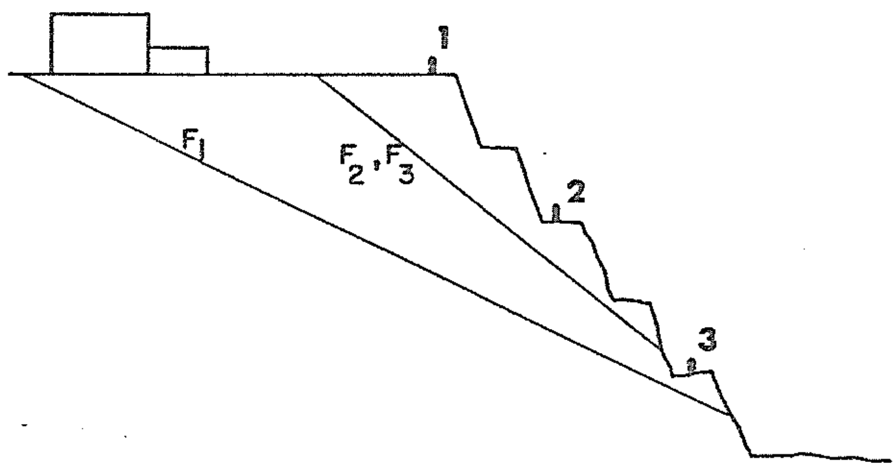


Fig. 11. Slope Instability Location Map.



PLAN VIEW



SECTION VIEW

Fig. 12. Stereographic Plot of Displacement Directions.

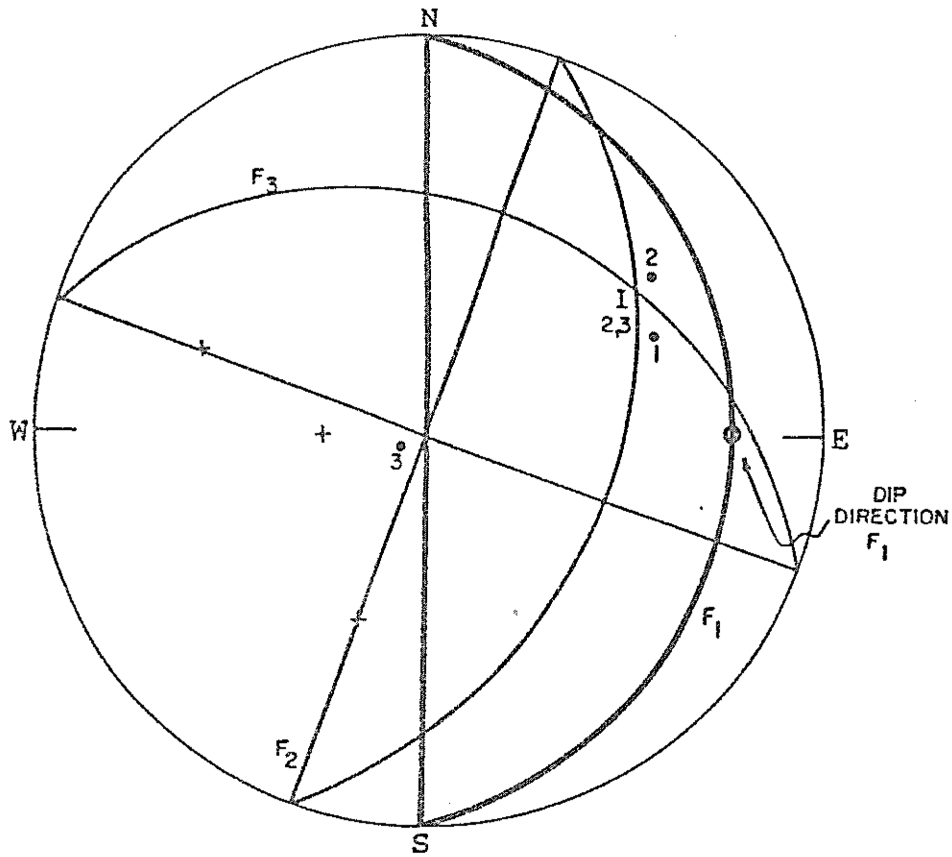


Fig. 12 (cont.). Stereographic Plot of Displacement Directions.

external disturbance is removed; and a progressive stage, where the failure will progress to the point of total collapse unless active control measures are taken (3). The displacement record appears to be of an exponential form such that the velocity plots as straight line segments on seismology graph paper with a change in slope at the onset of the progressive stage (Figure 13).

