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SALMON GROUND MOTIONS AND EFFECTS

Final Report

April 1, 1965

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In reply refer
to RFB03839

Mr. Otto H. Roehlk, Director
Operational Safety Division
Nevada Operations Office
U. S. Atomic Energy Commission
P. O. Box 1676
Las Vegas, Nevada 89101

Dear Mr. Roehlk:

Herewith is transmitted fifteen (15) copies of final report
entitled "INVESTIGATION OF SALMON GROUND MOTIONS AND EFFECTS".

This report presents the final results of a review of ground
motion and soils data.

Very sincerely,

ROLAND F. BEERS, INC.

L. B. Luhrs
Assistant Director
for Research

LBL:mja

Enclosures

TABLE OF CONTENTS

	<u>Page</u>
CONCLUSIONS.....	1
1. INTRODUCTION.....	3
2. RECORDING INSTRUMENTS & LOCATIONS.....	4
3. USABLE DATA.....	6
4. COMPUTER ANALYSIS.....	6
5. AMPLITUDE RESULTS.....	7
6. FREQUENCY RESULTS.....	9
7. INTERPRETATION OF RESULTS.....	10

APPENDIX A

APPENDIX B

TABLES 1-4

FIGURES 1-32

MAPS 1-26

CONCLUSIONS

1. The damage ranges for peak particle velocity and acceleration vary with azimuthal direction from the Salmon explosion. These ranges can be reliably defined only in two azimuthal directions owing to the insufficient number of ground motion measurements. These directions are East and South. The maximum damage ranges (in miles) in these directions for particle velocity (10 cm/sec damage criterion) are 4.8 and 3.4, respectively. For acceleration (0.1 g criterion) in these directions it is 8.3 and 8.9, respectively. The maximum estimated range of damage (in miles) for particle acceleration is 9.5 and for velocity 6.3.
2. Low frequency ground motion associated with surface waves was present at short distances from the Salmon explosion but was not measured by the recording instruments located at these distances.
3. None of the damage immediately surrounding the Salmon site originated from ground motion generated by the Mexican earthquake.
4. Areal variation in peak amplitudes of particle motion appears to have originated at the source.
5. There is a resemblance of correlation between

complaints and areal variation of peak amplitudes of particle motion.

6. There is a body of circumstantial evidence which suggests that damage originated from the Salmon shot, whatever mechanism was involved.
7. The anomalous long period pulses displayed by the records recorded at Hattiesburg and Columbia did not originate at the source. Hence they are probably associated with a local phenomenon.
8. There is no consistent relationship between the general soil conditions at Columbia, Hattiesburg, and the Gulf Oil Refinery - Purvis and the anomalous long period pulse observed at Columbia and Hattiesburg.

1. INTRODUCTION

On October 22, 1964 the Atomic Energy Commission detonated a five kiloton nuclear device called Salmon at a depth of 2700 feet within the confines of the Tatum Salt Dome located in Lamar County, Mississippi. According to accepted criteria, damage to buildings or other facilities from ground motion generated by the explosion should have been limited to a distance of 12 miles or less. However, damage claims were received from local residents located at distances in excess of 25 miles.

Before paying these claims, the Atomic Energy Commission desires to establish their validity. To do this, each of its operational safety contractors has been requested to conduct specified investigations in its area of contractual responsibility. The final scope of work to be performed by Roland F. Beers, Inc. was as follows:

1. Investigate the possibility that there were long-period surface waves associated with the Salmon event which were not observed by the instruments used within 100 miles of surface zero.
2. Analyze all ground motion data collected and presented by the USC&GS for observations made within 100 miles of surface zero.

3. Analyze data to determine possible correlations with:

- a) Reports of damage.
- b) Consolidation, compaction, or other changes in soils under bearing loads of structures.
- c) The subjective relationship between personnel observations of ground motion and their subsequent report of damage.

2. RECORDING INSTRUMENTS AND LOCATIONS

The seismic waves generated by Salmon explosion were recorded to distances of thousands of kilometers. In this study, attention has been primarily focused on the peak surface ground motions associated with these waves at distances of 100 miles or less. Insight into the character of the ground motions at these distances is provided by data recorded at 29 stations surrounding the test site.

Twenty-six of these 29 stations were established by the USC&GS and three were established by Wiss, Janney, Elstner & Associates. The location of each USC&GS station and its complement of instruments is shown on Figures 1 and 2.

The location of each Wiss, Janney, Elstner & Associates

station and its complement of instruments is shown on Figure 3.

A common failing of the recording instruments used at distances of 100 miles or less is poor low-frequency response. Hence, the seismic data acquired at these distances does not provide very much insight into the low-frequency characteristics of the ground motion. To obtain this insight, seismic data recorded with 25 second period Sprengnether instruments at the five nearest stations of the long-range seismic measurements (LRSM) program were analyzed. These stations are identified by the following names:

1. Jena, Louisiana
2. Eutaw, Alabama
3. Cumberland Plateau Observatory, Tennessee
4. Grapevine, Texas
5. Wichita Mountain Observatory, Oklahoma

The locations of these stations with respect to Salmon are shown on Figure 4.

Included in the information examined at distances greater than 100 miles is the data recorded by the three distant USC&GS velocity stations. The locations of these stations are shown with the (LRSM) stations on Figure 4.

3. USABLE DATA

All together, 165 usable seismic records were recorded with 11 types of instruments located at the 37 stations of interest. The distribution of this data by type and component of motion is shown by Table 1.

Of the 165 usable seismic records obtained, 43 were recorded on magnetic tape and 121 were recorded on paper. All 43 magnetic tape recordings and 94 of the paper recordings have been processed by computer. Not processed by computer were the 15 seismic paper recordings obtained by Wiss, Janney, Elstner & Associates and the 12 USC&GS Wood-Anderson paper recordings.

4. COMPUTER ANALYSIS

The analog computer programs used for analysis of magnetic tape seismograms recorded with NC-21 velocity meters extend the analyzable frequency range by compensating for non-linear transducer response, derive displacement and acceleration from recorded velocity, and provide amplitude-frequency information by band-pass filtering.

The analog computer programs used for analysis of magnetic tape seismograms recorded with long-period Sprengnether

and short-period Benioff displacement meters compensate for non-linear transducer response.

The digital computer programs used for analysis of paper seismograms recorded with USC&GS strong motion accelerometers, displacement and vibration meters extend the analyzable frequency range by compensating for non-linear transducer response, derive velocity from recorded acceleration and displacement, and provide Fourier spectra. Additionally, they extract the peak values of the total vector and component motions and determine the equation of the least squares regression line fitting each set of peak values.

5. AMPLITUDE RESULTS

Tables 2 and 3 list the amplitudes and arrival times of the vector (Z,R,T) components and total vector of corrected peak surface particle displacement, velocity, and acceleration for the USC&GS recording station locations. Table 4 lists the amplitudes, periods, and arrival times of the vector (Z,R,T) components of corrected peak surface particle displacement recorded at the AFTAC-LRSM stations from Salmon and the Mexican earthquake. No graphic display of the data from Table 4 is included.

The attenuation with distance and direction of peak amplitudes of the vector (Z,R,T) components and total vector for each type of ground motion is shown by Figures 6-29.

On Figures 6-18 the different plotted symbols (see Figure 5) denote the different types of instruments used in recording the data. The different plotted lines on these figures are the graphs of the least squares regression equations for different groups and combinations of data by type of instrument. Use of this procedure made it possible to compare corrected and uncorrected data and examine variation in the attenuation of amplitude with distance and the effects of control on this attenuation. On Figures 19-29 the different plotted symbols (see Figure 5) denote the azimuthal location of the recording station with respect to the Salmon site. The different plotted lines on these figures are the graphs of the least squares regression equations for different azimuthal groupings of the data.

Maps 16-19 show the areal variation of the amplitude of the vector (R,T) components of corrected and uncorrected (Wiss, Janney, Elstner & Associates; Stations 1N, 2N, 3N) surface peak particle displacement and velocity. Contour

maps of the vertical components of these particle motions and all of the components of particle acceleration have been omitted owing to poor areal control. However, the contour maps of these latter motions show a close correlation to the maps provided where data are available.

6. FREQUENCY RESULTS

A. Band-Pass Filtered Data

Figures 30, 31 and 32 show the results of an analysis of the amplitude-frequency composition of the vector components (Z,R,T) of the peak ground motions recorded at stations 10S, 20S, 160SW and 272SW. These graphs show the variation with distance of amplitude, frequency, and time duration of the particle velocity at the time of peak displacement, velocity, and acceleration, respectively.¹

B. Fourier Spectra Data

Maps 1-12 show the areal variation of the amplitude of the vector (Z,R,T) components of surface particle velocity at different frequency bandwidths. These results have been extracted from Fourier spectra.¹ They are, however, similar to the results extracted from the band-pass filtered data. This has permitted the inclusion of particle

¹Additional information on this analysis will be found in Appendix A.

velocity amplitudes for similar frequency bandwidths extracted by band-pass filtering with the data extracted from the Fourier spectra. The reader should note, however, that an adjustment in the measured band-pass data (recorded in tabular form on maps 7-12) for stations 10S and 20S is required to insure compatibility with the Fourier data. Tabular values for these stations were adjusted so that the number of cycles would approximately equal those of nearby stations--assuming the average amplitude times the number of cycles was constant. The adjusted values were contoured.

