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Shock Waves

Seismic excitation by space shuttles

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Abstract. Shock waves generated by the space shuttles Columbia (August 13, 1989), Atlantis (April 11, 1991) and Discovery (September 18, 1991) on their return to Edwards Air Force Base, California, were recorded by TERRAscope (Caltech's broadband seismic network), the Caltech-U.S.G.S Southern California Seismic Network (SCSN), and the University of Southern California (USC) Los Angeles Basin Seismic Network. The spatial pattern of the arrival times exhibits hyperbolic shock fronts from which the path, velocity and altitude of the space shuttle could be determined. The shock wave was acoustically coupled to the ground, converted to a seismic wave, and recorded clearly at the broadband TERRAscope stations. The acoustic coupling occurred very differently depending on the conditions of the Earth's surface surrounding the station. For a seismic station located on hard bedrock, the shock wave (N wave) was clearly recorded with little distortion. Aside from the N wave, very little acoustic coupling of the shock wave energy to the ground occurred at these sites. The observed N wave record was used to estimate the overpressure of the shock wave accurately; a pressure change of 0.5 to 2.2 mbars was obtained. For a seismic station located close to the ocean or soft sedimentary basins, a significant amount of shock wave energy was transferred to the ground through acoustic coupling of the shock wave and the oceanic Rayleigh wave. A distinct topography such as a mountain range was found effective to couple the shock wave energy to the ground. Shock wave energy was also coupled to the ground very effectively through large man made structures such as high rise buildings and offshore oil drilling platforms. For the space shuttle Columbia, in particular, a distinct pulse having a period of about 2 to 3 seconds was observed, 12.5 s before the shock wave, with a broadband seismograph in Pasadena. This pulse was probably excited by the high rise buildings in downtown Los Angeles which were simultaneously hit by the space shuttle shock waves. The proximity of the natural periods of the high rise buildings and the modal periods of the Los Angeles basin enabled efficient energy transfer from shock wave to seismic wave.

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Key words: Space shuttle, Seismic wave, Acoustic coupling

1. Introduction

Acoustic shock waves generated by the space shuttles Columbia (August 13, 1989), Atlantis (April 11, 1991) and Discovery (September 18, 1991) on their return to Edwards Air Force Base, California, were recorded by TERRAscope (Caltech's broadband seismic network), the Caltech-U.S.G.S Southern California Seismic Network (SCSN), and the University of Southern California (USC) Los Angeles Basin Seismic Network. The spatial pattern of the arrival times exhibits hyperbolic shock fronts from which the path, velocity and altitude of the space shuttle could be determined. The shock wave was acoustically coupled to the ground, converted to a seismic wave, and recorded clearly at the broadband TERRAscope stations. The acoustic coupling occurred very differently depending on the conditions of the crust surrounding the station. Since these are unique events, here we present the records and interpret them in terms of the difference in acoustic coupling. With well calibrated seismic instruments, we can estimate the shock wave pressures accurately.

2. Seismic tracking of space shuttles

Figure 1 shows the re-entry paths of the three space shuttles, Columbia (August 13, 1989), Atlantis (April 11, 1991) and Discovery (September 18, 1991) which flew above the SCSN stations and three TERRAscope stations, PAS (Pasadena), SBC (Santa Barbara) and ISA (Isabella). These paths were accurately determined from the arrival times of the shock waves at the SCSN stations. Several examples of the shock wave records are shown in Fig. 2. Figure 3 shows the shock wave arrival times for the space shuttle Columbia. The numbers attached to the station codes are the travel times in seconds measured from an arbitrary reference time. We can fit hyperbolas to the arrival time data as shown in Fig. 3.

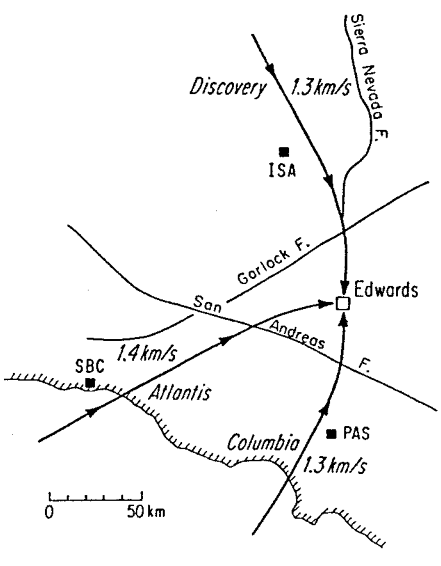

Fig. 1. The re-entry paths of the space shuttles Columbia (August 13, 1989), Atlantis (April 11, 1991) and Discovery (September 18, 1991) on their return to Edwards Air Force Base, California. The three TERRAscope stations, PAS, ISA and SBC are shown and approximate space shuttle velocities are indicated

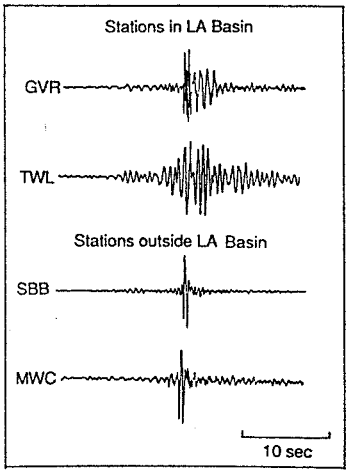

Fig. 2. Examples of the shock waves recorded at stations in the LA basin (top 2 traces) and those outside the LA basin (bottom 2 traces). Note the reverberations recorded on the top 2 traces

Figure 4 shows the approximate geometry of a shock wave front. The intersection between the shock front and the surface is given by a hyperbola shown in Fig. 4. Let U and c be the velocity of the space shuttle and the sound velocity, respectively. Then the asymptotes are given by $y = \pm(\tan\beta)x$, where $\beta = \sin^{-1}(1/M)$ and M is the Mach number (U/c). The distance between the apex of the hyperbola and the origin is given by $D = H/\tan\beta$, where H is the altitude of the shuttle.

