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STUDY TO DETERMINE SEISMIC RESPONSE OF SONIC BOOM-COUPLED RAYLEIGH WAVES

Technical Literature Review

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A literature search was performed regarding the seismic effects of sonic booms with emphasis on the coupled Rayleigh wave resonance phenomenon. The literature search covered 3 primary sources of information: a) Air Force Environmental Impact Assessment Documents, b) litigation and claims, and c) open scientific literature. The literature regarding sonic boom structural damage was reviewed under Task Order 0010. The investigations of seismic waves induced by sonic booms found the amplitudes of the ground motion insufficient to damage structures. Few instances were reported, however, where the actual resonant conditions of the sonic boom-coupled Rayleigh wave were observed. The ground motion amplification accompanying the resonance documented in these cases did not reach damaging levels. Nevertheless, it is theoretically possible that conditions exist which could result in damaging levels of ground shaking. In order to define under what specific conditions, if any, such resonance could occur, an additional literature review was conducted.

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FOREWORD

This technical literature review examining the possibility of generating potentially damaging resonant sonic boom-coupled Rayleigh waves was prepared by personnel for ACTA, Incorporated. ACTA is a member of the BBN Systems and Technologies Corporation team of experts engaged in research on Noise and Sonic Boom Impact Technology (NSBIT). This review was performed in partial fulfillment of Task Order 0018.

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EXECUTIVE SUMMARY

A literature search was performed regarding the seismic effects of sonic booms with emphasis on the coupled Rayleigh wave resonance phenomenon. The literature search covered 3 primary sources of information: a) Air Force Environmental Impact Assessment documents, b) litigation and claims, and c) open scientific literature. The literature regarding sonic boom structural damage was reviewed under Task Order 0010. The investigations of seismic waves induced by sonic booms found the amplitudes of the ground motion insufficient to damage structures. Few instances were reported, however, where the actual resonant conditions of the sonic boom-coupled Rayleigh wave were observed. The ground motion amplification accompanying the resonance documented in these cases did not reach damaging levels. Nevertheless, it is theoretically possible that conditions exist which could result in damaging levels of ground shaking. In order to define under what specific conditions, if any, such resonance could occur, an additional literature review was conducted to locate additional relevant references.

Review of Air Force environmental assessment documents showed few public concerns directly related to the coupled Rayleigh wave phenomenon. Indirectly related concerns focused upon specific structural types that may be damaged, including archaeological sites, historical structures, old adobe buildings, water wells and storage tanks, house trailers, and radio telescopes. In addition, much concern was expressed regarding the possibility of focused booms or superbooms.

A top-level review of litigation and claims history found no pertinent litigation or claims regarding the sonic boom-coupled Rayleigh wave phenomenon.

Review of the open scientific literature provides a better understanding of the phenomenon of air-coupled surface waves. This research shows that the resonant condition for sonic boom coupling to Rayleigh waves requires a low-velocity surficial layer. The strongest resonant coupling occurs when a low-velocity, loose soil layer overlies a more competent, consolidated soil or hard rock,

high-velocity layer, forming a waveguide in which the seismic energy can be trapped. The trapped energy propagates with little attenuation.

Air-coupled surface waves are highly monochromatic in character, consisting of relatively long, sinusoidal trains of oscillations at one particular frequency. Typically, only the fundamental mode (lowest frequency) is excited, but higher modes (with higher frequency content) are observed. The frequencies of the harmonic surface waves (called normal modes) within the waveguide are directly related to the seismic velocity and aircraft speed. The normal mode frequency is inversely proportional to the thickness of the waveguide.

Resonant coupling of the sonic boom with the Rayleigh waves occurs when the sonic boom carpet trace speed matches the Rayleigh wave phase velocity of the ground below. Seismic wave propagation within a waveguide is dispersive; the energy travels as waves comprised of many different frequencies each associated with a particular phase velocity. The range in phase velocities increases the chance that there will be at least one particular frequency associated with the sonic boom carpet trace speed. If the near-surface geology has relatively high Rayleigh-wave phase velocities ($V > 500$ m/sec), then only special maneuvers, such as the climbing maneuvers that increase the carpet trace speed to high values, would cause resonance.

Because of the acoustic impedance mismatch between air and the soil, one might expect weak coupling of the acoustic and seismic waves. Observations of air-coupled surface waves found the coupling to be greater than expected. Other studies of the air-coupled surface waves found that the mechanism for greater coupling is the dissipation of a low-velocity pore fluid wave in the upper soil layer. The acoustic wave in the air is readily coupled to an acoustic wave in the fluid filling the pore spaces between the soil grains at the earth's surface. Because the path connecting these pore spaces is very sinuous and complex, the pore fluid wave is rapidly dissipated by drag against the solid soil grains. The resulting reaction of the solid soil grains produces the seismic waves (both compressional and shear waves) in the ground. Shear waves are more strongly coupled, in general, because they have a lower velocity of propagation, closer to that of the acoustic wave in air. High porosity, low velocity soils would be associated with the greatest potential for strong sonic boom-coupled Rayleigh wave resonance. Lower porosity or increased moisture content tend to increase the seismic velocities and, therefore, diminish the possibility of the Rayleigh-wave resonance phenomenon. Resonance coupling was found to be a very local phenomenon; changing the near-surface soil conditions over a small area (<1 m^2) results in local enhancement of the coupling.

For the sonic boom-coupled surface waves to be potentially damaging, the resonant Rayleigh wave frequencies must be similar to that of structures in the area affected. Review of natural periods of structures that may be affected by the sonic boom-coupled surface waves shows that houses and other low-rise construction have natural response frequencies (1 to 10 Hz) comparable to Rayleigh wave frequencies of shallow, thin (1 to 100 m), low velocity (10 to 500 m/sec) soil layers. Because the surface waves are coupled to the sonic boom, affected structures will be shaken by the seismic waves at the same time the airborne pressure pulses strike. Therefore, the combined effect of these 2 loadings should be considered.

Earthquake strong-motion studies find that strong resonant interaction between the incident body waves (P- and S-waves) with low-velocity near-surface layers, such as the clay lake bed deposits in Mexico City, caused extreme shaking. Almost total destruction occurred to buildings with natural response frequencies that matched those of the resonant surface waves. These studies found that the greatest amplification occurred near the edges of the sedimentary basins, where strong, local, low-velocity surface waves were generated. Again, the strong resonance condition proved to be a very local effect.

STUDY TO DETERMINE SEISMIC RESPONSE OF SONIC BOOM-COUPLED RAYLEIGH WAVES--TECHNICAL LITERATURE REVIEW

1.0 INTRODUCTION

The main objective of Task Order 0018 is to investigate the generation of ground vibrations due to sonic booms, with particular emphasis on coupled Rayleigh waves. The key issues are whether these surface waves can be amplified and whether they can cause damage to structures. This report documents the results of the first phase of the study. A literature search was performed to expand the database of pertinent references regarding the seismic effects of sonic boom with emphasis on the coupled Rayleigh-wave resonance phenomenon. The literature search covered 3 primary sources of information on this subject: a) Air Force Environmental Impact Assessment documents, b) litigation and claims, and c) open scientific literature.

The literature regarding structural damage caused by sonic boom was reviewed under Task Order 0010. Seismic waves generated by sonic booms were observed by several investigators (Baron et al., 1968; Goforth and McDonald, 1968; McDonald and Goforth, 1969; Espinosa et al., 1968; Cook and Goforth, 1970; Bradley and Stevens, 1973; Grover, 1973; Weber, 1972). These studies found that the amplitude of the seismic motions was very small and insufficient to damage structures. Peak ground vibrations observed from overpressures of 3.5 psf were less than 1% of a strict damage threshold established by the Bureau of Mines (Goforth and McDonald, 1968).

Theoretical studies showed that the greatest ground motion and structure acceleration response would occur under the resonant condition, that is, when the velocity of the sonic boom pressure wave is equal to the velocity of the Rayleigh waves in the ground (Press and Ewing, 1951a; Goforth and McDonald, 1968; Baron et al., 1968). The resonant peak of the ground response is very narrow. If the velocity of the sonic boom shock wave deviates more than 10% from the Rayleigh wave speed, the ground coupling is greatly reduced. Few cases of the actual resonant conditions where the ground motions may be amplified by the sonic boom-Rayleigh wave coupling have been reported (Espinosa et al., 1968; Goforth and McDonald, 1968).