Maps 13-15 show the areal variation of the frequency having greatest Fourier or band-pass amplitude for vertical, radial, and transverse components of velocity.

7. INTERPRETATION OF RESULTS

A. Peak Amplitudes

Figures 6-17, showing the variation with distance of the peak amplitudes of the vector (Z,R,T) components and total vector for each of the particle motions, suggest that the data are more accurately described by two least squares regression equations rather than one. (It should be noted,

however, that these figures show the variation with distance of all the peak amplitude data without regard to direction.) Insight into the probable origin of this apparent change in rate of attenuation of amplitude with distance is provided by maps 16-19. These maps show that there is appreciable asymmetry in the areal variation of peak amplitudes with direction. When all of the data are plotted on one graph without considering direction (as in Figures 6-17), this asymmetry results in increased scatter and fallacious indications of rates of attenuation.

Figures 18-29 show the variation with distance and direction of the peak amplitudes of the vector (Z,R,T) components and total vector for each of the particle motions. The least squares regression equations fitted to this data according to its azimuthal location show that peak amplitudes of the particle motions attenuated most rapidly towards the south, least rapidly towards the north, and at a rate intermediate between north and south towards the east. These results, however, are based on meager, unequal amounts of data--the smaller the amount of data, the lower the rate of attenuation. Maps 16-19 reinforce this observation and show that it is also true areally.

The experimental validity of these results is thus questionable.

The damage ranges for peak particle velocity and acceleration vary with azimuthal direction from the Salmon explosion. These ranges can be reliably defined only in two azimuthal directions owing to the insufficient number of ground motion measurements. These directions are East and South. The maximum damage ranges (in miles) in these directions for particle velocity (10 cm/sec damage criterion) are 4.8 and 3.4, respectively. For acceleration (0.1 g damage criterion) in these directions it is 8.3 and 8.9, respectively. The maximum estimated range of damage (in miles) for particle acceleration is 9.5 and for velocity 6.3.

A table listing these ranges by components follows. CM and RL refer to values taken from contour maps and regression lines respectively.

B. Low Frequency Ground Motion

Corrected data recorded with USC&GS strong motion and velocity instruments show no evidence of low-frequency ground motion. This is not, however, sufficient basis

Distance to 10 cm/sec Velocity (Miles)

	Areally		South		East	
	CM	RL	CM	RL	CM	RL
Vertical	6.3	4.0	1.8	3.1	1.8	3.1
Radial	6.0	2.8	2.3	2.5	3.2	3.1
Transverse	1.2	1.2	1.0	1.6	0.4	0.6
Resultant Vector	4.8	4.0	2.3	3.4	4.8	3.7

Distance to 0.1 g Acceleration (Miles)

	Areally		South		East	
	CM	RL	CM	RL	CM	RL
Vertical	7.5	7.4	5.7	6.2	6.6	7.4
Radial	6.6	5.6	3.7	4.6	5.8	6.2
Transverse	5.7	4.0	2.6	3.4	1.9	2.8
Resultant Vector	9.5	9.3	8.9	6.2	8.1	8.3

for concluding that no low-frequency ground motion was present. Recovery of low-frequency information through use of frequency compensation is limited by the signal-noise ratio. Outside the designed range of frequency response, currently used recording instruments very quickly reduce the signal level to that of the background noise.

Some insight into the probable low-frequency character of the ground motions at short distances from Salmon is provided by the data recorded with long and short period displacement meters located at Jena and Eutaw, the closest (243 kilometers) AFTAC-LRSM stations (see Table 4). When compensated for the transducer's non-linear amplitude response across the frequency spectrum, the analyzable frequency range of this data covers periods ranging from 3.3 to 0.1 and 33.3 to 3.7 seconds.

This data shows that the lowest-frequency particle displacement was associated with surface waves of period 13.7 seconds. This period is the exception, however, as the longest periods of most of the particle displacement data are less than 10.0 seconds. Closer than 243 kilometers from Salmon the lowest-frequency particle displacements

must have had shorter periods owing to wave dispersion. A measure of the amount of this dispersion is provided by the difference in periods between Jena and Grapevine and between Eutaw and Cumberland Plateau. If the wave dispersion for these distances is diagnostic of the entire transmission path, the lowest frequency of the particle displacements at short distances from Salmon could not have been too different from those recorded at Jena and Eutaw. On the basis of the above data it would appear that the recording instruments located at short distances from Salmon did not record low-frequency ground motions even though such motions were present.

Additional support for the thesis that low frequency ground motion was present near Salmon is provided by the 0.7 to 7.9 seconds periods of the water level fluctuations recorded at Well HT-2 by the USGS. The longer period water level fluctuations of 6.25 and 7.9 seconds at HT-2 are commensurate with those which would be expected for the surface waves recorded at Jena and Eutaw at the distance of this well from ground zero (6,180 feet). The principal discrepancy in available water level fluctuation data is that no long period fluctuations were recorded at Wells

HT-3, HT-5, and E-9 located closer to ground zero than HT-2. A possible explanation for the absence of long period water level fluctuations in these wells is that they were located too close to the explosion.

There is a theoretical minimum for the distance from the shot at which Rayleigh waves can appear.¹ At this distance the Rayleigh wave amplitude is a minimum. For a theoretical shot buried 2,700 feet (the depth of Salmon) beneath the surface of an isotropic, elastic medium this distance is 1,692 feet. (For a shot in real media this distance must be modified.) Wells HT-3, HT-5, and E-9 were 1,780, 1,800, and 1,700 feet, respectively, from ground zero. Well HT-2, which did exhibit long period water level fluctuations, was 6,180 feet from ground zero. This suggests that low frequency Rayleigh waves were generated by Salmon.

C. The Mexican Earthquake

Table 4 includes a list of the peak amplitudes of the vector (Z,R,T) components of surface particle displacement recorded from the earthquake. Comparison of the earthquake and Salmon values shows that the ground motions resulting

¹Elastic Waves in Layered Media, W. M. Ewing, W. S. Jar-detzky, F. Press, McGraw-Hill, New York, 1957, pp. 60-61.

from the earthquake could not have been responsible for the damage near the Salmon site.

D. Origin of Areal Variation Peak Ground Motion

Correlation of Maps 16-19 with the regional geology of the area discloses no consistent relationships which would account for the observed areal variation of peak amplitudes. All of the high-velocity layers from the Clayton Formation to the surface which would appear to be potentially good refractors of seismic energy show changes in regional dip, thickness or velocity which are inconsistent with the areal variation of peak amplitudes of ground motion. The same also applies to the Wilcox-Midway Group as regards its having channeled seismic energy.

Correlation of Maps 1-15, showing the variation with direction of amplitude at different frequency band widths, with the regional geology also discloses no consistent relationship which can be interpreted as a possible source of the areal variation. These maps, however, are based on even less control than that used to delineate the areal variation of peak amplitudes of ground motion and suffer accordingly. It should be noted that the variation with

direction of the amplitude of ground motion at all of the frequency band widths shows many similarities to the areal variation of the peak amplitudes. This suggests that frequency did not play a significant role at the distances involved.

The areal variation of peak amplitudes of ground motion (see Maps 16-19) appears to have been determined by the location of the shot in Tatum Dome and the cross-sectional shape of this dome at shot level.

To evaluate this hypothesis, the transmission coefficients for shot-generated plane longitudinal waves incident to the salt dome surface at shot level were computed. Maps 25 and 26 show the azimuthal variation of these coefficients for emergent waves. An emergent ray (transverse or longitudinal, Maps 26 and 25 respectively) intersecting any contour line on these maps resulted from an incident ray having a transmission coefficient equal to the value defined by the line. Hence these radial contour lines define regions of high and low transmission out of the dome.

The assumption has been made that inside the salt dome shot-generated energy was predominantly transmitted as

longitudinal waves. Map 26 shows that the transverse transmission coefficients are small enough so that the radiation out of the dome should be related to Map 25 rather than Map 26. Map 25 shows a high correlation with Maps 16-19--supporting the above stated hypothesis.

Map 20 shows the geographic location of damage claims from the Salmon event. Maps 16-19, which display the areal variation in peak particle displacement and peak particle velocity show considerable correlation with the complaint map (20). This correlation is not necessarily significant--as the distribution and density of claims can be due to factors other than the magnitude of motion, e.g., population density, housing density, soils, type and quality of construction, vegetation, etc. However, it does indicate that there may be a reasonable correlation.

