STABILITY OF NUCLEAR CRATER SLOPES IN ROCK

Robert W. Fleming
Alton D. Frandsen
LTC Robert L. LeFrenz

U. S. Army Engineer Nuclear Cratering Group
Lawrence Radiation Laboratory
Livermore, California

INTRODUCTION

The United States Army Engineer Nuclear Cratering Group was established in 1962 to participate with the Atomic Energy Commission in a joint research and development program to develop nuclear engineering and construction technology. A major part of this research effort has been devoted to studies of the engineering properties of craters. The program to date has included field investigations of crater properties in various media over a broad range of chemical and nuclear explosive yields, studies of man-made and natural slopes, and studies directed toward the development of analytical and empirical methods of crater stability analysis. From this background, a general understanding has been developed of the effects of a cratering explosion on the surrounding medium and of physical nature of the various crater zones which are produced. The stability of nuclear crater slopes has been a subject of prime interest in the feasibility study being conducted for an Atlantic-Pacific sea-level canal.

Based on experimental evidence assembled to date, nuclear crater slopes in dry dock and dry alluvium have an initially stable configuration. There have been five nuclear craters produced to date with yields of 0.4 kt or more on which observations are based and the initial configurations of these craters have remained stable for over seven years. The medium, yield, crater dimensions, and date of event for these craters are summarized in Table I. It is interesting to note that the Sedan Crater has been subjected to strong seismic motions from nearby detonations without adverse effects.

TABLE I

APPROXIMATE DIMENSIONAL DATA FOR NUCLEAR CRATERS IN ROCK

<table>
<thead>
<tr>
<th>Event</th>
<th>Rock Type</th>
<th>Yield (kt)</th>
<th>Height of Crater Slope (ft.)</th>
<th>Average Slope Inclination (degrees)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEDAN</td>
<td>Alluvium</td>
<td>100</td>
<td>390</td>
<td>31</td>
<td>6 July 1962</td>
</tr>
<tr>
<td>SCHOONER</td>
<td>Tuff</td>
<td>35 (+ 5)</td>
<td>250</td>
<td>37</td>
<td>8 Dec. 1968</td>
</tr>
<tr>
<td>BUGGY</td>
<td>Basalt</td>
<td>1.2 (+0.2)*</td>
<td>100</td>
<td>38</td>
<td>12 Mar. 1968</td>
</tr>
<tr>
<td>CABRIOLET</td>
<td>Porphyritic Rhyolite</td>
<td>2.3 (+0.5)</td>
<td>140</td>
<td>38</td>
<td>26 Man. 1968</td>
</tr>
<tr>
<td>DANNY BOY</td>
<td>Basalt</td>
<td>.42 (+0.08)</td>
<td>80</td>
<td>35</td>
<td>5 Mar. 1962</td>
</tr>
</tbody>
</table>

*Row charge, 5 devices of yield 1.2 kt.
Numerous chemical explosives cratering experiments have been conducted in materials similar to those shown in Table I, as well as in wet clay shale. Several of these are listed in Table II.