Investigations reviewed under Task Order 0010 concluded that significant structure response to the sonic boom-coupled Rayleigh waves is very unlikely due to the very specific conditions required to produce the resonant condition, i.e., the aircraft must be traveling with a velocity equal to the Rayleigh wave velocity in the ground for a significant distance. Because these conditions are theoretically possible, however, there may be specific conditions for which sonic boom-coupled Rayleigh waves could reach a damaging level. In order to define under what specific conditions, if any, such resonance could occur, an additional literature review was conducted.

This review examines the effects of seismic resonance in soils as encountered in earthquake strong-motion studies and exploration seismology to see if such resonance conditions could be induced by the sonic boom seismic coupling. A more complete understanding of the resonant coupling phenomenon is sought. The resonant coupling phenomenon has been problematic in these other scientific disciplines: strong ground shaking of long duration has been very destructive in recent earthquakes and the ground roll encountered in exploration seismology has hampered high quality seismic reflection data acquisition in some areas. Additional research in these areas provides important data to address the sonic boom, Rayleigh-wave resonance problem.

2.0 ENVIRONMENTAL IMPACT ASSESSMENT DOCUMENTS

A review of Air Force Environmental Impact Assessment documents and public comments was conducted to establish the pertinent public concern surrounding this issue. Environmental Impact Statements for the Valentine and Reserve MOAs were reviewed in detail to determine concern relevant to the sonic boom-coupled surface waves. Results of this analysis are presented under 3 categories: (1) concerns specifically related to seismic effects of sonic boom; (2) concerns indirectly related to seismic effects; and (3) other concerns that may relate to the seismic response associated with sonic booms.

The entire issue of seismic effects of sonic booms generated only a limited public response. Most of the public concern specifically related to the seismic effects of sonic booms was directed toward the possible damage to archaeological or historical sites by the sonic boom and related shaking. No specific mention of the sonic boom-coupled surface wave phenomenon was found. Nevertheless, the pertinent concern is whether the sonic boom or seismic waves induced by the boom can damage archaeological or historical sites. Air Force Geophysical Laboratories (AFGL, Battis, 1983) performed a study addressing the possibility of sonic boom damage to Indian petroglyphs in support of the Valentine MOA environmental assessment. The study concluded that the damage potential was insignificant. Public comments suggested that the study done by AFGL was too limited in scope because its conclusions were based upon observations of only a few sonic booms with small overpressures

Another concern related to the seismic effects of sonic boom is the potential for damage to water wells and water storage tanks, which are critical facilities in the arid climate. The public comments expressed concern about the damage potential of the sonic boom propagating through the air into the well. Also, there is concern about the generation of rockfalls or landslides by the sonic boom in the mountainous areas. Lastly, a suggestion was made to install seismographs in the supersonic operating area to monitor the sonic boom effects; this was considered unfeasible by the Air Force, but could provide much needed data for evaluating the sonic boom-coupled surface wave phenomenon.

Public concerns that are indirectly related to the sonic boom-induced surface wave phenomenon are associated with particular types of structures that may be damaged by the sonic boom and possible coupled Rayleigh waves. In addition to the archaeological sites (mainly rock shelters, cliff dwellings, petroglyphs and other ruins), particular concern was expressed regarding the vulnerability of adobe buildings, the typical construction in these remote areas. This concern was enhanced because most adobe buildings would be considered substandard or not "up-to-code." Nevertheless, such buildings are the standard in the region, have survived many decades, and are still habitable. Because of inherent weaknesses in such construction, or because of the age of such structures, they may be particularly susceptible to damage from the sonic booms or seismic effects. Other unconventional structures that were mentioned include mobile homes, house trailers or campers that are set up in camping parks located in the MOAs and the radio telescope (Very Large Array or VLA) located near the Reserve MOA.

Lastly, other concerns that may be related to the sonic boom-coupled Rayleigh wave effects mostly involve the potential for focused booms or superbooms. This concern is relevant to this project in determining the types of maneuvers and resultant sonic boom wave character that may be responsible for air-coupled Rayleigh waves. The amplitude, durations, carpet trace speed, and lateral extent of such focused booms must be known to evaluate the seismic potential of supersonic operations.

3.0 LITIGATION AND CLAIMS

A top-level review of litigation and claims history was conducted to identify specific cases where damage was considered to have been caused by the seismic waves generated by the sonic boom coupling. No relevant litigation or claims were found. The following table lists the principal agencies and points-of-contact made in this search.

Points of Contact

TAC	Alan Chavez
TAC (Legal Staff)	Carolyn Davis
SAC (JAG)	Dan Jarlanski
SAC (Public Affairs)	Alan Dockery
Air Staff General Counsel	Doug Heady
Air Staff Claims and Litigations	Paul Cormier
Headquarters (LEEVX)	Herb Dean
Justice Department	Dorothy Burakreis
Air Force Systems Command	Ed Keppel

In no instance were the contacts familiar with any circumstance involving seismic effects or Rayleigh waves. When the concern about Rayleigh waves and resonance was mentioned, one source cited a claim involving an F-15 overflight of St. Louis at 41,000 ft for which the claimant asserted that a 14-ft masonry column was damaged by sympathetic resonance. The Air Force estimated the loading at 1.3 psf. The claim was denied. No expert testimony was offered. Another contact thought that a recent incident involving a hush house was attributable to resonant seismic waves. The Air Force investigating committee established that acoustic and not seismic vibration was the cause.

Based upon the above contacts, we reached the conclusion that there is no pertinent litigation.

4.0 OPEN SCIENTIFIC LITERATURE

Review of the scientific literature related to the occurrence of sonic boom-coupled Rayleigh waves is necessary to define the problem. The theory of air-coupled surface waves has existed for several decades (Lamb, 1932; Press and Ewing, 1951a and b; Press and Oliver, 1955; Ewing et al., 1957). The observation of the simultaneous arrival of a tidal disturbance with the airborne pressure wave associated with the eruption of Krakatoa in 1883 stimulated some of this research (Press and Ewing, 1951a). Additional, more detailed research, including experimental observations, was triggered by the development of the supersonic transport and concern for possible damage resulting from the associated sonic boom. Major papers relevant to the sonic boom-coupled surface waves were reviewed during Task Order 0010. Additional literature search and review of relevant material in other related aspects of seismology, including earthquake strong-ground motion and exploration seismology, provides important information regarding the near surface resonance phenomena that could result in damaging ground shaking.

