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EFFECT OF GROUND MOTION ON SEDAN CRATER SLOPES
FROM AN UNDERGROUND NUCLEAR EXPLOSION
IN THE VICINITY

ENVIRONMENTAL RESEARCH

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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
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EFFECT OF GROUND MOTION ON SEDAN CRATER SLOPES FROM AN UNDERGROUND NUCLEAR EXPLOSION IN THE VICINITY

By

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May 1, 1969

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Prepared under
Contract AT(29-2)-1163
for the
Nevada Operations Office
U. S. Atomic Energy Commission

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PREFACE

The original planning of the project was accomplished by Mr. Milon E. Essoglou, who is no longer with ERC. He has since provided helpful references to reports of other related investigations and analytical procedures. Mr. D. G. Rogich and Dr. W. W. Hakala provided comments on the report. Their help is very much appreciated.

Arrangements for surveys and aerial photography were made by Mr. Richard A. Johnson, Effects Evaluation Division, Nevada Operations Office, USAEC, Las Vegas. His effort and that of Holmes & Narver, Inc. (Las Vegas) and American Aerial Surveys, Inc. (Covina, California) are appreciated.

Ground motions were measured by U. S. Coast and Geodetic Survey at Sedan Crater Station. An excellent record was provided and is appreciated.

ABSTRACT

This study extended, and applied, existing procedures for predicting slides from earthquake ground motions to prediction of slides from ground motions caused by underground nuclear detonations. Data were obtained from measurements of the effects of a nearby nuclear event on Sedan Crater slopes comprised generally of granular material. A method of analysis, based on work by Professors H. Bolton Seed and R. E. Goodman, University of California, was developed to include vertical ground motion as well as horizontal. Measured transient ground displacements were used in calculating downslope displacements instead of developing them from acceleration measurements. Experimental checks were obtained on the validity of the procedures used.

Lack of instruments severely limited the number of ground motion measurements for this project. One station was established near the Sedan Crater to measure three components of acceleration and displacement. Slope surveys on six lines were made before and after a nearby event to determine permanent displacements. Pre- and post-shot aerial photography supplemented ground surveys.

Slopes in lower portions of the crater consisted of fallback material at about a 35° angle of repose. Resistance to sliding

was small. Computed displacements checked fairly well with those observed, but there was considerable scatter. In some cases, large displacements occurred at the lower stations. Various factors, such as local instabilities, creep, etc. may have contributed to these displacements.

Walls of the true crater comprised the upper third of the slopes. The average slope was about 38° and the angle of internal friction from pre-shot triaxial tests of core samples averaged about 43° . However, in order to simplify the analysis, it was necessary to assume that the material was at its angle of repose and that the angle of internal friction was 38° . With this simplified analysis, computed displacements were greater than observed values.

No analysis was made of displacements at stations on the crater lip which were small and were attributed primarily to compaction of fallback material comprising the upper portion of the lip.

In general, useful results were obtained for study of this specialized case of slope stability. For nuclear events, predictions can be made of peak accelerations, velocities, and displacements. This capability provides a better means of analyzing the effect on slopes than for earthquakes where motions may be

less well defined. Measurements and analyses should be made of slopes exposed to future ground motion where slope stability is in question.

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

The purpose of the project was to evaluate the stability of a crater slope exposed to significant ground motions from a nuclear explosion as a basis for improving capability to predict slope stability for operational safety for similar situations. Since the predicted peak vector acceleration at Sedan Crater from a nearby event was greater than 1.0 g, it offered a good opportunity for obtaining data and making analyses. Environmental Research Corporation carried out this study under Contract AT(29-2)-1163 with the Nevada Operations Office, USAEC (NVOO).

1.2 DESCRIPTION OF THE SEDAN CRATER

The Sedan event, a 100 kt nuclear detonation, occurred on July 6, 1962 at the Nevada Test Site. It was scheduled as a cratering experiment to study effects of nuclear explosions. The explosion occurred 635 feet below the surface and excavated a crater 1200 feet in diameter and about 320 feet deep with a volume of about 6.5 million cubic yards.

Approximately the upper third of the slopes consist of the walls of the true crater and, except for the lips, are free of fallback material ejected by the explosion. These slopes average about 38°. The lower two thirds of the slopes, at 35° angle of

repose, comprise fallback material (Figure 1.1). Around the crater there is a lip formed partly by upthrust of material and partly by fallback. Statements in this section are based on Reference 1 which provides comprehensive information related to stability of Sedan Crater slopes.

Since slope stability depends primarily upon characteristics of the soils, borings were made before and after the Sedan event and physical properties of media were established. Natural dry density for the pre-shot samples ranged from 95 to 124 pcf. The average angle of internal friction was about 43° . This was determined by drawing a tangent from the origin to the Mohr circle at failure for a confining pressure of 3 tons per square foot in a triaxial-load test. For remolded fallback material, a similarly determined angle of internal friction was 36° for a sample having a density after compaction of about 100 pcf. Soils consisted of desert alluvium, plus a relatively dense mixture of silt, sand and gravel. Fallback material, forming the lower parts of the slopes, was loose at the surface and at the angle of repose. Dry densities of samples taken at the slope surface varied from 70 to 104 pcf.