### Table II

**MAJOR CHEMICAL EXPLOSIVE CRATERING EXPERIMENTS**

<table>
<thead>
<tr>
<th>EVEN (SHOTS)</th>
<th>EXPLOSIVE CHARGE PER SHOT</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAGECOACH (Three)</td>
<td>20 tons TNT</td>
<td>Alluvium</td>
</tr>
<tr>
<td>BUCKBOARD (Three)</td>
<td>20 tons TNT</td>
<td>Basalt</td>
</tr>
<tr>
<td>SCOOTER (One)</td>
<td>500 tons TNT</td>
<td>Alluvium</td>
</tr>
<tr>
<td>Pre-SCHOONER I (Four)</td>
<td>20 tons NM*</td>
<td>Basalt</td>
</tr>
<tr>
<td>Pre-SCHOONER II (One)</td>
<td>85 tons NM</td>
<td>Rhyolite</td>
</tr>
<tr>
<td>Pre-GONDOILA I (Four)</td>
<td>20 tons NM</td>
<td>Wet Clay Shale</td>
</tr>
<tr>
<td>Project TUGBOAT, Phase I</td>
<td>1 and 10 tons AL-NH$_3$NO **</td>
<td>Saturated Coral</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-BUGGY I Rows (Four)</td>
<td>5 at 1/2 ton NM</td>
<td>Alluvium</td>
</tr>
<tr>
<td>Pre-BUGGY II Rows (Eight)</td>
<td>5 at 1/2 ton NM</td>
<td>Alluvium</td>
</tr>
<tr>
<td>DUGOUT Row (One)</td>
<td>5 at 20 tons NM</td>
<td>Basalt</td>
</tr>
<tr>
<td>Pre-GONDOILA II Row (One)</td>
<td>2 at 40, 3 at 20 tons NM</td>
<td>Wet Clay Shale</td>
</tr>
<tr>
<td>Pre-GONDOILA III, Phase I, 3-Row Array (Two)</td>
<td>14 at 1 then 7 at 1 ton NM**</td>
<td>Wet Clay Shale</td>
</tr>
<tr>
<td>Pre-GONDOILA III, Phase II, Row (One)</td>
<td>7 at 30 tons NM</td>
<td>Wet Clay Shale</td>
</tr>
<tr>
<td>Pre-GONDOILA III, Phase III, Row (One)</td>
<td>1 at 35, 1 at 15, 1 at 10, 2 at 5 tons AL-NH$_3$NO **</td>
<td>Wet Clay Shale</td>
</tr>
</tbody>
</table>

Due to the limited experience in wet media, other than the relatively low-yield clay shale craters, this paper will be concerned mainly with dry materials, although some qualitative discussion of seepage effects is included. Crater geometry, the factors affecting slope stability and the methods of analysis are discussed in general. This is followed by a discussion of those aspects of a crater slope which seem to bear directly on its potential stability. For convenience, the potential stability of fallback materials and rupture zone materials are discussed separately followed by a discussion of seepage characteristics. Finally, an example of stability analysis is presented.

**Crater Geometry.** A nuclear cratering detonation produces a crater with relatively predictable characteristics. A typical cross-section of a crater which illustrates crater nomenclature is shown in Figure 1.

*Liquid explosive nitromethane.*

**Aluminized ammonium nitrate slurry blasting agent.*

***Two outside rows fired simultaneously; center row then fired to produce a crater with flat side slopes.**
Figure 1. Cross Section of typical crater in hard rock showing zones of disturbance.
Empirical scaling laws have been developed that correlate crater dimensions with explosive yield. The apparent, or visible, crater is bounded by material which may be classified into three categories: the fallback and ejecta zone, the rupture zone and the intact material zone. The geometry of each zone is approximately as shown in Figure 1.

Factors Affecting Crater Stability. In addition to crater geometry, an analysis of crater stability requires a knowledge of the post-detonation physical and structural properties of the medium and the impact of such external factors as seepage, weathering and seismic loading. The post-detonation properties are predicted from pre-detonation investigations of the undisturbed medium. The state-of-the-art at the present time is such that external affects can only be discussed qualitatively.

METHODS OF ANALYSIS

Two basic methods of evaluating crater stability are normally cited: (1) the analytical approach and (2) the empirical approach. However, the technique presently used to assess slope stability involves a semi-empirical evaluation based primarily on a knowledge of crater phenomenology, various empirical studies and engineering judgment. This approach is dictated due to the general lack of detailed reliable prediction capabilities with respect to both crater geometry and physical properties in the range of yields significantly higher than those already tested.

The analytical approach involves the application of computational methods of slope analysis to crater geometry. This method as well as the empirical approach requires detailed information on slope configuration and material properties including susceptibility to weathering. The analytical approach is commonly used in soils engineering and rock mechanics studies but its applicability to explosive excavation is limited and principally of theoretical interest. This is because there is not yet a sufficient body of knowledge of relationships between preshot conditions and postshot materials properties and behavior to allow for rigorous analytical solutions. The empirical approach compares the anticipated crater geometry and material properties with observed behavior of natural or man-made cuts in similar materials and environment. This approach must be used with caution since crater formation processes result in slopes that are uniquely dissimilar to those produced by any other means, either natural or man-made.