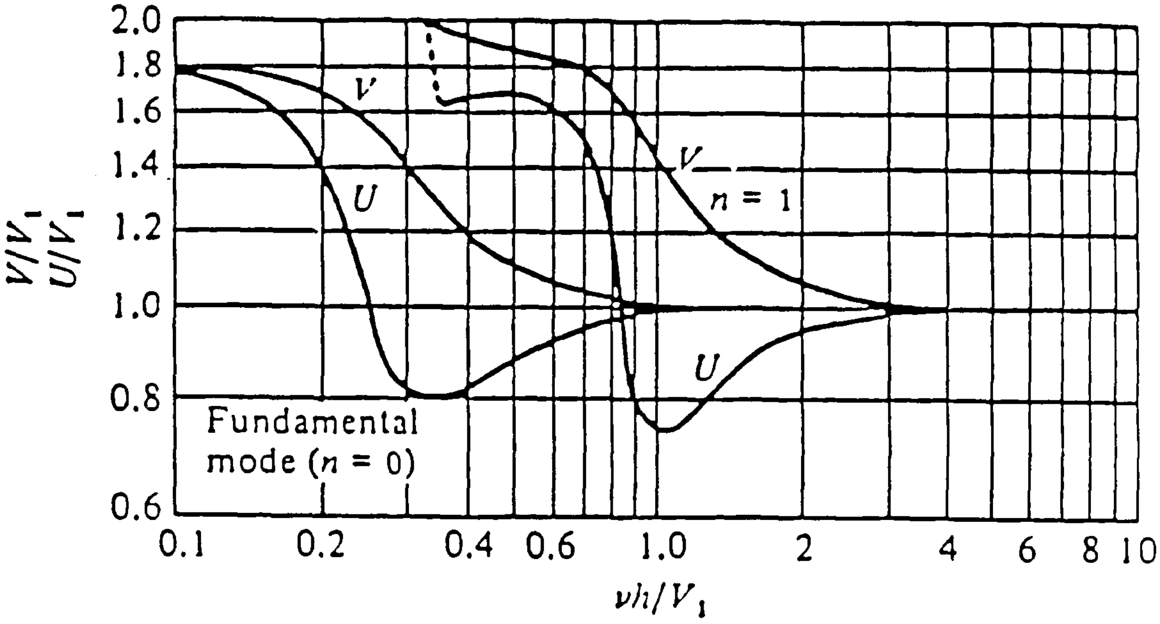
4.1 Air-Coupled Rayleigh Waves

Seismologists have known of the air-coupled Rayleigh wave phenomenon for almost half a century. Lamb (1932) derived the theoretical formulation for surface waves generated by propagation of an acoustic pressure pulse over an elastic medium. Following this approach, other seismologists (Press and Ewing, 1951a and b; Ewing and Oliver, 1955) studied the phenomena of air-coupled surface waves generated by air shots in seismic prospecting and of air-coupled flexural waves generated in ice and laboratory models. Other studies were concerned with the propagation of air-coupled surface waves generated by blasts or infrasound, such as those associated with mining activities, warfare, rocket launches, or tests (Crowley and Ossing, 1969; Donn et al., 1971; Sabatier and Raspet, 1988). Several good seismology textbooks which discuss the theory behind air-coupled surface waves are available (e.g., Ewing et al., 1957; Brekhovskikh, 1960; Bullen, 1960; and Aki and Richards, 1980).

A fundamental characteristic of air-coupled surface waves, predicted by theory and confirmed by experimental work, is their harmonic nature. Air-coupled surface waves are monochromatic: most of their energy is concentrated at one particular frequency. Rayleigh waves, such as those generated by earthquakes or explosions, are often "dispersive" because of the layered geological structure at the earth's surface. This dispersion means that surface wave energy of different frequencies travels with different velocities (Figure 4-1); with time, an original pulse-shaped waveform spreads out into a long train of sinusoidal waves with varying frequencies (Figure 4-2). For the air-coupled surface waves, the phase velocity, i.e., the velocity of wave crest propagation, must be equal to the sound velocity in the air above. This requirement ensures constructive interference between the incident air wave (sonic boom) with the Rayleigh wave traveling along the earth's surface. Because each discrete frequency is associated with one particular phase velocity of a dispersive seismic wave (for a given mode or harmonic), air-coupled surface waves propagate with only one frequency for each mode. Typically, only the fundamental mode is excited, although higher modes are sometimes observed (Espinosa et al., 1968; Goforth and McDonald, 1968).

Another effect of dispersion is to increase the duration of shaking. This is caused by the difference between the group velocity and the phase velocity. The group velocity is the velocity that the wave energy propagates (Figure 4-2). The group velocity may be greater than or less than the phase velocity in a dispersive medium. For typical geological materials, the group velocity is lower than the phase velocity (Figure 4-1). Because the group velocity is lower than the phase velocity, the seismic energy follows the arrival of the acoustic wave, i.e., the ground starts vibrating with the arrival of the sonic boom shock and continues reverberating for a time thereafter. Because the sonic boom continues to generate coupled Rayleigh waves along the ground surface, whose energy propagates at the group velocity, the vibrations from the earlier ground coupling reach a given observation point at some time after the arrival of the acoustic wave where the group velocity is lower than the carpet trace speed. Where the group velocity is higher, precursory seismic wave energy may arrive shortly before the acoustic wave. In general, however, because the surface waves are coupled to the sonic boom, affected structures will be shaking at the same time that the airborne acoustic pressure pulses arrive. Hence, the 2 effects: seismic shaking and acoustic wave overpressure may combine to produce a greater effect than if they arrived separately.

Sonic boom-coupled surface waves propagate with a phase velocity equivalent to the carpet trace speed of the sonic boom footprint. Because most rocks have high seismic velocities relative to most aircraft and sonic boom velocities, only low velocity, near surface soil layers are important in determining the characteristics of sonic boom-coupled Rayleigh waves. Studies of the coupling mechanism find greater coupling of the acoustic wave with the seismic wave than that predicted solely by the acoustic impedance mismatch at the air-soil interface (Sabatier et al., 1986a and b). The increased coupling occurs by the strong dissipation of an acoustic wave within the pore fluid of the soil that transmits the seismic wave energy into the solid matrix of the porous surface layer. The ground surface is not a uniform solid, but is a composite of solid soil grains surrounded by fluid filled pore space. Within this soil layer composite, 3 types of acoustic waves can propagate: (1) an acoustic pressure wave in the pore fluid; (2) a compressional wave in the solid soil grains; and (3) a shear wave in the solid soil grains. The sonic boom shock wave is readily coupled to the pore fluid generating the pore fluid wave. Because the pore fluid wave must travel an extremely sinuous and indirect path between the soil grains, its velocity of propagation is very slow. Furthermore, this acoustic pore fluid wave is strongly dissipated by drag on the solid soil grains. This strong dissipation couples the pore fluid wave motion directly into the solid soil grains as both compressional and shear waves. The shear waves are usually better coupled because their propagation velocity is slower and comparable to the velocity of the sonic boom shock. A more porous, air-filled surface layer results in better coupling.



After: Ewing et al., 1957

Figure 4-1. Typical surface wave dispersion curves showing the phase velocity (V) and group velocity (U) versus frequency (ν) for the fundamental (n=0) and first higher (n-1) modes, where V_1 is the seismic velocity and h is the thickness of the waveguide.

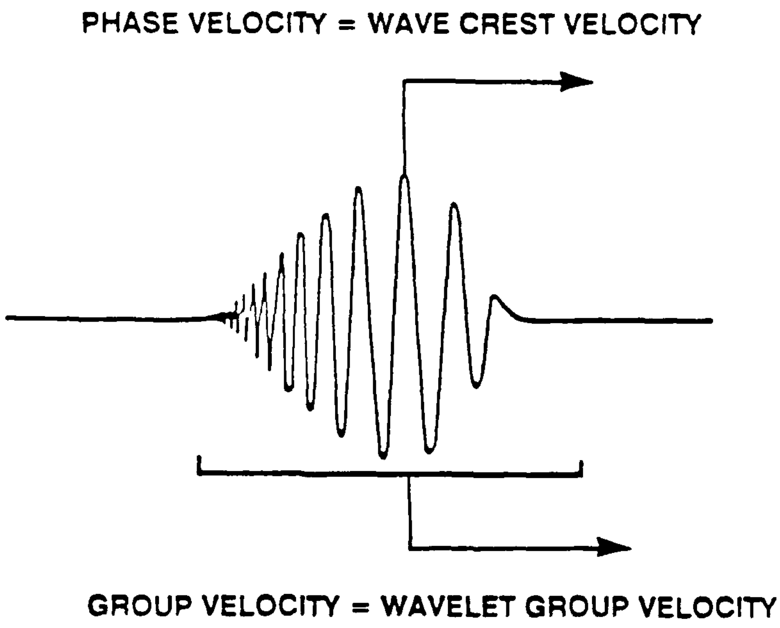


Figure 4-2. Phase velocity and Group velocity of dispersive surface waves. The phase velocity is the velocity of propagation of the wave crests. The group velocity is the velocity of propagation of the wave energy packet (group of wavelets).

The area of the surface required for the coupling was found to be very small (about 1 m^2; Sabatier et al., 1986b). These observations suggest that strong coupling of sonic booms with seismic surface waves is a local phenomenon--surficial geologic or soil conditions are most important in determining the coupling effect. This result is consistent with the measurements of seismic waves generated by sonic booms that showed the seismogram character to be more closely related to the geologic condition than to the sonic boom acoustic wave character (Goforth and McDonald, 1968).

For this study, sonic boom-coupled seismic waves with frequencies in the range typical of the natural response of structures are most significant. The Uniform Building Code (UBC), 1988 edition, gives equation (4-1) for the period of vibration of various buildings:

$$T = C_t\,(h_n)^{3/4} \qquad (4\text{-}1)$$

where T is the period of the fundamental mode in seconds, h_n is the height of the building in feet, and:

C_t = .035 for structures with steel moment-resisting frames,

C_t = .030 for reinforced concrete moment-resisting frames and eccentric braced frames,

C_t = .020 for all other buildings.