E. Origin of Anomalous Pulses

At Columbia and Hattiesburg, particle displacement recordings display an anomalous long period pulse which does not appear elsewhere. This pulse appears on both of the horizontal components recorded at Hattiesburg but only the transverse component recorded at Columbia. The periods of

this pulse range from an estimated 6 seconds at Hattiesburg to an estimated 16 seconds at Columbia. An examination of available data indicates that they do not originate from the source but from a local phenomenon.

The evidence supporting this conclusions is as follows.

The pulse was not recorded at the Gulf Oil Refinery where instruments similar to those used at Hattiesburg and Columbia were emplaced. The period of the pulse at Columbia exceeds the longest period motion observed at much greater distances at the LRSM stations.

F. Soil Response at the Vibration Meter Sites

The properties of the soils encountered in the upper 100 feet beneath the three vibration meter sites (Hattiesburg, Columbia and Gulf Oil Refinery) indicate low or non-sensitive stiff clays and dense sands. In view of the low intensity motion, high relative densities, insensitivity, and reasonable shear strengths of clays, it appears very unlikely that a) high pore pressures leading to liquefaction could have occurred in the sandy soils and b) that shear failures of the clayey soils occurred.

The differences in the soil conditions between the three sites do not conclusively support subsidence or other movement at Hattiesburg and Columbia as opposed to Purvis. At Hattiesburg there is a possibility that fill, which may be supporting the 40-year old warehouse, contains loose pockets tending to compact under vibration. This, however, is questionable as this fill must have been subjected to nearby truck and railroad vibration for at least 40 years. At

Columbia and Purvis the shallow foundation soils are not fill. Furthermore, the generally good quality of the buildings suggests that the soils beneath are most likely compacted--thus minimizing the likelihood of instability.

The relative proximity of regionally major rivers and saturation conditions at Columbia and Hattiesburg are in contrast with the Purvis site. However, there are higher relative densities at Columbia and Hattiesburg than at Purvis. Columbia and Hattiesburg rest on recent alluvium and Purvis on older Pleistocene silts, sands, and gravels. Finally, the absence of low plasticity clayey strata (CL) in the upper 95 feet at Purvis contrasts with the Hattiesburg and Columbia sites. Thus there is no consistent relationship between the observed ground motion and the general soil conditions at these sites.

If the irregular movement (suggesting tilting of the meters) registered by the instruments at Columbia and Hattiesburg is considered to be due to causes other than instrument malfunction, then some explanation may be sought in the presence of low plasticity clays interbedded with saturated silty sands at these two sites as opposed to Purvis.

Plausible mechanisms of movement or subsidence are not readily supported by the boring logs and the laboratory tests. The following general mechanisms are suggested--no conclusive evidence is available:

- a) Movement may have occurred at the interface between the overlying low plasticity stiff clays and thin, undetected layers of saturated, relatively loose silty sands. Such movements could have occurred if previous stresses had significantly decreased frictional resistance or if localized pore pressures buildup occurred in these undetected silty sand layers.
- b) Minute movements along slickensides of the clays may have been triggered by the low intensity vibration, provided significant prior stresses existed.

In conclusion, as the movement indicated by the vibration meters is at most in the neighborhood of one millimeter, it can reasonably be attributed to the complex response of subtle undetected variations of the in situ soils at Hattiesburg and Columbia. That more subsidence is indicated by the Hattiesburg rather than Columbia meter may be partially attributed to the fill.

A P P E N D I X A

APPENDIX A

Analysis of Band-Pass Filtered Data

Magnetic tape seismograms from NC-21 stations 10S, 20S, 160SW, and 272SW were band-pass filtered and displayed as described on pages 31-36 of Analog Computer Analysis of Magnetic Tape Seismograms by R. Lynch (NVO-1163-41). Center band frequencies used for this analysis were 0.41, 0.55, 0.75, 1.0, 1.35, 1.85, 2.5, 3.4, 4.6, 6.2, 8.4, and 11.3 cycles per second.

Peak acceleration, velocity, and displacement were determined from unfiltered records. The corresponding peaks were noted on the filtered records allowing for the 1.0 to 1.5 cycle delay of this filter. These peaks were associated with an event on each of the filtered records, the maximum amplitude of the associated events being noted. The largest maximum amplitude and the corresponding frequency was recorded from the filtered record with the corresponding-associated-event of largest maximum amplitude.

The event containing this largest maximum amplitude was terminated by being bordered in both increasing and decreasing time by two successive peaks or troughs of amplitude less than the maximum amplitude of the event. As no internal succession of two peaks or troughs less than the maximum amplitude were allowed, the event was

defined. The beginning and end of the event were chosen as the zero crossing following and preceding the early and late bordering low amplitude peaks and troughs respectively. The starting time, duration, and number of cycles of the event were recorded and the apparent frequency (equal to the number of cycles divided by the duration) was calculated and recorded.

Analysis of Fourier Frequency Data

Velocity spectra, the square of which is directly related to the energy spectra, were calculated from strong-motion seismographs and vibration meter recordings.

Velocity was obtained by differentiating displacement and by integrating acceleration. The Fourier transform of velocity from displacement was used to analyze frequencies below 3.00 cycles per second (cps) and the Fourier transform of velocity from acceleration was used to analyze frequencies above 3.00 cps. Where acceleration records were not available the Fourier transforms of velocity from displacement were used both above and below 3.00 cps.

The peak values, $\hat{Y}(f)$, of the Fourier transform of velocity and the frequency, f , at which they occurred were recorded in four frequency ranges: 0.351 to 0.861 cps, 0.861 to 2.14 cps, 2.14 to 5.34 cps, and 5.34 to 13.2 cps. The width of the associated pulse was taken as the difference between the two frequencies, on either side of the peak, at which the amplitude of the pulse was equal to 0.7 times the peak amplitude (the amplitudes between these two frequencies being greater than 0.7 times the

peak amplitude). Note that the root-mean-square (RMS) value of a sine (or cosine) wave is $0.707 = \sin 45^\circ$.

This pulse can be associated with the Fourier spectrum of a single characteristic frequency as discussed on pages 18-24 of Analysis and Interpretation of Squared Fourier Spectra by R. L. Gorman (NVO-1163-38). Using Figure C5 on page 24 of this reference one notes that the pulse width, measured from the 0.49 maximum amplitude points¹, is approximately 0.92 times the fundamental frequency. Hence the duration in time, Δt , of the single characteristic frequency to be associated with the measured peak pulse is

$$\Delta t = (\text{fundamental frequency})^{-1} = \frac{(0.92)}{(\text{Pulse Width})}.$$

The amplitude, Y_0 , associated with this single characteristic frequency can be computed as follows. Let

f = frequency associated with peak values of
Fourier transform (cps).

¹ $0.49 = (0.7)^2$, as Figure C5 represents a squared Fourier spectrum.

Δt = duration (sec) of frequency f

$$g(t) = \begin{cases} Y_0 \cos(2\pi ft), & t \in [0, \Delta t] \\ 0, & t \notin [0, \Delta t] \end{cases}$$

$\hat{Y}(f)$ = amplitude of Fourier transform at
frequency f

then

$$\hat{Y}(f) = Y_0 \int_0^{\Delta t} \cos^2(2\pi ft) dt = Y_0 \left(\frac{\Delta t}{2}\right)$$

provided $(f\Delta t)$ is an integer.

$$Y_0 = \left(\frac{2}{\Delta t}\right) \hat{Y}(f)$$

Y_0 , the amplitude associated with $\hat{Y}(f)$, the peak Fourier amplitude, was contoured on maps. The frequency f and its duration (no. of cycles) was noted.

Errata: A consistent error has been discovered which is within the margin of error of the measurements. For the sake of accuracy the values in the tables and on the maps should be multiplied by the following in order to obtain the best approximation to these values:

Multiply duration values in time and number of cycles by .88.

Multiply average amplitude by 1.14.

A P P E N D I X B

APPENDIX B

EVALUATION OF SOIL STABILITY AT THE CARDER VIBRATION METER INSTRUMENT STATIONS

INTRODUCTION

In order to establish a rational explanation for the anomalous signal suggesting the possibility of ground subsidence, the soil and related engineering aspects of the three Carder vibration meter instrument stations are examined. These instruments were located at the AEC warehouse at Hattiesburg; National Guard Armory, Columbia; and Gulf Oil Refinery near Purvis. The Hattiesburg and Columbia signals indicate what may be considered tilting of the vibration meter possibly caused by movement of the foundation and/or surrounding soil mass. The record at Gulf Oil Refinery does not indicate any irregularity. Elsewhere in the report these records are presented and discussed in detail.