The following statement is of interest. "Due to the inherent stability of the granular media, sliding occurs at the

Figure 1.1. General Soil Conditions.
(Figure 6.1, Reference 1)

surface and no deep failures involving large masses of materials should occur" (Reference 1). The depth of fallback material at the center of the crater is about 480 feet. This is the difference in elevation between the bottom of the true crater and the bottom of the apparent crater, Figure 1.1.

1.3 BACKGROUND

A review was made of the literature on slope stability, particularly slopes of loose non-cohesive material. Fallback material is in this category.

A factor in the initial resistance to sliding is the interlocking of soil particles. Resistance increases with displacement until maximum shear strength is mobilized. After further displacement, soil grains become arranged so as to facilitate sliding and shear resistance is reduced to a relatively constant level (Reference 3). In the case of the Sedan slopes, for the reasons stated below, it would be reasonable to assume that the soil particles of fallback material offer minimum resistance to sliding. At the time of the Sedan event, fallback material thrown up by the explosion probably slid down the slope on impact. Wind erosion has caused continuing degradation. Furthermore, prior to the nearby event discussed in this report, other events had produced sufficient ground motion to cause slides.

An example of such is the Bye event. Transient and permanent ground motions were measured at the Sedan Crater for the Bye event (Reference 2). Ground motions were measured at four stations as follows:

- I North side on soft low density lip.
- II Inside north edge about 25 feet down from top of tip on an outcrop ledge.
- III Bottom of crater.
- IV On south side diametrically opposite locations to Stations I and II on north side.

Observed ground motions for the Bye event were generally comparable to those for the nearby event discussed in this report. Measurements were more comprehensive for the Bye event than for the nearby event discussed in this paper, as more equipment was available. The U. S. Army Waterways Experiment Station recorded ground motion data and made before and after surveys of the slopes.

1.4 THEORY

A paper entitled "Earthquake-Induced Displacements in Sand Embankments," by Professors Goodman and Seed (Reference 4) appeared to provide the most useful basis for analysis. Excerpts follow:

"Reports of damage resulting from earthquakes include many examples of failures of banks of cohesionless materials. In the case of saturated loose cohesionless soils,....when the soil is dry or partially saturated, failure usually results from the sliding of a mass of soil near the surface with a resulting flattening of the over-all slope.

"Analysis of the magnitude of slope displacements during an earthquake necessarily involves two steps: (1) the determination of the threshold or yield acceleration, i.e., the acceleration at which sliding will begin to occur; and (2) the evaluation of the displacements developed in the time intervals when the yield acceleration is exceeded.

"In a previous paper (Reference 3), the writers have examined the determination of the yield acceleration, $k_y g$, for cohesionless soils. It was shown that for a cohesionless material with strength characteristics $s = p \tan \phi$ in which s = shear strength; and p = normal pressure on the failure plane, and ϕ = angle of internal friction, the yield acceleration may be expressed by the equation:

$$k_y g = \frac{\sin (\phi - \alpha)}{\cos (\phi - \alpha - \theta)} g \quad (1)$$

in which α = inclination of slope and θ = inclination of ground acceleration toward the slope below the horizontal. For a horizontal ground acceleration, this expression reduces to

$$k_y g = \tan (\phi - \alpha) g \quad (2)$$

which, for reasonable values of ϕ and α , is close to the most critical value of the yield acceleration.

"It was also shown (Reference 4) however, that dense cohesionless soils develop a small shear resistance even under no confining pressure, which can have a profound effect on the yield acceleration of the soil for small embankments. Thus, the strength of such soils can best be expressed by the equation:

$$s = s_i + p \tan \phi \quad (3)$$

in which s_i = shear strength intercept at zero normal pressure, a value which has been found to vary from about 0.2 psf for fine to medium uniform sand to approximately 3 psf for uniform coarse sand. It has been shown that the effect of the intercept, s_i , on the horizontal yield acceleration may be expressed by

$$k_y g = \tan (\phi - \alpha + \phi_{s1}) g \quad (4)$$

in which ϕ_{s1} = a correction factor (to be added to $\phi - \alpha$) which is a function of the shear strength intercept, s_i , and the slope length, l . Values of ϕ_{s1} have been presented in chart form (Reference 4). Thus, for purposes of calculating the yield acceleration, a slope of granular soil may be considered to have an augmented angle of internal friction.

$$\phi_{eq} = \phi + \phi_{s1} \quad (5)$$

and the horizontal yield acceleration can be computed from

$$k_y g = \tan (\phi_{eq} - \alpha) g \quad (6)$$

For practical purposes, the angle ϕ_{eq} could also be used to replace ϕ in Equation (1).

"For a slope subjected to a reasonably uniform acceleration throughout its height, yielding will begin when the acceleration exceeds the value $k_y g$. The extent of the ensuing displacements will depend on the nature of the ground motions and the stress-deformation relationship of the slope material.

"In analyzing the displacement of a sliding mass during an earthquake, it is assumed that it is a uniformly dense granular material subjected throughout its height to a constant horizontal acceleration. If the acceleration exceeds

the yield acceleration, a sliding mass of the surface will slide down the slope like a frictional block on an inclined plane."