Discussions with representatives of the Structural Engineers Association of California (SEAOC) pointed out that the coefficients C_t can range roughly from 80% to 100% of their nominal values.

Thus, based on the height (h_n) and type of building construction, one can estimate the ranges of fundamental periods and natural frequencies (i.e., natural frequency = 1/T) of the building response to vibration. These frequencies can be compared with the typical frequencies of air-coupled Rayleigh waves. From our preliminary evaluation of the natural response frequencies of typical structures that might be affected by sonic booms, low-rise and light conventional structures have natural frequencies of about 1 to 10 Hz. The Bureau of Mines Report (Siskind et al., 1980) tabulates the natural frequencies of over 50 houses in 2 directions (N-S and E-W). Nearly all of these frequencies lie in the range of 5 to 10 Hz. A very few fall outside the 5 to 10 Hz band. This range of frequencies was further substantiated by discussions with earthquake experts at the California Institute of Technology.

Rayleigh waves of the 1 to 10 Hz frequency band are generally limited to very shallow, low velocity soil layers with thicknesses less than about 100 m. Porous surficial soils studied by Sabatier et al. (1986a and b) regarding the coupling mechanism had thicknesses of about 1 to 5 m. Low velocity layers are often referred to as "waveguides" (Figure 4-3) because the wave energy is "trapped" within the low velocity layer by multiple reflections from the higher velocity layer below and the low density air above. Because of constructive interference between the multiply-reflected waves, only a particular set of discrete frequency waves can propagate within the waveguide without strong dissipation. These discrete frequency waves are called the "normal modes" of the waveguide. A simple method of estimating the natural response frequencies of the normal modes excited in a waveguide is presented below (following Sheriff and Geldar', [illegible], and Sabatier et al., 1986a).

For a single surface layer waveguide, the response frequencies of the normal modes are defined by:

$$f_n = \left(\frac{2n+1}{4H}\right) \cdot \left[\frac{c}{[1-(c/c_0)^2 \sin \phi_0]^{1/2}}\right] \quad \text{for } n = 0, 1, 2, \ldots \qquad (4\text{-}2)$$

where H is the thickness of the waveguide (low velocity soil layer), c is the seismic velocity (either compressional wave or shear wave) within the waveguide, c_0 is the acoustic velocity in the air, and ϕ_0 is the angle of incidence of the acoustic ray in the air (measured with respect to the vertical). The surface wave modes can be described as the result of the complex constructive interference pattern of multiply-reflecting body waves (compressional or shear waves) within the waveguide. The angle that these rays make with the horizontal boundaries of the waveguide must be beyond the critical angle, i.e., the angle for total internal reflection at the lower boundary. Therefore, the seismic velocity of the half-space (or lower layers that bound the waveguide) must be high enough to insure total reflectivity within the waveguide for trapping the seismic energy. Other waves with steeper reflection angles may exist, but these, called "leaky modes," dissipate more rapidly because some energy is transmitted into the high seismic velocity sublayer and leaks out of the waveguide.

For sonic boom coupling, a rough estimate of the natural frequencies that may be excited in the waveguide can be made as follows. Snell's Law states:

$$\frac{\cos \theta_0}{c_0} = \frac{\cos \theta_1}{c_1} = \text{Constant} \tag{4-3}$$

where θ_0 and θ_1 are the emergence angles (measured with respect to the horizontal) of the rays within the air and waveguide ($\sin \phi = \cos \theta$), and c_0 and c_1 are as the velocities of the 2 media. For constant, level, supersonic flight in a homogenous (unstratified) atmosphere, the relationship between the Mach speed **M** of the aircraft and the Mach angle θ_0, which is equal to the angle of emergence of the sonic boom at a flat, horizontal ground surface is given by:

$$\sin \theta_0 = [1 - (1/M)^2]^{1/2} \tag{4-4}$$

Combining this equation with the earlier relationship for the normal mode frequencies allows us to express the normal mode frequencies as a function of aircraft speed as follows:

$$f_n = \left(\frac{2n+1}{4H}\right) \cdot \left[\frac{1}{c^2} - \frac{1}{c_0^2}\left(\frac{1}{M^2}\right)\right]^{1/2} \tag{4-5}$$

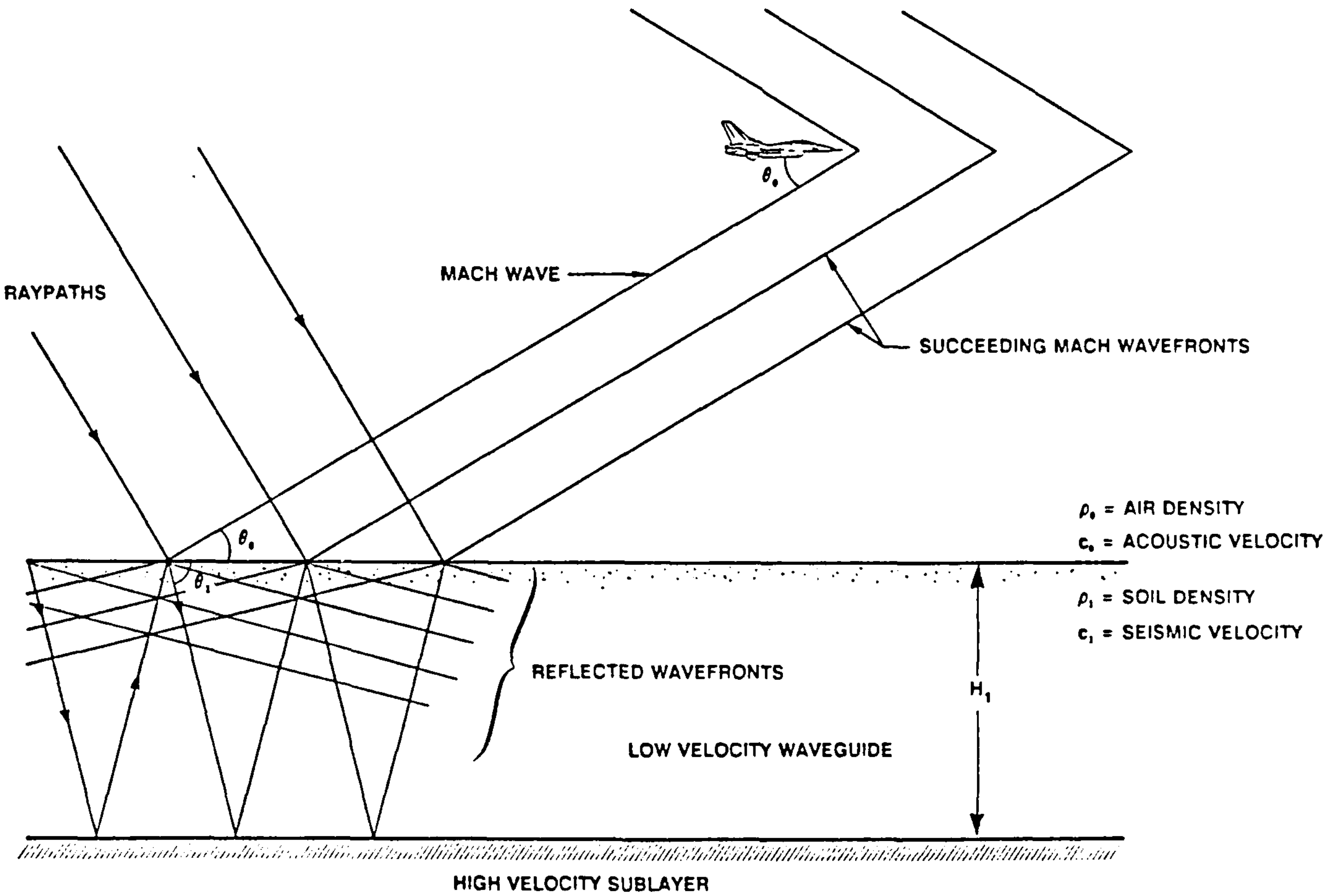


Figure 4-3. Normal Mode Propagation in a Wave Guide. Successive arrivals of the sonic boom "Mach wave" at the earth's surface result in refraction of this wave into the low velocity waveguide. The refracted waves become trapped in the low velocity waveguide and continue to reverberate, by bouncing back and forth between the boundaries of the waveguide. This reverberation is enhanced by constructive interference when the wave that travels from the top of the waveguide down and back to the next reflection at the top of the waveguide arrives "in-phase" with the wave refracted by the succeeding Mach wave intersection at that point. This constructive interference occurs only for a number of discrete frequencies, called normal modes, associated with the thickness and seismic velocity of the waveguide. The mode number, an integer value which varies from $n=0, 1, 2, \ldots$, is related to the number of wavelengths which can fit along the ray path within the waveguide between successive reflections. The fundamental mode ($n=0$) is associated with ¼ wavelength between the top and bottom of the wavelength. It is only ¼ wavelength because there is a phase reversal of 180° (π or ½ wavelength) at the upper (free) surface.