Analytical approach. The analytical or direct approach to crater stability would involve limiting equilibrium or stress-strain analyses. The limiting equilibrium method compares the forces or strength supporting the slope with the forces tending to cause the slope to fail along assumed failure surfaces. The method results in a calculated factor of safety which is the ratio of resisting to driving forces. Several different limiting equilibrium techniques are applicable depending on the nature of slope materials and the assumed failure geometry. For those materials which derive their strength primarily from cohesion, a slip circle or composite curved failure surface is applied. If the strength of the material is largely due to frictional resistance between fragments or along discontinuities, a planar or wedge-shaped surface is assumed. In both of these techniques, several trial failure surfaces are employed to obtain the location with a minimum factor of safety for the strength conditions assumed. The stress-strain method of analysis predicts the distribution of magnitude of stresses in the slope. Stress-strain characteristics of the cratered materials are compared with the calculated stress distribution to determine if there are zones of overstressed material. Other techniques, including the finite element method, may be used depending on the complexity of the problem. Stress-strain methods do not develop a factor of safety as defined previously. However, they do
delineate the zones of high stress concentration within a slope and may be useful in predicting the location of potential failure surfaces.

Reliable estimates of the predetonation medium properties are required to perform a stability analysis of a crater slope. For a homogenous, relatively soft medium, such as a soil or weak rock, the pertinent properties are density, strength, and seepage characteristics. In a fractured hard rock medium, the strength along structural discontinuities must also be estimated. A stress-strain analysis requires deformation characteristics including the Modulus of Elasticity and Poisson's Ratio for all of the materials. Analysis of the stability of slopes in a planned nuclear crater requires an accurate prediction of the above postshot parameters based on preshot measurements. To date, this has only been accomplished for the smallest scale craters.

To conduct an analytical study of crater stability, a numerical stability analysis would first be made based on the site data and a prediction of crater geometry and crater zone properties. From this numerical analysis, engineering judgment and technical experience, an assessment of stability would be developed.

**Empirical approach.** In the empirical or indirect approach, some of the properties necessary for an analytical analysis are used as indices to assess the overall characteristics of the materials. On the basis of the performance of natural and man-made slopes in similar materials and environment, a judgment is made of the stability of the predicted crater. The procedure for developing an empirical analysis includes an estimate of the crater zone properties based on site data and predicted crater geometry followed by a comparison of this information with appropriate empirical criteria developed from observations from man-made and natural slopes in various geographical locations. Utilizing this information, technological experience, and engineering judgment a prediction is made of the potential stability of the planned crater.

**STABILITY CHARACTERISTICS OF CRATERS IN ROCK**

As mentioned previously, site data are usually insufficient to predict crater zone properties in the detail necessary for a rigorous analysis*. (Satisfactory site documentation is especially difficult for crater slopes in hard rock when the mass strength is governed by the spacing, orientation and surface characteristics of discontinuities.) However, there are a number of general characteristics of crater slopes in rock that make them inherently stable and it can be shown that, except in unusual cases, they are initially stable. This can best be illustrated by a discussion of the stability characteristics of the individual crater zones.

**Fallback and Ejecta.** The formation of a crater in hard dry rock or dry alluvium results in cohesionless fallback and ejecta which have come to rest after violent impact. The density, size distribution and particle shape of the material comprising the fallback and ejecta are dependent on both the preshot media and the detonation. In hard rock the particle shape will generally be angular. The angle at which the fallback and ejecta come to rest is termed the angle of deposition. This angle corresponds to the cessation of particle movement and is generally several degrees flatter than the angle of repose which represents the angle at which particle movement resumes. The angle of repose is the maximum stable slope angle for a given cohesionless material. Table III contains typical angles of repose for various materials (Maclver, 1967). In general, the angle of repose for angular materials varies between 37 and 45 degrees. For nuclear craters in rock, slope angles generally range between 30 and 38 degrees.