Records of ground motion indicated that the vertical component of the acceleration might be significant. Therefore, it was included, thus adding another term.

Considering the forces indicated on Figure 1.2, the modified analysis based on Reference 4 follows:

$$\frac{W}{g} \frac{d^2x}{dt^2} + N \tan \phi_{eq} + k_v(t) W \sin \alpha = k_h(t) W \cos \alpha + W \sin \alpha$$

But

$$N = W [\cos \alpha - k_h(t) \sin \alpha - k_v(t) \cos \alpha]$$

Substituting and eliminating W

$$\begin{aligned} \frac{d^2x}{gdt^2} + \cos \alpha \tan \phi_{eq} &= k_h(t) \sin \alpha \tan \phi_{eq} \\ - k_v(t) \cos \alpha \tan \phi_{eq} &= - k_v(t) \sin \alpha + k_h(t) \cos \alpha \\ &+ \sin \alpha \end{aligned}$$

Collecting terms

$$\begin{aligned} \frac{d^2x}{gdt^2} &= - (\cos \alpha \tan \phi_{eq} - \sin \alpha) \\ &+ k_h(t) (\sin \alpha \tan \phi_{eq} + \cos \alpha) \\ &+ k_v + (\cos \alpha \tan \phi_{eq} - \sin \alpha) \end{aligned}$$

Figure 1.2. Forces on Sliding Block

Multiplying by $\cos \phi_{eq}$,

$$\begin{aligned} \frac{\cos \phi_{eq}}{g} \frac{d^2x}{dt^2} = & - (\cos \alpha \sin \phi_{eq} - \sin \alpha \cos \phi_{eq}) \\ & + k_h(t) (\sin \alpha \sin \phi_{eq} + \cos \alpha \cos \phi_{eq}) \\ & + k_v(t) (\cos \alpha \sin \phi_{eq} - \sin \alpha \cos \phi_{eq}) . \end{aligned}$$

After substituting equivalent trigonometric values for the above,

$$\begin{aligned} \frac{\cos \phi_{eq}}{g} \frac{d^2x}{dt^2} = & - \sin (\phi_{eq} - \alpha) + k_h(t) \cos (\phi_{eq} - \alpha) \\ & + k_v(t) \sin (\phi_{eq} - \alpha) . \end{aligned}$$

Divide by $\cos (\phi_{eq} - \alpha)$:

$$\begin{aligned} \frac{\cos \phi_{eq}}{g \cos (\phi_{eq} - \alpha)} \frac{d^2x}{dt^2} = & - \tan (\phi_{eq} - \alpha) + k_h(t) \\ & + k_v(t) \tan (\phi_{eq} - \alpha) . \end{aligned}$$

But

$$\begin{aligned} \frac{\cos \phi_{eq}}{g \cos (\phi_{eq} - \alpha)} &= \frac{\cos \phi_{eq}}{\cos \phi_{eq} \cos \alpha + \sin \phi_{eq} \sin \alpha} \\ &= \frac{1}{\cos \alpha + \tan \phi_{eq} \sin \alpha} , \end{aligned}$$

therefore, after substituting,

$$\frac{d^2x}{dt^2} \left(\frac{1}{g(\sin \alpha \tan \phi_{eq} + \cos \alpha)} \right) = k_h(t) - \tan(\phi_{eq}-\alpha)(1-k_v(t)) .$$

Transposing,

$$\frac{d^2x}{dt^2} = g(\sin \alpha \tan \phi_{eq} + \cos \alpha) \left[k_h(t) - \tan(\phi_{eq}-\alpha)(1-k_v(t)) \right] .$$

Now let

$$(\sin \alpha \tan \phi_{eq} + \cos \alpha) = C,$$

where $\tan (\phi_{eq} - \alpha) = k_y$ (see Equation (2)) and k_y = horizontal yield acceleration.

In this paper horizontal yield acceleration is distinguished as k_{yh} .

Substituting the above values,

$$\frac{d^2x}{dt^2} = Cg \left[k_h(t) - k_{yh} (1 - k_v(t)) \right] . \quad (7)$$

If only horizontal acceleration is involved this would reduce to

$$\frac{d^2x}{dt^2} = Cg \left(k_h(t) - k_{yh} \right) . \quad (8)$$

This is the same equation as that developed in Reference 4 with some changes in terminology.

Discussion follows with respect to the sign of $k_v(t)$. When the direction of the vertical component of acceleration is up, its numerical value would be added to $k_h(t)$ in Equation (7). In other words, it would contribute to downslope displacement. The only apparent way in which upward acceleration could contribute to downslope displacement would be by reduction of shear strength on the failure plane. For a cohesionless material shear strength $s = p \tan \phi$ (Reference 4). The value of s would be reduced by $k_v(t) g \cos \alpha \tan \phi$. The upslope component of vertical acceleration = $k_v(t) g \sin \alpha$. To meet the requirement for downslope displacement

$$k_v(t) g \cos \alpha \tan \phi > k_v(t) g \sin \alpha \quad .$$

If

$$\phi = \alpha \quad ,$$

then

$$k_v(t) g \sin \alpha = k_v(t) g \sin \alpha \quad .$$

Since these are equal, the vertical acceleration for this case would not contribute to downslope displacement.