Three soil exploration holes AEC-1, NGA-2, and NGA-1 were drilled at Hattiesburg, Columbia and Purvis respectively. In addition the preconstruction soil borings at the Gulf Oil Refinery were used to supplement the information. In this report only the results of these explorations will

be presented and discussed in the light of soil stability criteria. However, detailed and complete presentation of the boring logs as well as the results of laboratory analysis are presented in reports by the Waterways Experiment Station (WES). This is necessary because the preparation of this report could not await the completion of WES's reports on the soils and geology of the area. The analysis and evaluation is based on WES's midway reports and telecon transmission of logs and laboratory test results.

STABILITY CONCEPTS AND CRITERIA

Pertinent soil stability concepts and criteria are presented herein before describing and assessing the soil conditions at each site. It is important to stress that soil behavior under vibratory and earthquake loads is not so well understood as other aspects of soil mechanics where both experience and research have been greater.

The mechanism whereby soils lose their shear strength when subjected to vibrations or elastic waves of any origin depends, generally, on whether they are cohesive or cohesionless. Since most soils contain a distribution of grain sizes

varying from sands to silts to clays, their behavior would be the result of their combined characteristics.

Cohesive soils are those with sufficient clayey particle content such that their engineering behavior is significantly influenced by the sum of interparticle attractive and repulsive forces. These forces are electrochemical in nature and as a practical matter they manifest themselves through the property of thixotropy and the soil structure formed by the particles. Thus shear strength of clays depends heavily on these interparticle forces. When a clay sample is disturbed or remolded, its shear strength changes because of thixotropic and structural changes. Such a disturbance can be induced by vibrations. Since clays differ, the effect of remolding or disturbance causes varying degrees of change in shear strength. To measure the susceptibility of cohesive soils to a reduction of shear strength caused by a disturbance, the degree of sensitivity can be used. Sensitivity is defined as

$$S_t = \frac{\text{unconfined compressive strength undisturbed}}{\text{unconfined compressive strength remolded}}$$

Very sensitive clays are capable of slide flows. Adjectives

corresponding to various degrees of sensitivity are given in Terzaghi and Peck (Reference 1) as follows:

<u>Adjective</u>	<u>Sensitivity Ratio</u>
Most Clays	2-4
Sensitive	4-8
Extrasensitive	>8

These terms are not rigid and this scale can be expanded or subdivided to suit specific needs.

Cohesionless soils derive their shear strength and stability from the confining pressure and state of packing. The particles are too large for any electrochemical forces to exert appreciable influence compared to frictional forces. Loose saturated sands liquify when subjected to shock or vibration capable of building pore pressures, and thus reducing the intergranular pressures to zero. The state of packing, i.e., loose, medium or dense is measured by the relative density D_r . It indicates the in situ density in relation to the densest and loosest possible states of a soil with specific grain size particle distribution and particle shape.

Relative density is expressed by:

$$D_r = \frac{e_{\min} - e_{\text{nat}}}{e_{\max} - e_{\min}} = \frac{\gamma_{\text{nat}} - \gamma_{\min}}{\gamma_{\max} - \gamma_{\min}} \left(\frac{\gamma_{\max}}{\gamma_{\text{nat}}} \right)$$

where e is the void ratio* and γ is the unit dry density.

The subscripts are self-evident. Adjective and numerical values are given by Jumikis (Reference 2) as follows:

<u>Adjective</u>	<u>Percent Relative Density</u>
Loose	<33%
Medium	33% - 67%
Dense	67%>

In the field the standard penetration test (Terzaghi and Peck, p. 294) is a measure of relative density.

The characteristics of fine sands or coarse silts susceptible to liquefaction are given in Terzaghi and Peck as follows:

- a) Relative density less than about 0.4 to 0.5.
- b) Grains are chiefly rounded.

* Void ratio is the volume of voids to the volume of solids. It is related to porosity N by: $e = \frac{n}{1-n}$ or $n = \frac{e}{1+e}$.

c) The effective size* is less than 0.1 mm and the uniformity coefficient** less than 5.

d) The in situ porosity is at least 44%.

In addition to the looseness of soil the hydrodynamic head of the pore water is important. Recently Florin and Maslov (References 3 and 4) have proposed that the liquefaction potential be determined by considering the hydrodynamic head. This method, however, requires non-standard laboratory tests in the determination of dynamic compaction coefficients. Accordingly, the criteria recommended by Terzaghi and Peck are adopted herein.

Murphy (Reference 5) recommends that sands be compacted to a minimum relative density between 85 and 90% as a safeguard against excessive differential settlements during earthquakes.

More recently soil investigations have shown that some damage caused by earthquakes is attributable to loss of soil shear strength. Experience from these earthquakes is summarized

* This means that 10% of the particles are finer than 0.1 mm.

** Uniformity coefficient is the ratio D_{60}/D_{10} wherein D_{60} and D_{10} denote the diameter of the particle which has 60% and 10% of the sample finer than the size shown.

below as a further criterion of the susceptibility of certain soils to vibratory loading.

- a) The 1964 Alaska Earthquake. Reference 6 reports that slides were caused by liquefaction of uniform fine silty sands and failure of soft extremely sensitive clays. The uniformity coefficient of the sands appears to be less than 5 and voids ratios around 0.9 (porosity 47.5%). The clays display 0.3-0.5 tsf shear strength with sensitivities varying mainly from 15 to 50. The estimated accelerations were about 0.18 g and the duration of the main shock 4-7 minutes.
- b) The 1959 Jaltilplan, Mexico Earthquake. Reference 7 reports subsidence due to liquefaction of saturated fine uniform sands and silty sands with void ratios about unity (porosity 50%). Also it reports clays with sensitivities about 7+. Ground accelerations on firm ground were estimated at 0.07 g to 0.2 g.
- c) The 1960 Chilean Earthquakes. Reference 8 reports several soil failures attributable to liquefaction. The material was identified as 'silt'. It has 40

moisture content, a 50 to 70% liquid limit, a 10 to 30% plastic limit, an unconfined compressive strength in the natural state of 1 to 2 Kg/cm^2 (or tons/sqft), a sensitivity of 2 to 5, and it was classified generally as MH.* The intensity of the earthquake was X on the modified Mercalli scale.

Some recent experimental work is of interest and applicable to this case. It is cited below for background and supplemental criteria purposes.

- a) Experimental work by Pushkov (Reference 9) has led him to conclude that the liquefaction of fine saturated sands occurs when the particle velocity is about 7 cm/sec.
- b) Seed (Reference 10) has demonstrated by means of vibratory shear tests that the maximum shearing strain (or failure) depends on: total number of load cycles, duration of load cycle, and duration of interval between load cycles. Of interest to this study is the fact that loads considerably less than

* This group contains inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.

static failure loads can cause excessive deformations when cycled repeatedly. The soft, extremely sensitive Anchorage clays have failed after 50 cycles when loaded 80-100% of their peak static strength, at 1-2 cps frequency.

DESCRIPTION OF SOILS AND EVALUATION OF THEIR STABILITY

The Hattiesburg and Columbia sites are located on recent alluvium underlain by Tertiary clays shortly below the 100-foot depth. The Purvis site is on Pleistocene sands underlain by Tertiary clays at about the 95-foot depth. Complete geologic description will be reported by WES. The soil borings corresponding to Hattiesburg, Columbia and Purvis are identified by AEC-1, NGA-2 and NGA-3 respectively in a report being prepared by WES. NGA-3 in conjunction with the Gulf Oil Refinery preconstruction borings (reported in WES's Geology Report) was used in estimating the soil characteristics at the Gulf Oil Refinery site with reasonable confidence. A summary description of the soil properties at each site follows together with an evaluation of their susceptibility to vibratory motion.

Hattiesburg. With the exception of a clay, sand and gravel fill from 0 feet to 6 feet followed by a low plasticity clay (CL) from 6 feet to 12 feet and 32 feet to 40 feet, the entire boring indicates essentially a poorly graded sand (SP) or silty sand (SP-SM) to a depth of about 100 feet. From 40 feet to 99 feet the presence of clay and gravel layers has been reported. The contact with the Tertiary clay was established at 107-foot depth and the boring was terminated at 140 feet in clay. The low plasticity clay is insensitive with a sensitivity ratio averaging about one. Relative densities of 93% and 68% were measured in the sands and void ratios (using a specific gravity of 2.65) were calculated at 0.5 and 0.55 respectively. It is estimated that most sands from 40 feet to 107 feet would have a relative density around 90%. The relative densities indicate dense sands whose uniformity coefficient is about two and the effective size is considered to be greater than 0.1 mm. Accordingly, the liquefaction potential of these sands is extremely low. Further, an examination of the records (Table 2, main report) indicates that the intensity, frequency and number of cycles of reported motion

were insufficient to cause liquefaction of this dense sand. However, there is a possibility that loose pockets in the old fill (believed to be supporting the 40-year old warehouse) will have undergone compaction resulting in some subsidence. Since the area has been subjected to traffic vibrations of trucks and nearby railroad it seems questionable that such fill would still be loose after 40 years of service.