Assuming T = 0 at the onset of the progressive stage, the equation for the progressive stage would be

$$V = Voe^{St};$$

where

V = velocity;
S = slope of line;
t = time; and
Vo = velocity at T (onset of progressive stage).

They postulated that the velocity of the collapse point could be

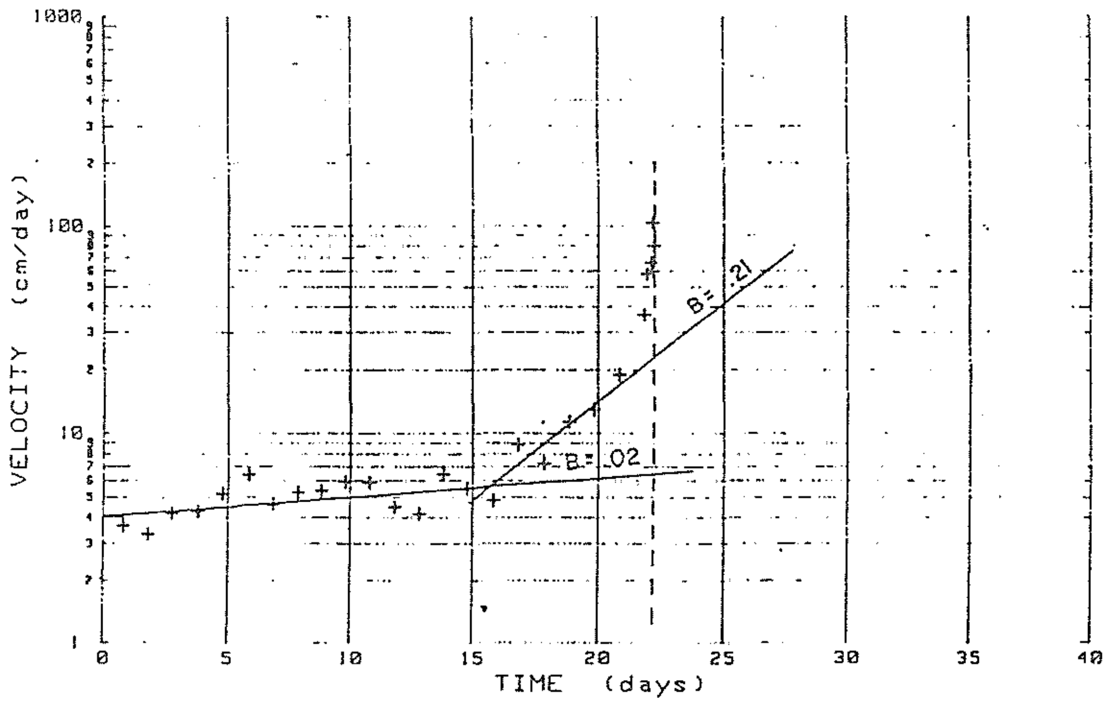


Fig. 13. Extensometer Displacement - Regressive and Progressive Stages

estimated by

$$V_{col} = K^2 V_o;$$

where K is an empirical constant. From the slope failures they obtained K values ranging from 4.6 to 10.4, with a mean of 7.21.

As can be seen in Figure 13, there may not be an abrupt collapse point but a contained acceleration. The projections of velocity are still useful estimators of future displacement rates, particularly if new projections are made as new data points are obtained.

Consideration must be given to the geometry of the failure. For an unstable area to continue to accelerate, there must be freedom to displace (a failing slope will stop if it hits the appropriate side of the pit). Thus, the predictors of slope behavior must be made on the basis of geometry and the potential changes in the forces acting on the unstable mass, as well as the velocity record.

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