However, if ϕ is greater than α it can be shown that $\cos \alpha \tan \phi$ is greater than $\sin \alpha$ and the requirement is satisfied. For practical purposes, ϕ_{eq} could be substituted for ϕ in the above.

It is appropriate in the above connection to consider the effect of horizontal acceleration on shear strength along the failure plane. When horizontal acceleration is toward the toe of the slope the component normal to the slope would be $k_h(t) g \sin \alpha$. This would reduce the pressure and correspondingly the shear strength. Conversely, when the direction is toward the slope the pressure would be increased and the shear strength correspondingly increased. In the latter case, it is believed that upslope displacement would be unlikely for the reason stated below. "The horizontal yield acceleration is equal to $\tan (\phi + \phi_{s1} + \alpha)$. Thus for reasonable values of ϕ and α , the acceleration necessary to cause uphill sliding is greater than 1.0 g and consequently only downhill motions need to be considered" (Reference 4, page 132).

CHAPTER 2

PROCEDURE

2.1 GENERAL

In August 1965, ERC (then Roland F. Beers, Inc.) sent a letter to NVOO suggesting the desirability of measuring ground motion at the Sedan Crater and observing displacements of slope material resulting from the planned nearby event. Since ERC had limited field personnel, technical support was required. It finally evolved that a reduced effort was recommended in September 1965. Lack of instruments to measure ground motion necessitated subsequent curtailment of that portion of the program, limiting it to the installation of one instrument station.

2.2 TRANSIENT MEASUREMENTS

One station for measurement of ground motion was established on the side of the crater furthest from ground zero (GZ). Relative locations of the Sedan Crater, the Sedan Crater Station and the nearby event GZ appear in Figure 2.1. U. S. Coast and Geodetic Survey installed the Accelerograph and made measurements of radial, transverse and vertical accelerations and displacements.

2.3 PERMANENT DISPLACEMENT OF SEDAN CRATER SLOPES

The final plan for before and after surveys of the slopes provided for six lines or profiles. Locations of measurements are shown on Figure 2.2. As indicated, the S line was oriented

Figure 2.1. Location Map Showing Nearby Event Ground Zero, Sedan Crater and Sedan Crater Accelerograph Station

Figure 2.2. Locations of Stations for Surveys of Sedan Crater to Measure Permanent Displacements Caused by Nearby Event.

on the azimuth from the nearby event GZ to the center of the Sedan Crater. Other lines were spaced around the crater at intervals of about 60°. Metal stakes five feet long were driven four feet (vertically) into the ground, leaving one foot length exposed. Measurements were made of the locations and elevations of the tops of the stakes before and after the nearby event.

2.4 AERIAL PHOTOGRAPHS

NVOO made arrangements for pre-shot and post-shot photography. This supplemented before and after surveys to determine changes caused by nearby event ground motions.

CHAPTER 3

RESULTS

3.1 GENERAL

Measurements of ground motion and permanent slope displacements by surveys and aerial photography were accomplished as planned.

3.2 GROUND MOTIONS

Records of measured accelerations and displacements at the Sedan Crater Station are shown in Figure 3.1. Peak values for the three components of acceleration and displacement (with computed resultant vector values) appear in Table 3.1. Peak vector accelerations for each mid-slope station were computed by use of the best fit regression equation for all stations. These computed vector accelerations were then divided by the vector acceleration at the Sedan Crater Station. This provided factors which were applied to observed values at the Sedan Crater Station in order to obtain values at the desired slope locations. The components for crater slope stations were assumed to bear the same relation to the vector as for those measured at the Sedan Crater Station.

Similarly, an equation providing the best fit to the observed peak displacements at all instrument stations of the nearby

Figure 3.1. Record of Ground Motions at Sedan Crater Station, Nearby Event.
(NOTE: This Figure shows the first portion of the record.
Complete record available on request.)

Table 3.1 Observed Peak Accelerations and
Displacements at Sedan Crater Station
and Computed Mid-Slope Accelerations
and Displacements, Sedan Crater

<u>Station</u>	<u>Component</u>	<u>Acceleration (g)</u>	<u>Displacement (cm)</u>
<u>Sedan Crater Station - Observed</u>			
	Vector	1.22	14.50
	Vertical	1.03	8.13
	Radial	0.656	12.65
	Transverse	0.526	10.83
<u>Mid-Slope Motions at Sedan Crater - Computed</u>			
A-4	Vector	1.56	18.6
	Vertical	1.32	10.4
	Radial	0.83	16.2
	Transverse	0.67	13.9
B-4	Vector	1.69	19.7
	Vertical	1.43	11.0
	Radial	.90	17.2
	Transverse	.73	14.7
C-4	Vector	1.73	20.0
	Vertical	1.46	11.2
	Radial	0.92	17.4
	Transverse	0.75	14.9
N-4	Vector	1.48	17.8
	Vertical	1.25	10.0
	Radial	0.78	15.5
	Transverse	0.64	12.3
S-4	Vector	1.69	19.7
	Vertical	1.43	11.0
	Radial	0.90	17.2
	Transverse	.73	14.7
W-4	Vector	1.58	18.7
	Vertical	1.33	10.5
	Radial	0.84	16.3
	Transverse	.68	14.0

event was developed. This equation was used in computing peak displacements at the mid-slope stations. Also, the same procedure was used in developing factors applicable to Sedan Crater Station displacement measurements.