*Equally true for conventional cuts.
Table III

TYPICAL ANGLES OF REPOSE FOR VARIOUS MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle of Repose (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shingle Stone</td>
<td>39</td>
</tr>
<tr>
<td>Ore, broken</td>
<td>45</td>
</tr>
<tr>
<td>Shale, broken</td>
<td>30-35</td>
</tr>
<tr>
<td>Shale, fragments</td>
<td>34-38</td>
</tr>
<tr>
<td>Marl, fragments</td>
<td>33-36</td>
</tr>
<tr>
<td>Metamorphic Rock, fragments</td>
<td>34-38</td>
</tr>
<tr>
<td>Stone, crushed</td>
<td>37</td>
</tr>
<tr>
<td>Limestone, fragments</td>
<td>38-42</td>
</tr>
<tr>
<td>Sandstone, soft</td>
<td>33-37</td>
</tr>
<tr>
<td>Sandstone, fragments</td>
<td>45</td>
</tr>
<tr>
<td>Igneous Rock</td>
<td>37-42</td>
</tr>
<tr>
<td>Rubble</td>
<td>45</td>
</tr>
</tbody>
</table>

after MacIver, 1967

The factor of safety of a cohesionless slope is usually expressed as

\[ F.S. = \frac{\tan \phi}{\tan B} \]

where \( B \) is the angle of slope inclination and \( \phi \) is the angle of internal friction. If it is assumed that the angle of internal friction equals the angle of repose,\(^1\) the factor of safety against surficial sliding can be calculated. MacIver (1967) found that for common methods of deposition such as dumping from trucks or conveyors, the factor of safety varied between 1.1 and 1.5.

Fallback stability was examined at the Pre-SCHOONER II crater in south-western Idaho. This crater was produced by an 85.5-ton single charge of nitromethane. The total slope height was about 70-feet and inclination about 37 degrees. The fallback material consisted of sub-round to angular particles of vitrophyre and felsite having an average particle size of 0.63-inches and a maximum size of 75-inches. The slopes were undercut by removing fallback materials from the bottom of the crater which steepened the slope from the initial angle of about 37 degrees to 42 degrees. By surficial readjustment, the slopes degraded to 38 degrees. The initial factor of safety against surficial adjustment was over 1.1. Thus it appears that the fallback materials are not only in themselves stable but they also provide a buttressing effect for the rupture zone and enhance the overall crater slope stability.

Rupture Zone. The materials in the rupture zone are similar to intact materials except they are more highly fractured. For other than very weak rocks, the strength of the rock mass against sliding is governed by the spacing and orientation of the natural and blast induced fractures and the frictional resistances of these fractures. The cratering phenomenon tends

\(^1\)The angle of internal friction actually is often greater than the angle of repose. This introduces a conservative element into the calculated factor of safety.
to disrupt natural discontinuities in the rupture zone. Figure 2 shows sub-
surface displacements produced by the Pre-GONDOLA I Bravo high-explosive
detonation. This experiment was a 20-ton single charge of nitromethane in
clay shale at Fort Peck, Montana. Crater dimensions are also shown on Figure
2. Witness pellets were placed in the ground prior to the detonation and
were recovered following the event. Large sub-surface displacements did occur
in this relatively small cratering experiment. Disruption appeared to increase
toward the surface such that the throughgoing fractures near the top of the
slope may well have been offset. Although dependent on initial orientation
of faults, fractures, and planes of weakness, deep-seated displacements re-
sulting from an explosion are generally radial, hence a major throughgoing
discontinuity such as a gouge zone associated with a fault might not be com-
pletely offset depending on its orientation, of course. This could result in
a serious crater slope weakness depending on orientation and properties and
illustrates the necessity for careful site documentation. Also, it has not
been verified that the displacements measured in the Pre-GONDOLA I test can
be extrapolated to detonations of larger yield.