Columbia. From 0 feet to 10 feet a low plasticity clay (CL) changes into a clayey sand (SC) followed by about 3 feet of silty sand (SM). From 12 feet to 25 feet there is a layer of uniformly graded silty sand (SP-SM) followed by high and low plasticity (CH to CL) clay to about 54 feet. From there to 100 feet there are silty sands (SM) and uniformly graded silty sands (SP-SM). The sensitivity of the clays ranges from 1 to 2.2 denoting very low sensitivity. Therefore, the Salmon induced disturbance is not likely to have caused remolding and loss of shear strength. The relative densities range from 89% to 97% corresponding to very dense sands, which are not susceptible to liquefaction. The uniformity coefficient is about three and the effective size, 0.14 mm,

is slightly greater than 0.1 mm. These gradation characteristics suggest possible liquefaction susceptibility. However, considering both relative density and gradation in view of the intensity and duration of the recorded motion (Table 2, main report) the likelihood of liquefaction seems extremely remote. Judging by the quality and newness of the structure, it is considered that the low plasticity clays supporting the structure are sufficiently compact and stable. Thus, the likelihood of movements of the shallow foundation soils seems small.

Purvis (Refinery). From 0 feet to 95 feet there are layers of silty sands (SM), some clayey sands (SC) and uniformly graded silty sands (SP-SM) with relative densities from 70% to 90%. The silty sands (SM) are predominant. The Tertiary clay is of low plasticity (CL) with a very low sensitivity of 1.1. Unconfined, undrained compressive tests and the standard penetration resistance show this to be a stiff to hard clay. (It is considered that all deep lying Tertiary clays in the area are equally stiff.) Although the effective size of the silty sands is less than 0.1 mm, the uniformity coefficient is about 20-100. The

uniformly graded silty sands (SP-SM) have uniformity coefficients about 2 to 3 and effective size about 0.15.

These gradation features partially meet the liquefaction susceptibility criteria previously stated. However, in the light of the high relative densities, these sands cannot be considered susceptible to liquefaction.

COMPARATIVE EVALUATION OF THE THREE STATIONS
AND FURTHER CONSIDERATIONS

In general the similarities and dissimilarities of the soil conditions in the top 100 feet can be summarized as follows:

- a) The recent alluvium sandy soils at Columbia and Hattiesburg when compared to the older Pleistocene sands at Purvis have a lower silt content and higher relative densities.
- b) The water contents are about 20% $\pm$ 10% increasing in clays (CL) and decreasing in sands (SP).
- c) At Columbia and Hattiesburg all sandy soils (SM, SP, SP-SM) below about the 20 $\pm$ foot depth appear to be saturated. At Purvis, saturations between 80% and 90% were calculated for the sandy soils (SM, SP-SM) at all depths. Above about the 20 $\pm$ foot depth, saturations between 50% and 75% were calculated at all three sites. All calculations are based on field determinations of moisture contents.
- d) The stiff Tertiary clays which underlie the entire region appear to be somewhat closer to the surface at Purvis than at Hattiesburg or Columbia. (This applies only at the instrument stations).

- e) The lowest undisturbed undrained shear strengths of recent alluvium clayey soils were reported at Hattiesburg (0.56 tsf). Also at Hattiesburg there is a fill which probably reports the 40 year old warehouse in proximity to the railroad. At Purvis, no significant clayey strata appear to be in the upper 95 feet above the Tertiary clay. And at Columbia there are substantial layers of lean and fat clays (CL, CH) interbedded with the silty sands (SM, SP-SM).

The differences of the soil conditions among the three sites do not conclusively support a view suggesting subsidence or other movement at Hattiesburg and Columbia as opposed to Purvis. The relative proximity of regionally major rivers and saturation conditions at Columbia and Hattiesburg can be contrasted with the Purvis site. However, the higher relative densities at Columbia and Hattiesburg can be oppositely contrasted with the lower densities at Purvis. Finally, the absence of low plasticity clayey strata (CL) in the upper 95 feet at Purvis contrasts with Hattiesburg and Columbia sites.

The United States Geological Survey reported that the explosion did not affect the water levels of two wells, one

in Hattiesburg at 100-foot depth (east of Leaf River) and one SE of Hattiesburg at 400-foot depth. The lack of response suggests that at these distances perceptible pore pressure rise did not occur, thus further rendering the liquefaction concept improbable.

An examination of the structures containing the instruments was conducted both at Hattiesburg and Columbia. No conclusive evidence of building movements was observed at Hattiesburg (old building and many cracks) and none at Columbia.

Laboratory tests to determine the shrink-swell potential of the clays were conducted on samples taken from another location in Hattiesburg (see WES soils report). These tests indicate no tendency to absorb water and swell measurably. Accordingly, soil movements due to shrinkage and swelling attributable to the summer drought and Hurricane Hilda appear unlikely. Furthermore, the general drainage of these three sites and the probable soil permeabilities suggest that Hurricane Hilda water should have been dissipated by the time of the event about three weeks later. Thus, oversaturation of foundation soils does not seem likely.

CONCLUSION

In general the properties of the soils encountered in the upper 100 feet beneath the subject sites indicate low or non-sensitive stiff clays and medium to dense sands. In view of the low intensity of the recorded motion, high relative densities, insensitivity and reasonable shear strengths, it is very unlikely that a) high pore pressures leading to liquefaction could have occurred in the sandy soils, and b) that shear failures of the clayey soils occurred.

If the irregular movement registered by the instruments at Columbia and Hattiesburg is considered to be due to causes other than malfunction, then some explanation may be sought in the fact that low plasticity clays (CL) were interbedded with dense saturated silty sands at these two sites as opposed to Purvis. Plausible mechanics of movement or subsidence are not readily supported by the boring logs and laboratory tests. The following mechanisms are offered, although they are admittedly lacking in supporting evidence:

- a) Movement may have occurred at the interface between the overlying clay strata and thin

undetected layers of saturated silty sands.

Such movements could have occurred if previous stresses had significantly decreased frictional resistance and if localized pore pressure buildup occurred in undetected layers of susceptible silty sands.

- b) Minute movements along slickenslides of the stiff clays may have been triggered by the low intensity vibration provided significant prior stresses existed.

In conclusion, since the movement indicated by the vibration meters is in the neighborhood of one millimeter at most, it can be reasonably attributed to the complex response of subtle undetected variations of the in-situ soils.

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U.S.C. & G.S.

<u>STATION</u>	<u>INSTRUMENT</u>	<u>DISPLACEMENT</u>	<u>ACCELERATION</u>	<u>VELOCITY</u>
1 South	S.M.	RT	RT	
1 South	S.M.	RT	---	
2 South	S.M.	ZRT	ZRT	
3 South	S.M.	R	ZRT	
4 South	S.M.	RT	ZRT	
5 South	S.M.	ZRT	ZRT	
6 South	S.M.	RT	ZRT	
1 East	S.M.	RT	RT	
1 East	S.M.	ZRT	ZRT	
2 East	S.M.	ZRT	ZRT	
3 East	S.M.	ZRT	ZRT	
4 East	S.M.	ZRT	ZRT	
5 East	S.M.	ZRT	ZRT	
6 East	S.M.	ZRT	ZRT	
Baxterville	S.M.	ZRT	ZRT	
Oil Field				
Purvis	S.M.	T	ZRT	
Lumberton	S.M.	RT	ZRT	
Gulf Refinery	V.M.	ZRT		
Hattiesburg	V.M.	RT		
Columbia	V.M.	RT		
10S	NC-21			ZZZZRT
20S	NC-21			ZZZZRT
160 SW	NC-21			ZZZZRT
272 SW	NC-21			ZZZZRT
Circumferential	W.A.	RT		
"	W.A.	RT		
"	W.A.	RT		
"	W.A.	RT		
"	W.A.	RT		
"	W.A.	RT		

WISS, JANNEY, ELSTNER & ASSOCIATES

1 North	Sprengnether	ZRT	
	M-B 61 Vibration		ZRT
2 North	Sprengnether	ZRT	
	Shure Bros.		ZRT
3 North		ZRT	

AFTAC-LONG RANGE SEISMIC MEASUREMENTS

Eutaw	L.P. Sprengnether	ZRT	
	Benioff	ZRT	
Jena	L.P. Sprengnether	ZRT	
	Benioff	ZRT	
Cumberland	L.P. Sprengnether	ZN	
Plateau	Benioff	NE	
Grapevine	L.P. Sprengnether	Z	
	Benioff	Not Analyzed	
Wichita Mt.	L.P. Sprengnether	Z E	