3.3 PERMANENT DISPLACEMENT FROM BEFORE AND AFTER SURVEYS

Before and after surveys determined the permanent displacements caused by nearby event ground motions. The displacements in a horizontal plane are shown in Figure 3.2; for the plane of each profile, they are shown in Figures 3.3 through 3.8.

The following statements apply to evaluation of the before and after surveys.

a) Five-foot stakes were driven vertically to a depth of four feet leaving one foot exposed. In February, 1966, about two months after the nearby event, Mr. L.R. West (ERC Field Representative) checked the inclination of the stakes and reported the following:

<u>Stake No.</u>	<u>Angle</u>	<u>Direction</u>
S-2	1°	N20°W
S-3	26°	N20°W
S-4	14°	N10°W
S-5	5°	N10°W
S-6	2°	N 5°W
C-2	3°	N
A-2	1°	W
A-3	25°	S35°W
N-2	Stake Bent	
N-3	18°	S
W-2	0°	
W-3	16°	S75°E
B-2	0°	

He also reported:

"The sides of the crater were to a large degree unconsolidated, loose, and still falling to the bottom. All of the stakes in the crater (each line, stakes 3 through 6) were leaning toward the bottom and were approximately perpendicular to the slope.

"Stakes A-4, A-5 and A-6 have been completely covered with slide material. These stakes are on a steep side of the crater where much material has slid down. Walking along the crater just inside the crater lip causes much movement of the material.

"Holmes & Narver, Inc. did not measure the stakes to be sure they were plumb during installation, therefore, any angle of 5° or less may or may not be due to slope movement."

b) Pre-shot surveys were completed October 10, 1965; the nearby event occurred in December 1965 and post-shot surveys were completed April 11, 1966. The period between surveys was about six months. Surveys in January and May 1963 showed relatively rapid changes in slopes in the three and one-half month period as a result of weathering and slumping, Reference 1. It was anticipated that the degradation would decrease with time. The fact that stakes were driven into the ground to a depth of four feet should have minimized the effect of surface weathering on the surveys. However, during the six-months period, some slumping may have resulted from erosion.

c) During this period there were several underground nuclear events which caused sufficient ground motion to produce some sliding. The motions caused by these events were calculated using ground motion prediction equations. Employing an approximation of the same procedures as in this report, it was calculated that the maximum increase in permanent downslope displacements would be about 17%.

3.4 AERIAL PHOTOGRAPHY

Since good data on slope deformation were obtained by the before and after surveys described above, no detailed analysis or development of before and after contours from the aerial photographs was attempted.

3.5 EFFECTS

Small cracks around the rim of the Sedan Crater are shown in Figure 3.2.

3.6 ANALYSIS OF DATA

Before and after surveys for Stations A-1, B-1, C-1, N-1, S-1 and W-1 on the crater lip showed small displacements in most cases (see Figures 3.3 to 3.8). These changes were considered as not susceptible to the adopted analytical procedure for slopes.

Stations 2 and 3 on lines A, B, C, N, S and W were located on the sides of the true crater (Figures 3.2 through 3.8). The material at these locations had been disturbed by the effects of

ELEVATION

SEDAN CRATER PROFILE 'A'
showing permanent displacements from nearby event

Figure 3.3

SEDAN CRATER PROFILE 'B'
showing permanent displacements from nearby event

Figure 3.4

Figure 3.5

Figure 3.6

3-12

SEDAN CRATER PROFILE 'S'
showing permanent displacements from nearby event

Figure 3.7

SEDAN CRATER PROFILE 'W'
showing permanent displacements from nearby event

Figure 3.8

the Sedan explosion but had not been ejected. Stations 4, 5 and 6 on lines A, B, C, N, S and W were located in fallback material, which increased in depth normal to the slope, with decrease in elevation (see Figure 1.1).

Station S-4 was selected for the initial analytical effort. Several methods were tried, with only partial success. The procedure used in Reference 4 is based on a higher shear strength of granular material after mobilization of resistance, dropping to a lower value after adjustment of grains. This did not seem to apply to conditions of Sedan Crater slopes because slides undoubtedly occurred during original fallback and from erosion thereafter (Reference 1). Also, there were other events causing sufficient ground motion at Sedan Crater to produce some slides. Therefore, it was concluded that there was no initial resistance to sliding associated with the rearrangement of particles.

Accelerations directed toward the center of the crater were plotted as a function of time. From these, velocity and displacement graphs were developed in accordance with procedure described as shown in Figure 8 of Reference 4. In view of the fact that k_y was assumed to be zero, the entire upper half of the acceleration graph was applicable. This method was reasonably successful but less directly applicable than that described in the next paragraph.