The real atmosphere is stratified, of course, and will cause refraction of the Mach wave (sonic boom) as it propagates to the ground. Nevertheless, Eq. 4-5 provides first order estimates of the natural frequencies of interest. The effects of atmospheric refraction can be easily considered by modifying the sin θ_0 term, or by defining a Mach number based upon the acoustic velocity at the ground level.

Examination of this equation reveals the following general conclusions: (a) as M increases, θ_0 decreases, the ray path of the sonic boom intersects the ground at a steeper angle, and f_n decreases. There is a low-frequency cutoff value (for infinite Mach number) determined by the following relation:

$$f_n = (2n + 1) \cdot \left(\frac{c}{4H} \right) \tag{4-6}$$

Further examination of the above equations shows that thicker layers and lower velocity waveguides have lower natural frequencies. For a nominal thickness of 25 m and a waveguide seismic velocity of 100 m/sec, the fundamental mode of the trapped wave is about 1 Hz. In the real earth, most low-velocity, near-surface waveguides are likely to have somewhat higher average seismic velocities. Very low-velocity, porous soil layers would be relatively thin (<10 m) because compaction at greater depths would rapidly decrease the porosity and increase the seismic velocity. Dry soils would tend to have lower seismic velocities because of the very low acoustic velocity of the air in the pore space. Increased moisture content would tend to increase the compressional wave velocity, while the shear wave velocity would stay very low because fluids have zero shear modulus. The effects of moisture content can be quite dramatic (Attenborough et al., 1986).

4.2 Earthquake Strong-Ground Motion

Recent observations of strong shaking during earthquakes show the destructive potential of resonant site conditions. In particular, resonant soil vibrations in Mexico City were responsible for almost total destruction of modern buildings in specific parts of the city. Such destructive ground motions are most unlikely for sonic boom-induced surface waves, yet the specific soil and shallow geologic structure responsible for the resonant conditions are relevant to the determination of potential resonant conditions for sonic boom-coupled Rayleigh waves. Important differences between earthquake-induced and sonic boom-coupled Rayleigh waves include: earthquakes are within the earth and, therefore, the seismic waves are very well-coupled to the ground; sonic booms are in the atmosphere and, in general, are weakly-coupled to the ground; phase velocities of earthquake waves are much higher than those of the air-coupled (sonic boom) surface waves and, therefore, may couple over a much broader bandwidth of Rayleigh wave energy; and seismic energy released during earthquakes is many orders-of-magnitude greater than that of a sonic boom. Notwithstanding these differences, the important effects of local site conditions during earthquake shaking are relevant to the possible Rayleigh wave resonance associated with sonic boom-coupled seismic energy.

Studies of the recent destructive earthquake in Mexico City showed that surface wave resonance in low seismic velocity, clay lake bed deposits was responsible for most of the destruction to buildings (Anderson et al., 1986). Even though much of Mexico City is built upon the ancient lake bed, the major destruction was confined to parts of this basin that were near the edge, where the clay layer was about 25 m to 45 m thick. The high water content and low rigidity of the clay deposits are associated with very low shear wave velocities (<100 m/sec) that allowed the incident body wave (P- and S-waves) from the distant earthquake to become trapped in this near surface waveguide and amplified into strong, harmonic surface waves (Bard et al., 1988; Celebi et al., 1987; Lermo et al., 1988; Romo et al., 1988; Rukos et al., 1988; Sanchez-Sesma et al., 1988; Seed et al., 1988; Singh et al., 1988). The natural frequency of this surface wave resonance was essentially the same as the natural frequency of the 9-18 story buildings in this area (0.2 to 0.5 Hz), resulting in almost total destruction of such structures. In addition to the strong amplification, the duration of the strong shaking was increased several fold because of both the near-surface effects and the underlying deep sedimentary basin structure.

A major conclusion of these studies is that local variations in the near-surface seismic velocity structure are very significant--strong shaking at sites separated by only a few hundred meters showed substantial variation in amplitudes, duration, and character. This conclusion is consistent with our previously stated conclusions regarding the air-coupled Rayleigh wave phenomenon. Another important observation from the earthquake studies is that local surface waves generated near the edge of the basin propagate toward the region of thickening low velocity layer thickness and produce longer duration of shaking in the thicker areas. Because these locally-generated surface waves have very low group velocity (velocity at which the energy propagates), they dissipate rapidly with distance, and so the strong shaking effects are confined to the edges of the basin.

4.3 Exploration Seismology

Exploration seismologists are very familiar with the ringing of near-surface layers in some areas, which is considered a serious coherent noise problem that makes acquisition of good subsurface reflection data very difficult. Most of this coherent noise is called "ground roll," and is, in fact, the Rayleigh wave (sometimes called pseudo-Rayleigh wave) energy trapped in the near surface, low velocity layer. Recognition that some of this ground roll propagates at the same velocity as the sound speed in the air led seismologists to study the theoretical aspects of the air-coupled Rayleigh wave phenomenon (Press and Ewing, 1951b; Press and Oliver, 1955). Modern land-based exploration seismology often uses buried dynamite shots to avoid strong air-coupled ground roll in some difficult data areas. Most of the literature discussed in the air-coupled Rayleigh wave section (4.1) of this report is related to the exploration seismology problem. The use of geophone spreads, with several geophones spaced out over a substantial distance, and numerous controlled source locations and shot times allowed the experimental confirmation of the air-coupled surface wave theory. The near-surface, low-velocity waveguide is known as the weathering layer in exploration seismology.

5.0 CONCLUSIONS

Review of Air Force environmental assessment documents showed few public concerns directly related to the coupled Rayleigh wave phenomenon. Indirectly related concerns focused upon specific structural types that may be damaged, including archaeological sites, historical structures, old adobe buildings, water wells and storage tanks, house trailers, and radio telescopes. In addition, much concern was expressed regarding the possibility of focused booms or superbooms. All of these issues will be considered in the final report for this project.

A top-level review of litigation and claims history found no pertinent litigation or claims regarding the sonic boom-coupled Rayleigh wave phenomenon.

Review of the open scientific literature provides a better understanding of the phenomenon of air-coupled surface waves. Several decades of research in the seismological community have focused on the air-coupled surface wave problem with regard to the low frequency "ground roll" that causes unwanted interference in seismic exploration. This research demonstrates that the resonant condition for sonic boom coupling to Rayleigh waves requires a low velocity surficial layer or waveguide. The strongest resonant coupling occurs when a low velocity layer overlies a more competent (compacted soil or hard rock) high velocity layer, forming a waveguide in which the seismic energy can be trapped and propagate with little attenuation.

Air-coupled surface waves are highly monochromatic in character, consisting of relatively long, sinusoidal trains of oscillations at one particular frequency. Typically, only the fundamental mode is excited, but higher modes (with higher frequency content) are observed. The frequencies of the normal modes within the waveguide are directly related to the seismic velocity and aircraft speed. The normal mode frequency is inversely proportional to the thickness of the waveguide.

Resonant coupling of the sonic boom with the Rayleigh waves occurs when the carpet trace speed of the sonic boom matches the Rayleigh wave phase velocity of the ground below. Because a given wave propagation within a waveguide is dispersive, with many different frequencies each associated with a particular phase velocity, in general, there will be at least one particular frequency associated with the sonic boom carpet trace speed. If the near-surface geology has relatively high Rayleigh wave phase velocities, then only special maneuvers, such as the climbing or diving maneuvers that increase the carpet trace speed to high values, would cause the resonant condition.