TABLE 1

SALMON EVENT (4018)
STRONG MOTION DATA

Station	Record Number	Component	Slant Range (meters)	Peak Displacement (cm)	Time of Arrival of Peak (sec)	Peak Velocity (cm/sec) Derived from Displacement	Time of Arrival of Peak (sec)	Peak Acceleration (g's)	Time of Arrival of Peak (sec)	Peak Velocity (cm/sec) Derived from Acceleration	Time of Arrival of Peak (sec)
1 EAST	4017	V	1460	0.1966x10 ¹	0.2600	0.5990x10 ²	0.2300	0.1500x10 ¹	0.3500	0.3006x10 ²	0.2500
"	"	R	"	0.1473x10 ¹	0.8500	0.2295x10 ²	0.8200	0.7076x10 ⁰	0.8400	0.2052x10 ²	0.8300
"	"	T	"	0.2794x10 ⁰	1.5400	0.5846x10 ¹	1.5700	0.3836x10 ⁰	0.3334	0.4868x10 ¹	0.2800
"	"	VRT	"	0.1972x10 ¹	0.2600	0.6012x10 ²	0.2300	0.1504x10 ¹	0.3300	0.3087x10 ²	0.2500
1 EAST	4019	V	1460	----	----	----	----	----	----	----	----
"	"	R	"	0.1405x10 ¹	0.8750	0.2171x10 ²	0.8333	0.7316x10 ⁰	0.8800	0.1961x10 ²	0.8667
"	"	T	"	0.2352x10 ⁰	1.5083	0.4731x10 ¹	1.6833	0.3269x10 ⁰	0.3567	0.5232x10 ¹	1.3734
"	"	VRT	"	0.1405x10 ¹	0.8750	0.2171x10 ²	0.8333	0.7367x10 ⁰	0.8800	0.1966x10 ²	0.8667
2 EAST	4021	V	1980	0.7625x10 ⁰	0.4600	0.1997x10 ²	0.4300	0.1160x10 ¹	0.9200	0.2356x10 ²	0.4000
"	"	R	"	0.8503x10 ⁰	1.2000	0.1591x10 ²	1.3800	0.5133x10 ⁰	1.1900	0.2067x10 ²	1.0667
"	"	T	"	0.3211x10 ⁰	3.1800	0.3758x10 ¹	1.4100	0.1793x10 ⁰	1.4667	0.4213x10 ¹	0.3433
"	"	VRT	"	0.8625x10 ⁰	1.2000	0.2018x10 ²	0.4300	0.1160x10 ¹	0.9200	0.2405x10 ²	0.4000
3 EAST	4018	V	2160	0.8286x10 ⁰	0.5800	0.2192x10 ²	0.6400	0.1463x10 ¹	0.6834	0.2523x10 ²	0.7167
"	"	R	"	0.8380x10 ⁰	2.1100	0.1261x10 ²	2.0000	0.6388x10 ⁰	1.5334	0.1670x10 ²	2.0467
"	"	T	"	0.1664x10 ⁰	4.5700	0.3435x10 ¹	1.7500	0.1492x10 ⁰	1.2600	0.2920x10 ¹	1.7667
"	"	VRT	"	0.8383x10 ⁰	2.1100	0.2215x10 ²	0.6400	0.1516x10 ¹	0.6800	0.2617x10 ²	0.7167
4 EAST	4012	V	3110	0.1213x10 ⁰	1.4143	0.3726x10 ¹	1.2429	0.4936x10 ⁰	2.1800	0.6581x10 ¹	1.1866
"	"	R	"	0.6387x10 ⁰	1.9572	0.1781x10 ²	2.0000	0.1168x10 ¹	2.2000	0.2025x10 ²	2.8700
"	"	T	"	0.1157x10 ⁰	6.0572	0.2890x10 ¹	2.2286	0.1727x10 ⁰	2.1933	0.3573x10 ¹	2.1533
"	"	VRT	"	0.6411x10 ⁰	1.9572	0.1802x10 ²	2.0000	0.1200x10 ¹	2.2000	0.2523x10 ²	2.8700
5 EAST	4015	V	4080	0.4803x10 ⁰	1.6700	0.8752x10 ¹	1.7000	0.3938x10 ⁰	1.6950	0.9067x10 ¹	1.6650
"	"	R	"	0.5451x10 ⁰	2.3700	0.1227x10 ²	2.4200	0.3156x10 ⁰	2.3550	0.9866x10 ¹	2.4200
"	"	T	"	0.8693x10 ⁻¹	4.0900	0.2108x10 ¹	4.1500	0.6805x10 ⁻¹	2.4100	0.2149x10 ¹	4.1250
"	"	VRT	"	0.5614x10 ⁰	2.3700	0.1237x10 ²	2.4200	0.3947x10 ⁰	1.6950	0.9890x10 ¹	2.4200
6 EAST	4022	V	6060	0.4750x10 ⁰	2.0437	0.1275x10 ²	1.9187	0.3129x10 ⁰	2.1637	0.8420x10 ¹	2.1273
"	"	R	"	0.2112x10 ⁰	3.0249	0.6250x10 ¹	3.0812	0.1994x10 ⁰	3.1091	0.6132x10 ¹	3.0910
"	"	T	"	0.6457x10 ⁻¹	5.0312	0.1927x10 ¹	4.9937	0.8067x10 ⁻¹	5.0182	0.1543x10 ¹	4.9819
"	"	VRT	"	0.4842x10 ⁰	2.0437	0.1276x10 ²	1.9187	0.3170x10 ⁰	2.1637	0.8637x10 ¹	2.1273
PURVIS	4016	V	14500	----	----	----	----	0.4295x10 ⁻¹	6.8636	0.1140x10 ¹	5.9727
"	"	R	"	----	----	----	----	0.2003x10 ⁻¹	6.7273	0.7544x10 ⁰	6.6909
"	"	T	"	0.2390x10 ⁻¹	16.4250	0.2964x10 ⁰	13.4250	0.1082x10 ⁻¹	13.0000	0.2320x10 ⁰	13.3909
"	"	VRT	"	----	----	----	----	0.4307x10 ⁻¹	6.8636	0.1209x10 ¹	5.9818
1 SOUTH	4011	V	1460	----	----	----	----	----	----	----	----
"	"	R	"	0.1144x10 ¹	1.0000	0.2628x10 ²	0.8900	----	----	----	----
"	"	T	"	0.6608x10 ⁰	0.9100	0.1210x10 ²	1.0000	----	----	----	----
"	"	VRT	"	0.1146x10 ¹	1.0000	0.2713x10 ²	0.8900	----	----	----	----
1 SOUTH	4014	V	1460	----	----	----	----	0.4883x10 ¹	0.3300	0.3909x10 ²	0.3200
"	"	R	"	0.1144x10 ¹	0.9933	0.3877x10 ²	0.8833	0.1155x10 ¹	0.8134	0.2548x10 ²	0.9100
"	"	T	"	0.6014x10 ⁰	0.9100	0.1806x10 ²	0.9800	----	----	----	----
"	"	VRT	"	0.1145x10 ¹	0.9933	0.4035x10 ²	0.7700	0.4895x10 ¹	0.3300	0.4212x10 ²	0.3200
2 SOUTH	4024	V	1980	0.9388x10 ⁰	0.3500	0.2194x10 ²	0.3215	0.8779x10 ⁰	0.3765	0.1682x10 ²	0.3882
"	"	R	"	0.8902x10 ⁰	0.9857	0.1551x10 ²	1.0286	0.4176x10 ⁰	1.0000	0.1557x10 ²	1.5677
"	"	T	"	0.5940x10 ⁰	1.2929	0.7427x10 ¹	1.2500	0.2577x10 ⁰	1.3147	0.7744x10 ¹	1.4618
"	"	VRT	"	0.1048x10 ¹	1.2929	0.2206x10 ²	0.3215	0.8857x10 ⁰	0.3765	0.1727x10 ²	0.3882
3 SOUTH	4020	V	2160	----	----	----	----	0.5943x10 ⁰	0.5542	0.1449x10 ²	0.4750
"	"	R	"	0.5722x10 ⁰	1.4666	0.1528x10 ²	1.4166	0.6192x10 ⁰	1.4459	0.1301x10 ²	1.4250
"	"	T	"	----	----	----	----	0.2710x10 ⁰	1.4417	0.3990x10 ¹	1.1875
"	"	VRT	"	----	----	----	----	0.6708x10 ⁰	1.4459	0.1484x10 ²	0.4750
4 SOUTH	4023	V	3110	----	----	----	----	0.4981x10 ⁰	1.7350	0.1270x10 ²	1.6450
"	"	R	"	0.5394x10 ⁰	2.0667	0.1208x10 ²	2.1167	0.3649x10 ⁰	2.2250	0.1043x10 ²	2.1150
"	"	T	"	0.1668x10 ⁰	2.9333	0.2545x10 ¹	2.8833	0.1310x10 ⁰	2.2050	0.2461x10 ¹	2.7350
"	"	VRT	"	0.5398x10 ⁰	2.0667	0.1209x10 ²	2.1167	0.5188x10 ⁰	1.7350	0.1387x10 ²	1.6450
5 SOUTH	4025	V	4080	0.1658x10 ⁰	1.6235	0.5931x10 ¹	1.8353	0.2786x10 ⁰	1.6200	0.5028x10 ¹	1.8250
"	"	R	"	0.3979x10 ⁰	2.3177	0.6593x10 ¹	2.3882	0.2024x10 ⁰	2.3300	0.7192x10 ¹	2.3750
"	"	T	"	0.1132x10 ⁰	6.9177	0.1646x10 ¹	2.5177	0.8691x10 ⁻¹	2.5600	0.1818x10 ¹	6.8600
"	"	VRT	"	0.4001x10 ⁰	2.3177	0.6858x10 ¹	2.3765	0.2814x10 ⁰	1.6200	0.7424x10 ¹	2.3750
6 SOUTH	4026	V	6060	----	----	----	----	0.2663x10 ⁰	2.2461	0.8445x10 ¹	2.1923
"	"	R	"	0.1531x10 ⁰	7.6000	0.3251x10 ¹	3.0769	0.1088x10 ⁰	3.7000	0.2823x10 ¹	3.7384
"	"	T	"	0.5960x10 ⁻¹	5.6000	0.1288x10 ¹	3.1077	0.4781x10 ⁻¹	4.8538	0.1232x10 ¹	5.5076
"	"	VRT	"	0.1532x10 ⁰	7.6000	0.3264x10 ¹	3.0769	0.2706x10 ⁰	2.2461	0.8581x10 ¹	2.1923
BAXTERVILLE OIL FIELD	4013	V	9680	0.1279x10 ⁰	4.0546	0.2771x10 ¹	4.0909	0.5811x10 ⁻¹	2.9000	0.1433x10 ¹	3.6215
"	"	R	"	0.3234x10 ⁻¹	10.2909	0.8669x10 ⁰	5.8727	----	----	----	----
"	"	T	"	0.9320x10 ⁻¹	4.7818	0.2748x10 ¹	4.8364	0.7962x10 ⁻¹	4.6000	0.1650x10 ¹	5.2500
"	"	VRT	"	0.1279x10 ⁰	4.0546	0.3046x10 ¹	4.8364	----	----	----	----
LUMBERTON	4010	V	17700	----	----	----	----	0.2237x10 ⁻¹	8.6236	0.8004x10 ⁰	8.6706
"	"	R	"	0.6248x10 ⁻¹	8.5429	0.1105x10 ¹	8.6286	0.2622x10 ⁻¹	8.6941	0.1012x10 ¹	8.4941
"	"	T	"	0.5729x10 ⁻¹	8.5429	0.1060x10 ¹	8.6286	0.1582x10 ⁻¹	8.6824	0.5841x10 ⁰	8.4706
"	"	VRT	"	0.8477x10 ⁻¹	8.5429	0.1531x10 ¹	8.6286	0.3303x10 ⁻¹	8.6941	0.1216x10 ¹	8.6471
GULF OIL REFINERY	4007	V	18683	0.1121x10 ⁰	7.4000	0.2600x10 ¹	7.9640	----	----	----	----
"	"	R	"	0.5990x10 ⁻¹	27.0900	0.1154x10 ¹	9.8360	----	----	----	----
"	"	T	"	0.3659x10 ⁻¹	10.2700	0.7195x10 ⁰	----	----	----	----	----
"	"	VRT	"	----	----	----	----	----	----	----	----
COLUMBIA	4008	V	27852	----	----	----	----	----	----	----	----
"	"	R	"	0.2019x10 ⁻¹	14.0200	0.4001x10 ⁰	----	----	----	----	----
"	"	T	"	0.2075x10 ⁻¹	18.4700	0.2792x10 ⁰	18.3700	----	----	----	----
"	"	VRT	"	----	----	----	----	----	----	----	----
HATTIESBURG	4009	V	32663	----	----	----	----	----	----	----	----
"	"	R	"	0.2182x10 ⁻¹	16.7200	0.3871x10 ⁰	21.0000	----	----	----	----
"	"	T	"	0.4199x10 ⁻¹	16.4800	0.1108x10 ¹	17.0000	----	----	----	----
"	"	VRT	"	----	----	----	----	----	----	----	----