3.6.1 Analysis of Slope Displacement at Station S-4, Revised Procedure

Since the measured displacements as a function of time are available at the Sedan Crater Station (Figure 3.1), it appeared that these could be utilized to arrive at a computed downslope displacement.

The lower slopes consisting of fallback material were reported to be at the angle of repose (Reference 1). If so, the following changes would affect Equation (7) derived previously, when $\phi_{eq} = \alpha$

$$\frac{d^2x}{dt^2} = C g \left(k_h(t) - k_{yh} (1 - k_v(t)) \right)$$

$$k_{yh} = \tan (\phi_{eq} - \alpha) = 0$$

The above equation then reduces to $\frac{d^2x}{dt^2} = C g k_h(t)$, where $g k_h(t)$ = horizontal acceleration in cm/sec² or feet/sec² depending on which value of g is selected. The equation may be written

$$\frac{d^2x}{dt^2} = C \frac{d^2x_h}{dt^2}$$

According to developed theory, downslope displacement will occur only when horizontal velocity is toward the center of the crater. For the displacement record (Figure 3.1), this would be

only during the period when displacement is increasing in a positive direction for slopes on the side of the crater nearest the explosion. (For slopes on the side furthest from the explosion, the period would be considered only when displacement is increasing in a negative direction.)

If we solve the differential equation above, then

$$x = C x_h$$

That is, the downslope displacement equals the horizontal displacement at that station multiplied by the constant C for that station.

Referring to Figure 3.1, note that the direction of ground motion is the reverse of that of the pendulum. The period of positive velocity (when displacement is increasing in a positive direction), extends from negative to positive peak displacements. Adding values of trace amplitude from the record for Sedan Crater Station gives the following results:

0 to + 0.8	0.8
-3.2 to + 2.9	6.1
-1.95 to + 1.95	3.9
-0.50 to + 15	0.65
-0.95 to + 1.05	2.00
-0.96 to + 0.42	1.38
-0.18 to + 0.50	0.68
-0.38 to + 0.30	0.68
-0.06 to + 0.12	0.18
-0.18 to + 0.22	0.40
-0.15 to + 0.20	0.35
0 to + 0.25	0.25
-0.16 to + 0.30	0.46
-0.01 to + 0.18	0.17
-0.1 to + 0.10	0.09
	<u>18.09</u> cm

Dividing by the instrument magnification factor, $\frac{18.09}{0.253} = 71.5$ cm.

The above value represents the sum of the horizontal displacements in a direction toward the center of the crater.

Since the motion is desired at Station S-4 and measurements were at the Sedan Station, it is necessary to correct for the difference in location. This is done on the basis of the ratio of the peak radial displacement observed at Sedan Station, 12.65 cm, and the corresponding computed value at Station S-4, 17.2 cm (Table 3.1).

$$\text{Ratio} = \frac{17.2}{12.65} = 1.36$$

$$x_h = 1.36 \times 71.5 = 97.24$$

$$C = \sin \alpha \tan \phi_{eq} + \cos \alpha$$

Since $\alpha = 35^\circ$, it follows that $\phi_{eq} = 35^\circ$

$$C = \sin 35^\circ \tan 35^\circ + \cos 35^\circ$$

$$= 1.221$$

Table 3.2 shows the slope angle from the profile, Figure 3.7, obtained by use of a protractor. It was considered probable that the general slope angle would be more significant as a determinant of displacement. Therefore, 35° is used for all stations 4 through 6 on all lines.

TABLE 3.2 COMPARISON OF COMPUTED AND MEASURED DISPLACEMENT

Station	Slope α°	α Used In Comp. $= \phi_{eq}$	Comp. Disp. ft.	Observed Disp. ft.	*Difference ft.
S-1				.9	
2	38	38°	4.0	2.5	-1.5
3	43	38°	4.0	3.1	-0.9
4	36	35°	3.9	11.0	+7.1
5	36	35°	3.9	12.3	+8.4
6	36	35°	3.9	10.9	+7.0
B-1				1.8	
2	21	38°	5.1	2.2	-2.9
3	54	38°	5.1	1.4	-3.7
4	38	35°	4.9	5.1	+0.2
5	29	35°	4.9	4.1	-0.8
6	23	35°	4.9	3.9	-1.0
C-1				.6	
2	39	38°	5.5	3.4	-2.1
3	39	38°	5.5	1.8	-3.9
4	36	35°	5.3	3.5	-1.8
5	31	35°	5.3	3.6	-1.7
6	18	35°	5.3	Lost	
N-1				.5	
2	41	38°	3.7	1.6	-1.1
3	43	38°	3.7	4.6	+0.9
4	35	35°	3.5	2.0	-1.5
5	35	35°	3.5	8.5	+5.0
6	35	35°	3.5	9.8	+6.3
A-1				.5	
2	38	38°	4.3	.8	-3.5
3	41	38°	4.3	6.3	+2.0
4	33	35°	4.2	3.8	-0.4
5	33	35°	4.2	3.9	-0.3
6	25	35°	4.2	1.8	-2.4
W-1				.5	
2	15	38°	4.1	2.4	-1.7
3	38	38°	4.1	2.9	-1.2
4	35	35°	4.0	2.2	-1.8
5	32	35°	4.0	4.4	+0.4
6	29	35°	4.0	1.1	-2.9

* Difference = observed minus computed.