In general, induced fractures in rock will be clean. That is, the frac-
ture will not initially be filled with clay or other weak material and the po-
tential stability along the fracture can be compared to the frictional resist-
ance of sliding rock against rock. If the fracture is continuous and impinges
on both the ground surface and the fallback materials, a block of rupture zone
material will be in a state of incipient failure for those cases when the in-
clination of the fracture equals the friction angle (see Figure 3). Examples
of measured frictional resistance on dry natural and sawed joints for quartz
monzonite, granite and dolomite are presented in Figure 4 together with re-
sults of testing on intact specimens. (Lane, 1967). The frictional resist-
ance along clean natural joints varied from 31 to 34 degrees and along a sur-
face prepared by sawing the quartz monzonite, it was 28 degrees.

These data suggest that for dry materials, a throughgoing clean discon-
tinuity dipping toward the crater would have to be inclined steeper than
about 30 degrees to develop an unstable block. The combination of approxi-
mately 30 degree frictional resistance for the extreme assumption of a through-
going fracture, the apparent increase in disruption of material toward the
surface (Figure 2) and the relatively flat crater slope suggests that fail-
ures of this type are unlikely without outside loading.

Seepage Characteristics. The seepage of ground water through a crater
slope could affect stability through the development of seepage forces or by
erosive action. None of the large craters produced to date have been in
saturated materials so that seepage effects must be inferred from direct data.

Seepage pressures are a function of the permeability of the medium and
the amount of water available (storage and infiltration) which may flow
through the slope. Although specific values of permeability are not required
for a stability analysis, knowledge of relative permeabilities between zones
is required to assess seepage pressures. The effective porosity is determined
by the extent and magnitude of interconnected voids and fractures. Figure 5
is a plot showing both the effective porosity and percent increase in frac-
tures surrounding a crater in rock. There is more than 20 percent increase
in effective porosity and a 400 percent increase in fractures. The increase
in permeability associated with the increase in effective porosity cannot be
quantitatively determined, but is estimated to be substantially increased
over the intact material probably by more than an order of magnitude. The
porosity of the fallback has been calculated from bulk densities to be on
the order of 29 to 37 percent for basalt and rhyolite at the Nevada Test Site
(Hughes, 1968). Although this porosity is generally higher than that in the
rupture zone, there are presently no other data available to evaluate
Figure 2. Subsurface displacements in close-in portion of Pre-GONDOLA I, BRAVO, rupture zone (displacement along radial line).
Ejecta

Assumed fracture

\[ W \cos \theta = N \]

\[ T = W \sin \theta \]

\[ T = N \tan \phi \]

\[ \tan \theta = \frac{W \sin \theta}{W \cos \theta} = \tan \phi \]

Incipient failure of block neglecting buttressing effect of fallback

Figure 3. Fracture in the rupture zone showing relationship between inclination of fracture and friction angles.

Figure 4. Intact strength versus frictional strength along fractures for selected competent rocks (after Lane, 1967).
Figure 5.

Representation of decrease in intensity of blast-induced fracturing and effective porosity with distance from true crater.
differences in the permeability between the two zones. If the permeability of the fallback is less than the rupture zone, adverse seepage conditions may occur when infiltration or the amount of water in storage is very large. More likely the reverse case should occur and seepage will be vertical and enhance stability.

SAMPLE STABILITY APPRAISAL

A number of alignments have been investigated as potential routes for a sea-level canal. The following is an example of a stability appraisal performed on the materials along Route 25 in northwest Colombia to help assess project feasibility. Two of the alignments are shown on Figure 6. Predicted crater slope heights for the alignment 25E ranged from 550-feet in the shallower cuts to 1950-feet in the Continental Divide area.

Summary of Route Geology and Physical Properties. The principal rocks along the nuclear portion of the Route 25 alignment are the Choco volcanics. Outcrops of younger sedimentary rocks are faulted into the volcanic rocks in the vicinity of the Nercua-Upper Truando Valley area and along the east flank of the Saltos Highlands.