Other studies of the air-coupled surface waves found that the mechanism for greater coupling is the dissipation of a low velocity pore fluid wave in the upper soil layer. High porosity, low velocity soils would be associated with the greatest potential for strong sonic boom-coupled Rayleigh wave resonance. Lower porosity or increased moisture content tend to increase the seismic velocities and, therefore, diminish the possibility of the Rayleigh wave resonance phenomenon. The resonance coupling phenomenon was found to be a very local phenomenon; changing the near surface soil conditions over a small area (<1 m^2) results in local enhancement of the coupling mechanism.

For the sonic boom-coupled surface waves to be potentially damaging, the resonant Rayleigh wave frequencies must be similar to that of structures in the area affected. Review of natural periods of structures that may be affected by the sonic boom-coupled surface waves shows that houses and other low-rise construction have natural response frequencies (1 to 10 Hz) comparable to Rayleigh wave frequencies of shallow, thin (1 to 100 m), low velocity (10 to 500 m/sec) soil layers. Because the surface waves are coupled to the sonic boom, affected structures will be shaken by the seismic waves at the same time the airborne acoustic pressure pulses strike. Therefore, the combined effect of these two loadings should be considered.

Earthquake strong-motion studies find that strong resonant interaction between the incident body waves (P- and S-waves) with low-velocity near-surface layers, such as the clay lake bed deposits in Mexico City, caused extreme shaking. Almost total destruction occurred to buildings with natural response frequencies that matched those of the resonant surface waves. These studies found that the greatest amplification occurred near the edges of the sedimentary basins, where strong, local, low velocity surface waves were generated. Again, the strong resonance condition proved to be a very local effect.

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APPENDIX A - ANNOTATED BIBLIOGRAPHY

Seismo-Acoustics and Air-Coupled Rayleigh Waves

Battis, J. C., 1983, Seismo-acoustic effects of sonic booms on archeological sites, Valentine Military Operations Area: U.S. Air Force Geophysics Laboratory, Technical Report *AFGL-TR-83-0304, ERP, No. 858*, Hanscomb AFB, Massachusetts, 36 pp.

Abstract--Seismo-acoustic recordings of sonic booms were made at two sites in the Valentine Military Operations Area (MOA). Each location was selected as representative of a class of significant archeological sites found within the MOA. These studies indicate that sonic booms are unlikely to cause damage to the archeological finds. The expected motions are, at worst, 8% of the limits set by strict blasting codes and comparable to velocities that could be produced by local earthquakes which have occurred in the Valentine area. At these levels of motion, competent rock will be unaffected by the transmission of seismic waves. The predicted velocity levels are unlikely to initiate either fracture or spalling in rocks. However, it is possible that in rocks where natural meteorological action has initiated these erosive mechanisms, the sonic boom induced motion could accelerate the processes to some small, and probably insignificant, degree.

Baron, M.L., H. H. Bleich, & J. P. Wright, 1966, An investigation of ground shock effects due to Rayleigh Waves generated by sonic booms: NASA Contractor Report, *CR-451*, Weidlinger Consulting Engineers, New York, NY. 49 pp.

Abstract--Expressions are derived for the steady state vertical displacements produced at the surface of an elastic half-space by a line load of finite length, which moves with a constant velocity in a direction either parallel or perpendicular to its length. These expressions are used to estimate the response of structures to the seismic disturbances produced by a sonic boom which moves at speeds close to the speed of surface waves in the medium. Shock amplification factors for the accelerations imparted to the structure are obtained for a range of parameters. The results show that the accelerations produced at these speeds are generally quite small and that the resonance peak which occurs when the applied load moves with the surface wave speed is extremely narrow.

Cook, J. C. & T. T. Goforth, 1970, Ground motion from sonic booms: *Journal of Aircraft*, Vol. 7, pp. 126-129.

Abstract--To ascertain the degree of hazard to structures from sonic boom-induced ground vibrations, seismic measurements were made under NASA support during a series of sonic boom tests in 1967 and 1968. The maximum ground vibration velocity observed was 340 m/sec at 90 Hz, corresponding to a sonic boom overpressure of 3.5 lb/ft^2. This is less than 1% of the structural damage threshold established experimentally by the U.S. Bureau of Mines and others, of 50,800 μm/sec. It is therefore very unlikely that any structural damage to slabs, foundations, wells, etc., can occur because of sonic booms. Incidental to the study, seismic precursor waves were observed which provide a possible basis for automatic warnings of approaching sonic booms, to reduce their startle effect.

Crowley, F. A. & H. A. Ossing, 1969, On the application of air-coupled seismic waves: Air Force Cambridge Research Laboratories, *Environmental Research Papers, No. 302.*

Abstract--Seismic measurements taken on Rogers Lake Playa, Edwards AFB, California, were prompted by a concern that ground vibrations excited by F-1 rocket engines might affect the role of playa cracking. These measurements relate to other Air Force interests. Specifically, the note characterizes seismic waves excited by F-1 rockets, sonic booms, and atmospheric explosions to: (1) Playa landing areas; (2) Ground conditions affecting sonic booms and rocket firings sensed in buildings; (3) Detection of acoustic sources using seismic systems; (4) The playa's selective distortion of acoustic wave characteristics; and (5) Consideration of a playa seismic alarm system.

Donn, W. L., I. Dalins, V. McCarty, M. Ewing, & G. Kaschak, 1971, Air-coupled seismic waves at long range from Apollo launchings: *Geophysics*, Vol. 26, pp. 161-171.

Abstract--Microphones and seismographs were colocated in arrays on Skidaway Island, Georgia, for the launchings of Apollo 13 and 14, 374 km to the south. Simultaneous acoustic and seismic waves were recorded for both events at times appropriate to the arrival of the acoustic waves from the source. Significant comparisons of the true signals are (1) the acoustic signal is relatively broadband compared to the nearly monochromatic seismic signal; (2) the seismic signal is much more continuous than the more pulse-like acoustic signal; (3) ground loading from the pressure variations of the acoustic waves is shown to be too small to account for the seismic waves; (4) the measured phase velocities of both acoustic and seismic waves across the local instrument arrays differ by less than 6% and possibly 3% if experimental error is included. It is concluded that the seismic waves are generated by resonant coupling to the acoustic waves along some 10 km of path on Skidaway Island. The thickness of unconsolidated sediment on the

island is appropriate to a resonant ground wave frequency of 3.5 to 4 Hz, as observed. Under appropriate conditions, ground wave observations may prove more effective means of detecting certain aspects of acoustic signals in view of the filtering of wind noise and amplification through resonance.

Espinosa, A. F., P. J. Sierra, & W. V. Mickey, 1968, Seismic waves generated by sonic booms: A geoacoustical problem: *Journal of the Acoustical Society of America*, Vol. 44, No. 4.pp. 1074-1082.

Abstract--Low and very low-frequency air-coupled seismic waves were efficiently generated on different occasions by jet fighter planes flying at high altitudes and at Mach 3 numbers greater than 1.2. The experiments presented in this investigation were clearly recorded on a geophone array containing up to 12 short-period vertical component stations, and a singular station recording the transverse and radial type of motion. A higher mode, seismic, coupled wave from sonic booms has been observed for the first time. Correlation is made between the acoustical signal registered at the microphone stations in Cape Kennedy and the first impulsive onset of the seismic waves recorded at the array setup. The seismic waves coupled from sonic booms are explained as a constructive interference phenomenon in the surficial ground layers. Fourier-transform techniques are applied to some of the seismograms, and some interesting features are delineated.

Kanamori, H., J. Mori, D. Anderson, T. Heaton, & L. Jones, 1989, Seismic response of the Los Angeles basin to the shock wave caused by the Space Shuttle Columbia: *Transactions of the American Geophysical Union*, Vol. 70, (no. 43), pp. 1191-2.