Downslope displacement is then computed as follows:

$$\begin{aligned}x &= C x_h = 1.221 \times 97.24 = 118.7 \text{ cm} \\&= 3.9 \text{ feet}\end{aligned}$$

The observed permanent displacement = 11 feet, and the difference between the computed and the observed displacement is 7.1 feet. Since the slope angle is near the angle of repose it is possible that local instabilities may result. Greater scatter would be anticipated under these conditions. Also, during the six-month period between pre-shot and post-shot surveys additional displacement may have resulted from the following: erosion, creep, movements of personnel, and nuclear detonations. Approximate calculations indicate that displacements caused by ground motions from nuclear detonations during this period may have been as much as 17% of those computed for this event.

3.6.2 Analysis at Station N-4

The same procedure was used for Station N-4 except that directions toward the center of the crater were considered positive instead of negative (Figure 3.1). Displacements from plus peaks to negative peaks were selected: + 0.80 to -3.20, etc. The computed downslope displacement was 3.6 feet and the observed 2.5 feet, a negative difference of 1.1 feet.

3.6.3 Slope Stations S-2, S-3, N-2 and N-3

These stations on the sides of the true crater had greater stability and steeper slopes. The slopes were composed of material more or less in its original state as opposed to the fallback material at Stations S-4 and N-4. They were denser and, although disturbed by cratering movements, their physical properties and angle of internal friction differed from the fallback material as disclosed from tests (Reference 1).

Since there was no consistent relationship between the motions, the only satisfactory way to compute simultaneously the effect of the horizontal and vertical components of motion would have been to develop a computer program based on Equation (7). This was not practicable at the time and did not appear warranted on the basis of the quality and assumptions inherent in the data. It was decided, therefore, to treat these upper slopes in a manner similar to the fallback regions, that is assume that upper slopes were at the angle of repose and that $\phi_{eq} = \alpha$. The displacement record was used to compute the total motion for the stations on the upper slopes.

$$C = \sin \alpha \tan \phi_{eq} + \cos \alpha \text{ (Equation 7)}$$

$$\alpha = \phi_{eq} = 38^\circ$$

$$\begin{aligned} \text{Therefore } C &= \sin 38^\circ \tan 38^\circ + \cos 38^\circ \\ &= 1.269 \end{aligned}$$

Correction factor for difference in location of Station S-3
and Sedan Crater Accelerograph Station = 1.36

$d_h = 71.5$ cm (sum of horizontal displacements toward center of crater developed from Figure 3.1)

$$x = C x_h = 1.269 \times 1.36 \times 71.5 = 123.5 \text{ cm or } 4.0 \text{ ft.}$$

Stations N-3, N-2 and S-2 were analyzed in the same manner. The same slope, 38° was used for stations 2 and 3 on all lines. It is believed that localized variations in slope would not be significant as determinants of general downslope displacements.

3.6.4 Stations on Lines A, B, C and W (Figure 3.2)

These stations are located on slopes at an angle to the line from GZ. Hence, the procedure used was first to add up all the transverse displacements a) where velocity was from right to left and b) vice versa. The resultant (in the plane of the profile) was obtained by adding the components of the total radial and total transverse displacements. The procedure then was similar to that for lines S and N.

3.6.5 Results

Displacements computed by the above procedures and those observed by before and after surveys are compared in Table 3.2.

CHAPTER 4

DISCUSSION

4.1 GENERAL

Computed and observed displacements compare fairly well, considering the uncertainties involved. More detailed study of conditions along each line might disclose the reasons for variation. It is not certain that additional effort would clarify results substantially. Several questions arose in the process of analysis and those that appear to be more important are discussed below.

4.2 VALIDITY OF THE MODEL

It is assumed that the loose sand can be represented by a block on an inclined plane, with the inclined plane and the block both subjected to the same ground motion. It has been assumed that sliding occurs only when velocity is toward the center of the crater, and this may not be completely true. A possible mechanism may be as follows. The velocity increases to a peak value in the direction of the center of the crater, then begins to decrease. The deceleration causing the decrease may not be as effective on surface loose particles since there is no tensile bond. In the case of stations in fallback material,

little resistance to sliding exists. Therefore, surface particles would tend to move down the slope with the initial momentum imparted at the time of the peak velocity discussed above. During this period the surface particles would be in continuing motion, disassociated in part from particles directly underneath. The tendency would be to have a loosening of the surface material as it slides. In other words, the portion of the slope represented by the sloping plane is pulling away from the loosely coupled particles. When the velocity is reversed, and motion is again toward the center of the crater, the tendency would be to increase compaction of the surface material because of the outward acceleration of the slope. The force associated with the acceleration would increase the frictional resistance to sliding. This would tend to bring the surface material to rest.