The Choco volcanics consist of a number of related rock types, all of which are "basic igneous" or closely related pyroclastics. The distinction between these rock types is commonly obscure. The dominant type is basalt, which grades to diabase and gabbro, or to agglomerate and flow breccia due to local changes in grain size or structure. The Choco volcanics are described as "massive" showing no discernible attitudes.

The sedimentary rocks along the alignment belong to the Sautata, Nercua and Truando groups. The Sautata group is primarily tuffaceous calcareous siltstone and sandstone, grading in places into tuffaceous limestone and calcareous tuff. The rocks are thin to medium bedded.

The rocks of the Nercua group are mainly conglomerates, composed of basalt fragments in a sandy calcareous matrix. Some pebbly siltstones and sandstones are also present. The rocks are thin to medium bedded, and generally hard and dense. Neither of these groups has been penetrated by borings.

The Truando group consists of various sedimentary rock types. The most common is tuffaceous siltstone, moderately soft to moderately hard, thin to medium bedded but occasionally massive. Interbedded with this rock type are tuffaceous sandstones; some of which are soft and friable, and some of which are calcareous and moderately hard. The Truando group also includes interbedded tuffaceous limestones, thin beds of conglomerate, and thin beds of claystones.

The physical properties of the rocks along the alignment were determined from geophysical logging, borehole photography and laboratory testing. Test results are summarized on Table IV.

Average unconfined compressive strengths for the Choco volcanics is about 6500 psi. The average seismic velocity is about 14,000 ft/sec with an in situ density of about 2.7 gm/cm³. The physical properties of the sedimentary rocks are variable, but generally less competent than the Choco volcanics with the exception of the calcareous sandstone of the Truando group. Rocks of the Nercua and Sautata groups were not tested but are generally considered somewhat similar to the Truando group based on the visual description and type of topography in the outcrop areas.

Natural Slope Data - Route 25 Area. The alignment for Route 25 was
Figure 6. Route 25 alignment.
### Table IV

**AVERAGE VALUES OF SELECTED PHYSICAL PROPERTIES, ROUTE 25**

<table>
<thead>
<tr>
<th>ROCK TYPES</th>
<th>Description</th>
<th>Water Content</th>
<th>Porosity</th>
<th>Saturation</th>
<th>Laboratory Wet Bulk Density $(g/cm^3)$</th>
<th>Unconfined Compressive Strength $(psi)$</th>
<th>Average P-Wave Seismic Velocity $(ft/sec)$</th>
<th>In Situ Density $(g/cm^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOCO VOLCANICS</td>
<td>&quot;igneous&quot;</td>
<td>3</td>
<td>10</td>
<td>86</td>
<td>2.67</td>
<td>6500</td>
<td>13,400</td>
<td>2.7</td>
</tr>
<tr>
<td>CHOCO VOLCANICS</td>
<td>&quot;pyroclastic&quot;</td>
<td>4</td>
<td>12</td>
<td>83</td>
<td>2.62</td>
<td>6400</td>
<td>14,300</td>
<td>2.6</td>
</tr>
<tr>
<td>SANDSTONE, CALcareous, TRUANDO GROUP</td>
<td></td>
<td>6</td>
<td>16</td>
<td>84</td>
<td>2.41</td>
<td>6200</td>
<td>---</td>
<td>2.3</td>
</tr>
<tr>
<td>CONGLOMERATE, TRUANDO GROUP</td>
<td></td>
<td>13</td>
<td>29</td>
<td>86</td>
<td>2.14</td>
<td>2200</td>
<td>---</td>
<td>2.4</td>
</tr>
<tr>
<td>SILTSTONE, TRUANDO GROUP</td>
<td></td>
<td>41</td>
<td>54</td>
<td>93</td>
<td>1.74</td>
<td>1000</td>
<td>7,000</td>
<td>1.7</td>
</tr>
<tr>
<td>SANDSTONE, POROUS</td>
<td></td>
<td>17</td>
<td>36</td>
<td>80</td>
<td>2.08</td>
<td>690</td>
<td>---</td>
<td>2.3</td>
</tr>
</tbody>
</table>
selected in part on the basis of its relatively low topographic expression across the Continental Divide. Greater relief is present both north and south of the planned route. The highest and steepest slopes in highland and coastal areas up to 15 km south of Route 25E were measured from aerial photographs and topographic maps. The highest slope, measured along the coast where wave action is impinging on the toe, is 1300-feet at an inclination of 35 degrees. Slopes about a thousand feet high exist at inclinations of about 29 degrees. No significant slope failures were observed on the aerial photographs indicating that the slopes have been formed by erosional processes rather than through mass wasting.