Abstract--Shock waves generated by the Space Shuttle Columbia on its return to Edwards Air Force base on August 13, 1989, were recorded by the southern California Seismic Network. The arrival times can be best explained with Mach cones propagating N40E across the Los Angeles basin. From the propagation velocity of the Mach cone and its shape, we determined the velocity and the altitude of the Space Shuttle to be 800 m/sec (Mach 2.35), and about 20 km respectively. The seismograms recorded at the stations in the Los Angeles basin exhibit reverberations before and after the shock wave, while those from stations outside the basin show no reverberations. The broadband record obtained at the IRIS-TERRAscope station at Pasadena shows a distinct pulse having a period of about 3 sec which arrived 12.5 sec before the shock wave. The distinct onset, the particle motion direction and the arrival time of this pulse indicate that this pulse originated from a point near downtown Los Angeles. This pulse is followed by shorter period reverberations which have spectral peaks at 0.76, 1.17, 1.62, and 2.00 Hz. The reverberations can be interpreted as the response of the Los Angeles basin to the shock wave. A simple calculation using the Thomson-Haskell method shows that the observed

spectrum at frequencies higher than 1 Hz is consistent with a soft superficial layer with a two-way P-wave travel time of about 2 sec.

Press, F. & W. M. Ewing, 1951a, Ground roll coupling to atmospheric compressional waves: *Geophysics*, Vol. 16, pp. 416-430.

Abstract--A theoretical treatment of ground roll originating from air shots and hole shots is given, shown that coupling of ground roll to compressional waves in the atmosphere exists for both air and hole shots. Experimental data obtained in the field are in excellent agreement with theory results namely, that the effective coupling exists for surface waves whose phase velocity is equal to the speed of sound in air. In regions where Rayleigh wave velocities vary with period due to layering in such a way that they are less than the speed of sound in air for short periods and exceed this value for longer periods, this coupling gives rise to a unique surface wave pattern on seismic records. It is shown that body wave and surface wave character is almost independent of charge elevation in the range from 0 (on the ground) to 30 feet. In a reciprocal manner ground roll from hole shots was recorded with air microphones predicted by the theory.

Press, F. & W. M. Ewing, 1951b, Theory of air-coupled flexural waves: *Journal of Applied Physics*, Vol. 22, pp. 892-899.

Abstract--The theory of air-coupled flexural waves in a floating ice sheet is derived for the case of an impulsive point source situated either in the air or in the water. It is found that new branches are introduced to the dispersion curve of flexural waves as a result of coupling to compressional waves in the atmosphere. Experimental data are briefly reviewed.

Press, F. & J. Oliver, 1956, Model study of air-coupled surface waves: *Journal of the Acoustical Society of America*, Vol. 27, pp. 43-46.

Abstract--Flexural waves generated in a thin plate by a spark source are used to investigate properties of air-coupled surface waves. Both ground shots and air shots are simulated in the model. Effects of source elevation, fetch of air pulse, and cancellation by destructive interference are studied.

Raspet, R. & G. E. Baird, 1988, The acoustic surface wave above a complex impedance ground surface: *Journal of the Acoustical Society of America*, Vol. 85 (2), pp. 638-640.

Abstract--A surface wave like term arises in the analysis of spherical wave propagation above a complex impedance plane. Whether this wave is a true independently propagating surface wave,

or a reaction to the incident air wave, has been the subject of discussion for a number of years. In this article, it is demonstrated that this term is a true surface wave that can exist independent of the body wave in air.

Sabatier, J. M., H. E. Bass, & L. N. Bolen, 1986, Acoustically induced seismic waves: *Journal of the Acoustical Society of America*, Vol. 80 (2), pp. 646-649.

Abstract--When an airborne acoustic wave is incident at the ground surface, energy is coupled into the ground as seismic motion. In a previous publication (Sabatier et al., J. Acoust. Soc. Am. 78, 1345-1352, 1986) the ground surface was modeled as an air-filled poroelastic layer overlying a semi-infinite, nonporous elastic substrate. In this work, the model is extended to include calculations of the normal seismic transfer function (ratio of the normal soil particle velocity at a depth d to the acoustic pressure at the surface). Measurements of the seismic transfer function for three sites are considered and compared to the predicted values. Generally good agreement between theory and experiment is achieved by best fits assuming the soil or seismic attenuation. This is accomplished by specifying the ratio of the imaginary to real part of the measured seismic P- and S-wave speeds. The seismic transfer functions quite typically exhibit minima and maxima which are associated with the seismic layering of the ground surface. Typical layer depths are 1-2 m. An analytical expression predicting the location of these maxima is offered based on hard substrate and the experimental and theoretical comparisons are reasonable.

Sabatier, J. M. & H. E. Bass, 1986, On the location of frequencies of maximum acoustic-to-seismic coupling: *Journal of the Acoustical Society of America*, Vol. 80 (4), pp. 1200-1202.

Abstract--Measurements of the acoustic-to-seismic transfer function (ratio of the normal soil particle velocity at a depth d to the acoustic pressure at the surface) for outdoor ground surfaces quite typically reveal a series of maxima and minima. In a publication (Sabatier et al., J. Acoust. Soc. Am. 80, 646-649, 1986), the location and magnitude of these maxima are measured and predicted for several outdoor ground surfaces using a layered poroelastic model of the ground surface. In this paper, the seismic transfer function for a desert site is compared to the seismic transfer function for holes dug in the desert floor which were filled with pumice (volcanic rock). The hole geometry was rectangular and the hole depths varied from 0.25-2.0 m. The P- and S-wave speeds, densities, porosities, and flow resistivities for the desert floor and pumice were all measured. By varying the hole depth and the fill material, the maxima in the seismic transfer function can be shifted in frequency and the locations of the maxima compare reasonably with that of a hard-backed layer calculation. The area or extent of the acoustic-to-seismic coupling for pumice was determined to be less than 1 m^2.

Sabatier, J. M. & R. Raspet, 1988, Investigation of possibility of damage from the acoustically coupled seismic waveform from blast and artillery: *Journal of the Acoustical Society of America*, Vol. 84, pp. 1478-1482.

Abstract--This article examines the source of ground vibrations in regions adjacent to artillery fire or explosive operations. Measurements have been performed to evaluate the possibility of damage from high levels of ground-borne vibration in the vicinity of residential homes. The result of these measurements demonstrates that the acoustically coupled seismic wave is much larger than the directly coupled seismic wave from large scale impulsive sources. The theory of acoustic-to-seismic coupling is extended to impulsive sources, in order to investigate the damage potential of the acoustic-to-seismic coupled wave with respect to the airborne wave. The results of the theory are compared to controlled measurements made using a small scale impulsive source. In addition, the theory and experiment are shown to be in good agreement with the large scale impulsive source with reasonable assumed values of the seismic velocities and layer depths. The theory is used to develop the acoustic-to-seismic coupling ratio for a typical blast wave over the expected range of wave speeds and porosities normally encountered. Worst-case scenarios are developed. It is demonstrated that it is unlikely that damage will occur to houses due to the acoustically coupled seismic wave unless the acoustic pulse pressure exceeds 162 dB.

Weber, G., 1972, Sonic boom exposure effects II.1: Structures and terrain: *Journal of Sound and Vibration*, Vol. 20, pp. 505-509.

Abstract--Effects on structures due to pressure waves from explosions and guns have been known and studied for a long time. Experience has shown that peak overpressures from 5 to 15 kN/m^2 might crack panes and cause superficial damage to houses. The pressure waves from supersonic aircraft with peak overpressures in the order of 50-150 N/m^2 would thus seem to be too low to create structural damage. Nevertheless, a growing number of damage claims have been recorded. Extensive data on sonic boom damage have now been accumulated from many investigations which have taken place over the past ten years. Available data show some features which are relatively easy to define and attempts are made in this document to make conclusive statements concerning sonic boom exposures and the occurrence of damage on structures. In many areas, where it is not to easy to obtain adequate data, suggestions are made concerning suitable research. Three general sets of parameters determine the effect of sonic booms on structures and terrain: (i) the generation; (ii) the propagation of shock waves; (iii) the characteristics of the structures. The first two of these parameters are better known than the third. If the specific aircraft design, flight and weather conditions are known, the free field pressure wave characteristic can be predicted. In following the effect of sonic booms on topographical features and ground motion effects on structures will be evaluated and then the structural parameters will be discussed.

Earthquake Strong-Motion

Bard, P.-Y., M. Campillo, F. J. Chavez-Garcia, & F. Sanchez-Sesma, 1988, The Mexico earthquake of September 19, 1985--A theoretical investigation of large- and small-scale amplification effects in the Mexico City Valley: *Earthquake Spectra*, Vol. 4, No. 3, pp. 609-633.