4.3 RELATIONSHIP OF COMPONENTS OF MOTION

Study of the record from the Sedan Crater Station shows no simple relationship between components of motion. For example, when the vertical acceleration is at a maximum in the initial portion of the record, the radial component of acceleration is very small. The peak value of vertical acceleration exceeds 1.0 g and therefore upward ballistic motion should occur, causing separation. Employing the procedures used in this report it developed that resulting downslope displacement would be small

because the horizontal acceleration had low amplitude at the time. It would appear that the separation and subsequent fallback to the slope would cause some sliding but this was neglected. One effect of the vertical component of motion is to vary the normal pressure on the slope which in turn increases or decreases the frictional resistance.

A lack of simple relationship will be noted on the record (Figure 3.1) for vertical, radial and transverse components. The method of adding all displacements, in the same direction, is only approximate.

4.4 DIRECTION OF RESULTANT GROUND MOTION

The direction and amplitude of ground motions would not necessarily be the same on the slopes as on flat areas at the same distance. This was neglected in the analyses.

4.5 STATIONS NEAR THE BOTTOM OF THE CRATER

The stations near the bottom have flatter slopes. Using the value of $k_y = \tan(\phi - \alpha)$ would have resulted in high resistance and a very small downslope movement. Displacement was generally much greater than that computed on the basis of $k_y = 0$. The greater depth of fallback material normal to the slope may have contributed to this. Alternatively, it may have resulted from

localized instability, erosion, personnel walking in the area or effects of ground motion between surveys.

4.6 EFFECTS OF GROUND MOTION BETWEEN SURVEYS

There were a number of events in the general vicinity of Sedan Crater between the dates of the pre-shot and the post-shot surveys. These events could have caused some sliding which might have increased the observed displacements from pre-shot and post-shot surveys by as much as 17%.

4.7 APPLICATION OF PROCEDURE TO NEW SITUATIONS

The procedure followed in this report requires either a record similar to that for the slope investigated or a simulated record. For earthquakes, the same procedure might be employed, though no investigation has been made of this.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL

The investigation of the effects of ground motion from a nearby event on the Sedan Crater slopes was useful. It was planned to assist in the development of a better means of evaluating the probability of slides in non-cohesive materials for operational safety. It may also be of value in connection with estimating the effects of ground motion on existing craters by subsequent explosions of a series for the proposed Interoceanic Canal.

5.2 ANALYTICAL PROCEDURE

The procedure developed by Professors Seed and Goodman was modified as described in paragraph 1.4. This consisted of the addition of a relatively simple expression, which was derived to include the effect of vertical acceleration. For this investigation it was not practical to include an analysis of its effect. A rigorous analytical method should include the simultaneous effects of both horizontal and vertical components of motion, employing Equation (7).

5.3 RESULTS OF ANALYSIS

There was considerable scatter in the data but considering the inherent difficulty in predicting slides in a non-cohesive material standing at the angle of repose, the analysis was reasonably successful.

5.4 USE OF COMPREHENSIVE GROUND MOTION PREDICTIONS FOR ANALYSES OF EFFECTS OF UNDERGROUND NUCLEAR EXPLOSIONS ON SLOPE STABILITY

The major effort of investigators of the effect of ground motion on slope stability has been in connection with earthquakes. Also, because it has been desirable to analyze the forces affecting the slopes, greater consideration has been given to ground accelerations. Means are available for predicting peak acceleration, velocity and displacement from underground nuclear explosions. These predictions can be made for the peak values of the three components and the peak resultant vector. In the future, it may be possible to predict the time history for each type of motion and component. Therefore, it appears that the investigator will have a far more useful basis for his analysis than has been the case for earthquakes. In this report, approximate methods were employed, for example, use of the sum of horizontal displacements of the ground toward the center of the crater to calculate total downslope displacement.

5.5 FUTURE INVESTIGATIONS

The opportunities for measurements of ground motion from underground nuclear explosions should be exploited. Consideration might be given to two types of tests as follows:

- (a) Non-destructive - In this category would be the measurements at the top, bottom and along the slope, and measurements of ground motions in the vicinity of a slope but sufficiently far away as not to be affected by local relief. The purpose would be to determine the relative ground motions for analytical purposes. This would be in general accord with plan of instrumentation adopted for the Sedan Crater to investigate the effects of ground motion caused by the Bye event.
- (b) Damage Investigation - Where damage to slopes is anticipated, measurements along the slopes may be difficult because of poor coupling and possible damage to instruments. Damage assessment can be established by pre- and post-shot measurements and photography. Also, some simple types of transient shear measurements at critical points along the slopes may be possible. Ground motion measurements

should be made in the vicinity to establish as accurately as possible the motion to which the slope is subjected.

- (c) Use of Computers - The use of computers to simulate the ground motion and response of the slope material was considered but ERC computers were being used on high priority work and in view of the uncertain quality of the data programming for slope stability computations did not appear to be warranted. This did not permit employment of an analytical procedure which included vertical as well as horizontal components of motion as a function of time. Therefore, the analysis was carried out manually. This was time consuming and made necessary the use of approximate procedures. The evaluation of observed data in relation to theory would be materially accelerated and benefited by use of computers. Particularly, the effects of change in parameters could be obtained readily for comparison with observations.

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