Slope Data - Other Geographic Areas. Slope information for areas other than along Route 25 were investigated for high steep slopes underlain by materials with properties similar to the Choco volcanics. The general conclusion reached from these studies was that, for hard rock with unconfined compressive strengths of two thousand psi or greater, stability of slopes to a height of 2000-feet is largely independent of the intact rock strength.

One of the areas studied was Waimea Canyon and the leeward side of the island of Kauai, Hawaii. The rocks consist of thin to massive flows of subaerial picrite and olivine basalts (Tertiary-Pliocene age) with scattered pyroclastic rocks including volcanic ash and cinders present locally. Mean annual rainfall varies greatly up to a maximum on Mt. Waiaheale of 466-inches. Weathering extends to depths of 200-feet near the headwaters of Waimea Canyon. No strength data are available on these rocks but P-wave seismic velocities are about the same as the Choco volcanics (U. S. Corps of Engineers, Hawaii). The U. S. Bureau of Reclamation investigated a dam site (Kokee Water Project) a few miles east of Waimea Canyon. The deepest borings (150-feet) did not entirely penetrate through the weathered zone. Table V summarizes some index properties of weathered to fresh basalt obtained from the borings.

<table>
<thead>
<tr>
<th></th>
<th>Highly Weathered</th>
<th>Transition Zone</th>
<th>Moderately Weathered</th>
<th>Fresh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Sp G</td>
<td>3.61 to 3.65</td>
<td>3.43 to 3.41</td>
<td>3.10 to 3.23</td>
<td>--</td>
</tr>
<tr>
<td>Bulk Sp G</td>
<td>1.17 to 1.45</td>
<td>1.78 to 1.89</td>
<td>2.63 to 2.75</td>
<td>2.84 to 2.74</td>
</tr>
<tr>
<td>Estimated Bulk Sp G</td>
<td>1.27</td>
<td>1.78</td>
<td>2.75</td>
<td>3.07</td>
</tr>
<tr>
<td>Percent Porosity</td>
<td>68</td>
<td>48</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>Unit Weight, lbs/cu. ft.</td>
<td>73-90</td>
<td>109-118</td>
<td>164-173</td>
<td>177-191</td>
</tr>
</tbody>
</table>

Data courtesy of USBR

Highest, steepest slopes were measured from topographic maps. (See Figures 7 and 8 for location and results). Slopes range from about 1/2 horizontal to 1 vertical for slopes 900-feet high to 1 1/2 horizontal to 1 vertical for slopes 3600-feet high. Admittedly, the comparison of slopes in Hawaii to Colombia is very tenuous and dependent on assumed physical and environmental similarity.
Figure 7. Scaled slope location.
INCLINATION VS. HEIGHT OF KAUA'I SLOPES

Figure 8.

HEIGHT OF SLOPE (meters)

HEIGHT OF SLOPE (feet)

INCLINATION OF SLOPE

(degrees)

CANYONS

SEA COAST
Slope Stability. The rock types to be encountered along Route 25 will produce a fallback zone exhibiting characteristics of angular, cohesionless materials. In the Choco volcanics the particle sizes are expected to be relatively coarse with only moderate amounts of fine material. In the sedimentary units relative particle size is uncertain, but due to the weak nature of some of the beds a considerably larger volume of fines is expected. These materials will come to rest at their angle of deposition, resulting in an initially stable configuration.