Abstract--The linear, large-scale and small-scale amplification effects in the Mexico City valley, related to both the surficial clay layer and the underlying thick sediments, are investigated with two-dimensional (2D) models and compared with the results of simple one-dimensional (1D) models. The deep sediments are shown to be responsible, on their own, for an amplification ranging between 3 and 7, a part of which is due to the 2D effects in case of low damping and velocity gradient. This result is consistent with the observed relative amplification around 0.5 Hz at CU stations with respect to TACY station. The amplification due to the clay layer is much larger (above 10), and the corresponding 2D effects have very peculiar characteristics. On the one hand, the local surface waves generated on any lateral heterogeneity exhibit a strong spatial decay, even in case of low damping (2%), and the motion at a given site is therefore affected only by lateral heterogeneities lying within a radius smaller than 1 km. On the other hand, these local 2D effects may be extremely large, either on the very edges of the lake bed zone, or over localized thicker areas, where they induce a duration increase and an overamplification. The main engineering consequences of these results are twofold: i) microzoning studies in Mexico City should take into account the effects of deep sediments, and ii) as the surface motion in the lake bed zone is extremely sensitive to local heterogeneities, 1D models are probably inappropriate in many parts of Mexico City.

Celebi, M., J. Prince, C. Dietel, M. Onate, & G. Chavez, 1987, The culprit in Mexico City--Amplification of motions: *Earthquake Spectra*, Vol. 3, No. 2, pp. 315-328.

Abstract--Mexico City has repeatedly suffered from the long-distance effects of the earthquakes that originate as far away as the subduction trenches near the Mexican Pacific Coast. The Michoacan, Mexico earthquake of 19 September 1985 was no exception and caused extensive damage to property and numerous loss of lives. The unique subsurface condition resulting from the historical lake bed has distinct resonant low frequencies around 0.5 Hz. The strong earthquake motions from long distances as well as the locally originating weak motions cause large amplifications at resonant low frequencies in the subsurface environment of Mexico City lake bed. In this paper, the resonant frequencies and associated amplifications of motions recorded in January, 1986. These ratios confirm that the amplifications of motions at resonant frequencies due to the subsurface conditions is indeed the culprit.

Lermo, J., M. Rodriquez, & S. K. Singh, 1988, The Mexico earthquake of September 19, 1985--Natural period of sites in the Valley of Mexico from microtremor measurements and strong motion Data: *Earthquake Spectra*, Vol. 4, No. 4, pp. 805-834.

Abstract--The period at which peak in the microtremor Fourier velocity spectra occurs in the transition and lake bed zones of the valley of Mexico is found to be the natural period of the site. These periods in the valley are compiled from the microtremor measurements carried out by Instituto de Ingenieria, UNAM and scientists from Japan (for a total of 181 sites). Using this data and the natural periods estimated from strong motion recordings (36 sites), an isoperiod contour map of the valley of Mexico is presented. This map may be useful in future design of important structures.

Romo, M. P., A. Jaime, & D. Resendiz, 1988, The Mexico earthquake of September 19, 1985--General soil conditions and clay properties in the Valley of Mexico: *Earthquake Spectra*, Vol. 4, No. 4, pp. 731-752.

Abstract--We present and discuss the results of resonant column and cyclic triaxial tests on clay samples obtained from different sites within the Lake zone in the Valley of Mexico. Of particular interest are the nearly elastic behavior and low damping ratio even for shear strain amplitudes as high as 0.3 (%). A hyperbolic model reproduces adequately well the resulting shear modulus vs strain curves. Degradation of shear modulus caused by load repetition is negligible for strains lower than about 1 (%) but increases significantly for higher strains. A power-type expression fits well the modulus degradation vs number of cycles curves. Results from static triaxial tests indicate that for compression stress paths the induced pore water pressure is uniquely related to axial strains. Analyses of ground motions show that one dimensional wave propagation models may be used to predict free field seismic motions in most parts of the Lake zone.

Rukos, E. A., 1988, The Mexico earthquake of September 19, 1985--Earthquake behavior of soft sites in Mexico City: *Earthquake Spectra*, Vol. 4, No. 4, pp. 771-786.

Abstract--From the September 19, 1985 earthquake there are several acceleration records for the soft (lake bed) sites in Mexico City. One-dimensional propagation models of the incident seismic accelerations incorporate the wave propagation profiles at three of those sites. The undamped computed surface acceleration spectra compare well with the recorded ones for two sites. The other one does not produce adequate results, which is probably due to incomplete information on the shear wave velocities. Further investigation with the site impulse function indicates that the surface accelerations during the September 19, 1985 event had a frequency content determined, to a certain extent, by the natural periods of the site. Direct inspection of the recorded spectra for the September 19, 1985 earthquake at the studied sites shows that the relation between spectral periods corresponds to the closed form solution of a homogeneous layer with a fixed base. This relation may be different for other earthquakes recorded at these sites.

Sanchez-Sesma, F., S. Chavez-Perez, M. Suarez, M. A. Bravo, & L. E. Perez-Rocha, 1988, The Mexico earthquake of September 19, 1985--On the seismic response of the Valley of Mexico: *Earthquake Spectra*, Vol. 4, No. 3, pp. 569-589.

Abstract--In order to explain damage and observed ground motions in Mexico City during the 1985 Michoacan earthquake, simultaneous considerations must be given to source, path, and site conditions. This is clear from teleseismic records and local vertical displacements. Incident waves had an important part of energy in the frequency band of 0.3-1 Hz. Damage distribution and observed motion in the lake bed zone cannot be satisfactorily explained using one-dimensional theory. The effects of lateral irregularities are required. To assess its effects we describe the stratigraphic setting of the valley and discuss some features of damage distribution with results for one- and two-dimensional wave propagation models. These are useful to establish on quantitative basis the importance of lateral heterogeneity.

Seed, H. B., H. M. P. Romo, J. I. Sun, A. Jaime, & J. Lysmer, 1988, The Mexico earthquake of September 19, 1985--Relationships between soil conditions and earthquake ground motions: *Earthquake Spectra*, Vol. 4, No. 4, pp. 687-729.

Abstract--Comparisons are presented between the characteristics of ground motions at five sites underlain by clay at which ground motions were recorded in Mexico City in the earthquake of September 16, 1985 and for which analyses of ground response have been made, based on the measured properties of soils and the motions recorded on hard formations at the National University of Mexico. It is shown that the ground response in areas of Mexico City underlain by clay is extremely sensitive to small changes in the shear wave velocity of the clay and it is suggested that a probabilistic approach which allows for uncertainties in shear wave velocity measurements and in the characteristics of the motions on the hard formations is desirable to assess these effects of local soil conditions on the characteristics of ground motions likely to develop at sites underlain by soft clays, and that the use of these procedures also provides a useful basis for estimating the general nature of the ground motions in the extensive heavy damage zone of Mexico City in the 1985 earthquake.

Singh, S. K., J. Lermo, T. Dominquez, M. Ordaz, J. M. Espinosa, E. Mena, & R. Quaas, 1988, The Mexico Earthquake of September 19, 1985--A study of amplification of seismic waves in the Valley of Mexico with respect to a hill zone site: *Earthquake Spectra*, Vol. 4, No. 4, pp. 653-673.

Abstract--Since the installation of an extensive digital strong-motion array by Fundacion Javier Barros Sierra in 1987, 3 moderate earthquakes have been recorded by the array and by the accelerographs operated by Instituto de Ingenieria, UNAM. Using this new data and results from the analysis of previous accelerograms we present spectral ratios at 40 sites in the valley of Mexico with respect to a hill zone site in Ciudad Universitaria (CU). Clear evidence for nonlinear behavior of the clay is found at Central de Abastos Oficina (CDAO) site during the great Michoacan earthquake (Ms=8.1). At four other lake bed sites this behavior is not seen either because none occurred or because of poorer quality of data. The spectral ratio at a given site appears to be roughly independent of magnitude (except, perhaps, during great earthquakes when lake bed sites may behave nonlinearily), azimuth, and depth of earthquakes with epicenters ≥200 km from the city. On the lake bed sites of the valley the relative amplification (RA) varies between 8 and 56 and the natural period lies between 1.4 to 4.8 sec. Relative amplification maps at periods centered at 3, 2.5, 2, 1.5, and 1 seconds are presented. The area where severe damage and collapse of buildings in the city was concentrated during the Michoacan earthquake correlates well with the area with RA≥14 in the period range of 1.75 to 2.75 sec.