TABLE 2

SALMON EVENT - NC-21 DATA

Station	Record Number	Component	Slant Range (meters)	Peak Displacement (cm)	Time of Arrival (sec)	Peak Velocity (cm/sec)	Time of Arrival (sec)	Peak Acceleration (g's)	Time of Arrival (sec)
10 SOUTH	0100	V	17,800	0.1015×10^0	11.1	0.1116×10^1	8.3	0.3417×10^{-1}	8.6
"	"	V	18,100	0.3235×10^0	11.2	0.1383×10^1	8.5	0.3643×10^{-1}	8.5
"	"	V	18,400	0.8924×10^{-1}	11.5	0.9148×10^0	8.5	0.2676×10^{-1}	8.6
"	"	R	17,800	0.7809×10^{-1}	12.0	0.8701×10^0	8.7	0.2278×10^{-1}	8.7
"	"	T	17,800	0.2231×10^{-1}	9.8	0.3347×10^0	14.0	0.8541×10^{-2}	14.1
"	"	VRT	17,800	0.1060×10^0	11.4	0.1138×10^1	8.2	0.3303×10^{-1}	8.5
20 SOUTH	0200	V	30,800	0.2547×10^{-1}	14.1	0.4396×10^0	13.4	0.1019×10^{-1}	13.3
"	"	V	31,400	0.2647×10^{-1}	14.6	0.4895×10^0	14.2	0.1197×10^{-1}	14.2
"	"	R	31,700	0.2597×10^{-1}	19.3	0.4595×10^0	17.3	0.9427×10^{-2}	14.5
"	"	T	31,700	0.1249×10^{-1}	17.3	0.1698×10^0	19.3	0.4689×10^{-2}	15.6
"	"	VRT	31,700	0.2997×10^{-1}	14.6	0.5395×10^0	14.5	0.1228×10^{-1}	14.4
160 SOUTHWEST	1600	V	272,700	0.2115×10^{-3}	138.8	0.3249×10^{-2}	43.1	0.1048×10^{-3}	45.2
"	"	V	273,000	0.3806×10^{-3}	139.1	0.3329×10^{-2}	43.2	0.1088×10^{-3}	47.1
"	"	V	273,300	0.2960×10^{-3}	44.7	0.2932×10^{-2}	45.2	0.7859×10^{-4}	45.3
"	"	V	273,600	0.3214×10^{-3}	138.7	0.2219×10^{-2}	51.6	0.6287×10^{-4}	45.0
"	"	R	273,000	0.4019×10^{-3}	101.4	0.4279×10^{-2}	55.2	0.7456×10^{-4}	55.2
"	"	T	273,000	0.2960×10^{-3}	149.0	0.2774×10^{-2}	83.8	0.6447×10^{-4}	83.7
"	"	VRT	273,000	0.4759×10^{-3}	138.5	0.4359×10^{-2}	84.0	0.1048×10^{-3}	47.1
272 SOUTHWEST	2720	V	450,700	0.1142×10^{-3}	88.5	0.8235×10^{-3}	77.5	0.1457×10^{-4}	64.6
"	"	V	451,000	0.8035×10^{-4}	84.1	0.6810×10^{-3}	84.5	0.1457×10^{-4}	64.6
"	"	V	451,300	0.7189×10^{-4}	84.7	0.6494×10^{-3}	84.6	0.1335×10^{-4}	64.7
"	"	V	451,600	0.7612×10^{-4}	84.7	0.6494×10^{-3}	84.5	0.1295×10^{-4}	64.7
"	"	R	451,000	0.1100×10^{-3}	168.5	0.6650×10^{-3}	91.0	0.1133×10^{-4}	84.3
"	"	T	451,000	0.1142×10^{-3}	162.2	0.5541×10^{-3}	161.0	0.8901×10^{-5}	120.0
"	"	VRT	451,000	0.1142×10^{-3}	168.5	0.8392×10^{-3}	84.5	0.1457×10^{-4}	64.6