In the areas where the alignment crosses the Choco volcanics, slope heights range from 550 to 1950 feet. Most of the rock is highly and irregularly fractured. The fractures are commonly healed. Laboratory slaking tests indicate that where volcanic breccia occurs, with high percentages of montmorillonite, the materials are susceptible to rapid weathering. The rest of the Choco volcanics are not expected to weather rapidly. Because of the general lack of any well developed or consistent structure dipping towards the alignment, and since the major part of these rocks probably weather slowly, no large sections of instability are expected. Local failures could occur where the alignment intersects faults, although only a few such faults have been mapped.

The alignment crosses beds of the Nercua and Sautata groups where slope heights will range from 875 to 1350 feet. Very little information is available for these rocks. However, descriptions of the rocks indicate they are generally thin-bedded, hard, and highly fractured. Some less competent beds can be expected in the Sautata group which generally overlies the Nercua. Bedding in the Sautata and Nercua groups apparently strikes about normal to the alignment and dips about 30 degrees SW. Weathering characteristics are unknown. Based on lithologic descriptions in the data collection reports and the fact that topography in this area is relatively rugged and steep, crater slopes are generally expected to remain stable.

Where the alignment crossed the Truando group slope heights range from 900 to 1350 feet. Limited laboratory tests show that at least part of these sediments are very weak and may even be partially unconsolidated. The extent of failures which may occur will be dependent on the distribution and orientation of the weak beds in the section. The general dip of the beds is towards the Atrato Lowlands at a low angle. Since the strike is generally perpendicular to the crater centerline, it is the least critical. However, since the median grain size of the fallback and ejecta is expected to be relatively small, sheet erosion and associated weathering could cause some modification of the crater slopes over the life of the project.

Appraisal Summary. In summary, because of the extreme paucity of detailed information along Route 25E, predictions concerning stability are somewhat tenuous. However, based on the information that is available and considering the nature of cratering explosions, it appears reasonable to believe that instability would be restricted to areas underlain by the weaker rock types of the sedimentary units and local areas of adverse geologic structures. These areas have to be identified during the design stages.

Summary. The assessment of crater slope stability in rock requires specific information on crater geometry, geologic conditions and rock properties at the site and seepage and weathering characteristics of the materials. Normally,
documentation of site characteristics and prediction of crater characteristics are not sufficiently refined to permit rigorous analysis and a more generalized approach incorporating empirical data and engineering judgment must be applied. Craters are not strictly analogous to other slopes so that a straight empirical evaluation has limited use.

Fortunately there are certain general characteristics of craters and crater slopes that make them inherently stable. Fallback from hard dry rock media will behave as cohesionless material and may be studied using methods developed for stability of rubble, talus and rockfill. Factors of safety for the fallback portion of a crater slope should range between 1.1 and 1.5. One experiment which consisted of increasing the steepness of fallback to the point of failure revealed an initial factor of safety of over 1.1 against surficial sliding. Rupture zone materials would most likely fail along surfaces of natural or blast-induced fractures if the strength of the intact rock is significantly larger than the frictional resistance to sliding. Tests of frictional resistance on material and sawed discontinuities in an igneous rock and dolomite measured strengths of 28 to 34 degrees compared to an intact strength of 49 to 56 degrees. The combined observations of near 30 degree frictional resistance along a throughgoing fracture, disarrangement of fractures in the rupture zone making throughgoing fractures unlikely and the relatively flat overall crater slope (30 to 38 degrees) suggest the rupture zone will be stable.

Likewise, seepage problems in rock slopes are unlikely unless the crater intercepts a major surface drainage or the rock contains an unusually large amount of water in storage. As part of the cratering mechanism, excellent drainage characteristics are provided through the development of a system of fractures that progressively increase in number from intact rock to the fallback. Hydraulic conductivity of the fallback has been calculated empirically for two materials at the Nevada Test Site and could vary from 1 to 1900 cm per second. Materials of this type are for all practical purposes free draining.

A sample empirical stability analysis for planned slopes along an inter-oceanic canal route is provided to illustrate the types of information assembled and the way it is used. A major uncertainty in sample analysis in the assessment of crater stability in general is the possibility of long-term changes in strength and seepage characteristics in response to weathering agents.

REFERENCES CITED