TABLE 3

			SALMON EVENT SHORT PERIOD (BENIOFF) BANDWIDTH 3.3 to 0.1 SECONDS			SALMON EVENT LONG PERIOD (SPRENGNETHET) BANDWIDTH 33.0 to 3.7 SECONDS			SALMON EVENT LONGEST PERIOD OBSERVED BANDWIDTH 33.0 to 3.7 SECONDS		MEXICAN EARTHQUAKE LONG PERIOD BANDWIDTH 33.0 to 3.7 SECONDS		
Station	Distance in km	Component	Peak Displacement in cm X 10 ⁻⁴	Period of Peak in Seconds	Time of Arrival of Peak From 1600 Z in Seconds	Peak Displacement in cm X 10 ⁻⁴	Period of Peak in Seconds	Time of Arrival of Peak From 1600 Z in Seconds	Peak Displacement in cm X 10 ⁻⁴	Period of Peak in Seconds	Peak Displacement in cm X 10 ⁻⁴	Period of Peak in Seconds	Time of Arrival of Peak From 1604:15 Z in Seconds
EUAL	242	Z	3.68	0.80	90	3.6	6.7	141	1.4	13.7	0.44	10.6	16.6
		R	8.18	0.90	112	1.7	6.7	141	1.2	7.2			
		T	7.02	0.90	112	3.5	3.7	228	1.3	11.2			
JELA	243	Z	4.2	1.00	110	3.8	8.3	166	3.4	9.5	0.90	10.5	13.5
		R	4.86	2.00	95	11.4	7.1	169	7.9	8.7	2.30	10.8	13.5
		T	6.15	3.30	80	3.5	6.1	194	1.7	8.1	0.90	10.6	13.5
CPO2	618	Z				0.6	6.4	228	0.5	10.0	0.40	11.5	17.1
		N	1.11	1.70	183	0.43	5.3	228	0.3	9.7			
		E	1.34	1.40	187								
GVTX	728	Z				0.6	6.3	407	0.4	8.4	1.10	12.8	10.4
WMO2	931	Z							0.3		0.22	16.1	10.9
		N									0.10		
		E							0.3				

TABLE 4

Figure 1. Area Map Showing Locations of USC&GS Instrument Stations Within 6 Miles of Ground Zero

Figure 2. Area Map Showing USC&GS Instrument Stations Located at Distances Greater Than 6 Miles

Figure 3. Area Map Showing Location of Wiss, Janney, Elstner & Associates Instrument Stations.

Figure 4. Long Range Seismic Measurements (LRS) Program
Stations and Long Distance USC&GS Velocity Stations

LEGEND

- O Strong Motion Stations
- Δ NC-21 Stations
- Other Recording Stations

AZIMUTHAL PLOTS

- East
- South
- ★ North

Figure 5

Slant Range, meters

Figure 6

Slant Range, meters

Figure 7

Figure 8

Figure 9

Slant Range, meters

Figure 10

Figure 11

Slant Range, meters

Figure 12

Figure 13

Figure 14

Slant Range, meters

Figure 15

Figure 16

Slant Range, meters

Figure 17

Slant Range, meters

Figure 18

Slant Range, meters

Figure 19

Figure 20

Slant Range, meters
Figure 21

Slant Range, meters

Figure 22

Slant Range, meters

Figure 23

Figure 24

Figure 25

Figure 26

Figure 27

Slant Range, meters
Figure 28

Figure 29

Figure 30

Figure 31

Figure 32

Station	Average amplitude (cm/sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	.0389	61	6
2E			
3E	.0041	80	15
4E			
5E	.0451	40	1
6E	.0187	46	2
1S			
2S	.0882	78	7
3S			
4S			
5S	.0030	52	5
6S			
10S			
20S			
COLUMBIA			
HATTIESBURG			
GULF OIL	.0010	.67	26
PURVIS			
BAXTERVILLE	.0036	.63	3
LUMBERTON

CONTOURS IN AVERAGE AMPLITUDE (cm/sec)

MAP NUMBER 1

VERTICAL .35 to .86
ROLAND F. BEERS, INC.

Station	Average Amplitude (cm/sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	205	.89	2
2E			
3E	.064	.59	2
4E	.052	.85	6
5E	.0059	.71	1
6E	.0235	.79	12
1S	.046	.88	5
2S	.020	.84	7
3S			
4S			
5S	.0020	.73	22
6S	.0080	.77	8
10S			
20S			
COLUMBIA	.00053	.78	29
HATTIESBURG	.00042	.89	70
GULF OIL	.0027	.77	11
PURVIS			
BAXTERVILLE	.0007	.81	19
LUMBERTON	.0023	.70	10

CONTOURS IN AVERAGE AMPLITUDE (cm/sec)

MAP NUMBER 2

0 1 2 3 4 5
MILES
SCALE

RADIAL .35 to .861

ROLAND F. BEERS, INC.

Station	Average amplitude (cm/sec)	Frequency cycles/sec	Number of cycles
1N			
2N			
3N			
1E	.106	2.02	18
2E	.079	2.07	15
3E	.136	1.56	5
4E	.360	2.11	6
5E	.102	1.57	6
6E	.030	1.26	10
1S	.661	2.02	5
2S	.096	1.67	15
3S	.060	1.98	19
4S	.049	1.79	9
5S	.035	1.48	11
6S	.012	1.90	30
10S			
20S			
COLUMBIA	.0012	1.73	62
HATTIESBURG	.000086	1.66	133
GULF OIL	.0019	1.69	71
PURVIS			
BAXTERVILLE	.0025	1.39	32
LUMBERTON	.0024	1.55	44

CONTOURS IN AVERAGE AMPLITUDE (cm/sec)

MAP NUMBERS

0 1 2 3 4 5
MILES
SCALE

RADIAL .86 to 2.14

ROLAND F. BEERS, INC.

Station	Average amplitude (cm/sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	.063	3.32	27
2E	.058	4.20	29
3E	.127	4.25	17
4E	.123	5.12	19
5E	.043	4.91	31
6E	.021	4.86	23
1S	.305	3.54	8
2S	.086	2.33	20
3S	.165	5.11	17
4S	.0089	3.59	46
5S	.066	4.72	14
6S	.035	3.32	16
10S	.246	3.4	2
20S	.09	4.6	1.5
COLUMBIA	.00029	2.54	61
HATTIESBURG	.00097	2.62	401
GULF OIL	.00489	4.11	43
PURVIS	.0016	3.25	61
BAXTERVILLE	.010	5.1	87
LUMBERTON	.0064	2.74	39

CONTOURS IN AVERAGE AMPLITUDE (cm/sec)

MAP NUMBER 9

W. 1.5
SCALE

TRANVERSE 2.14 to 5.34

ROLAND F. BEERS, INC

Station	Average amplitude (cm/sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	1.28	8.52	11
2E	.841	6.60	8
3E	2.94	7.04	5
4E	.250	7.06	18
5E	.217	6.78	18
6E	.058	8.22	32
1S	6.92	5.58	3
2S	.751	5.47	10
3S	.214	5.42	18
4S	.319	6.27	26
5S	.151	8.01	20
6S	.187	8.09	14
10S	.414	6.2	3
20S			
COLUMBIA			
HATTIESBURG			
GULF OIL	.0016	6.55	53
PURVIS	.0095	7.00	44
BAXTERVILLE	.0144	5.78	50
LUMBERTON	.0104	5.51	33

CONTOURS IN AVERAGE AMPLITUDE (cm/sec)

MAP NUMBER 10

0 1 2 3 4 5
MILES
SCALE

VERTICAL ABOVE 5.34

ROLAND F. BEERS, INC.

Station	Average amplitude (m sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	661	5.51	15
2E	078	2.07	15
3E	709	3.86	10
4E	182	6.36	10
5E	216	6.00	19
6E	062	5.52	34
1S	261	5.38	7
2S	176	4.59	5
3S	768	5.11	13
4S	343	5.77	18
5S	118	5.66	23
6S	078	5.49	26
10S	425	2.5	2.5
20S	305	3.4	2
COLUMBIA	00071	2.23	108
HATTIESBURG	00034	2.17	21
GULF OIL	0082	6.35	33
PURVIS	0044	3.96	75
BAXTERVILLE	0135	6.36	50
LUMBERTON	0095	3.19	47

MAP NUMBER 14

ROLAND F. BEERS, INC.

Station	Average amplitude (cm/sec)	Frequency in cycles/sec	Number of cycles
1N			
2N			
3N			
1E	271	7.04	14
2E	093	6.60	23
3E	127	4.25	17
4E	123	5.12	19
5E	043	4.23	26
6E	033	5.52	18
1S	305	3.54	8
2S	401	6.51	11
3S			
4S	062	5.83	36
5S	066	4.72	14
6S	035	3.32	16
10S	246	3.4	1.5
20S	093	4.6	1.5
COLUMBIA	0003	2.34	61
HATTIESBURG	00097	2.62	401
GULF OIL	0049	4.11	43
PURVIS	0016	3.25	61
BAXTERVILLE	0163	6.32	54
LUMBERTON	0084	2.74	39

MAP NUMBER 22 — ISOPACH MAP, UPPER CRETACEOUS, INCLUDING CLAYTON LIMESTONE

MAP NUMBER 23 — ISOPACH MAP, WILCOX GROUP AND PORTERS CREEK CLAY

MAP NUMBER 24—ISOPACH MAP, INTERVAL FROM TOP OF TATUM LIMESTONE MEMBER, CATAHOULA SANDSTONE,
TO TOP OF THE WILCOX GROUP