Figure 5 shows the travel time and the velocity of the space shuttle Columbia across the LA basin as determined from Fig. 3. Significant deceleration occurred from the coast to the Mojave Desert (Saddleback). The velocities are 1300 m/s (M = 4.3, c = 300 m/s is used), 900 m/s, and 700 m/s at the coast, the San Andreas fault, and the Mojave Desert, respectively.

Table 1. The altitude and the speed of the space shuttles determined from seismic data

		Distance Range (km)	H (km)	U (m/s)	M
Columbia	(8/13/1989)	30-110	28	810	2.7
Atlantis	(4/11/1991)	30-150	34	1,350	4.5
Discovery	(9/18/1991)	30-130	36	1,260	4.2

From the shock wave arrival times and the relation $D = H/\tan\beta$, we estimated the Mach number and the altitude H over a given distance range from Edwards Air Force Base using the method by Mori and Kanamori (1991).The results are listed in Table 1. Since the shuttle velocity and altitude vary approximately linearly over a distance range of 30 to 150 km (see Fig. 5), the values listed in Table 1 can be considered the average over the distance range given in the table. Figure 6 shows the data calculated for a nominal entry flight profile published by NASA. Our results are generally consistent with the values shown in Fig. 6.

3. General features of acoustic coupling

Since TERRAscope stations have a very broadband response, we can process the data to obtain a record that gives the actual ground motion displacement without distortion. First we show displacement records thus obtained for the three space shuttles to illustrate the variability of acoustic coupling caused by different site conditions.

Figure 7a shows the record at ISA during the re-entry of Discovery. A very clear impulse with an amplitude of 0.2 μm is recorded. This impulse is the signature of the shock wave hitting the ground in the immediate vicinity of the station. Aside from this pulse, no significant energy is observed on this record, indicating that very little acoustic coupling occurred. The station ISA is located on the Sierra Nevada batholith which consists of hard basement rock with P and S velocities of 5 to 6 and 3 to 3.5 km/s, respectively, Fig. 8a. Although the topography of the Sierra Nevada is fairly complex, no particularly distinct features exist in the vicinity of the station. Since the velocity of the space shuttle Discovery above ISA is about 1.4 km/s, much lower than the velocities of the basement rock beneath ISA, the efficiency of acoustic coupling is very low.

In contrast, the record at PAS during the re-entry of Columbia (Fig. 7b) exhibits very strong acoustic coupling. The shock wave is not obvious on the displacement record; it can be identified only on the high-pass filtered record. As Fig. 8b shows, although PAS is located on bedrock, the thick Los Angeles (LA) basin is located adjacent to the station. The long period (about 2 s) motion with an amplitude of 0.5 μm followed by reverberations seen on the displacement record is the result of acoustic coupling between the shock wave and the structures in the vicinity of the LA basin. Kanamori et al. (1991) concluded that the 2 s pulse is a seismic P wave excited by the high-rise buildings in the

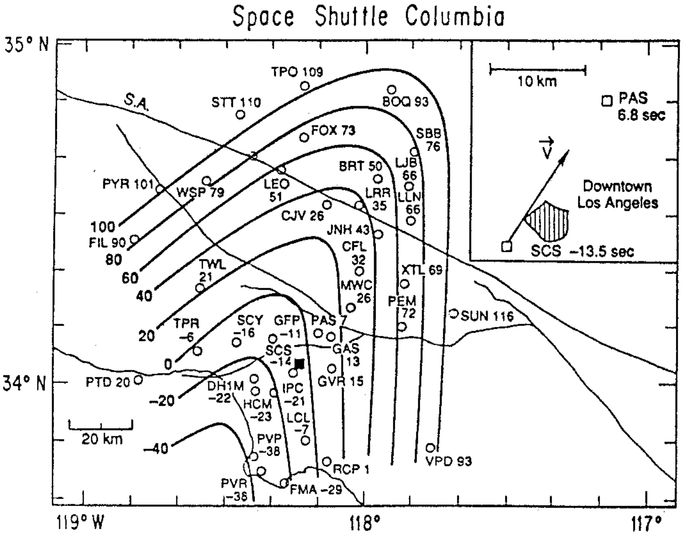

Fig. 3. Arrival times of the shock waves which were caused by the space shuttle Columbia, and recorded by seismic stations of the Southern California Seismic Network and The University of Southern California Los Angeles Basin Seismic Network. The numbers below the station codes are the arrival times in seconds from an arbitrary reference time. Hyperbolas at 20 s intervals are fitted to the arrival time data. The inset shows the stations PAS and SCS with respect to downtown Los Angeles. The vector V indicates the shuttle path. The arrival time difference between PAS and SCS is 20.3 s

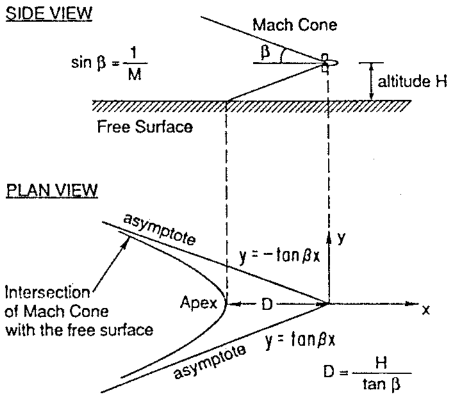

Fig. 4. Geometry of a Mach cone. The top figure is the side view and the bottom is the plan view. The altitude H is estimated from D, the distance between the apex of the Mach cone and the origin

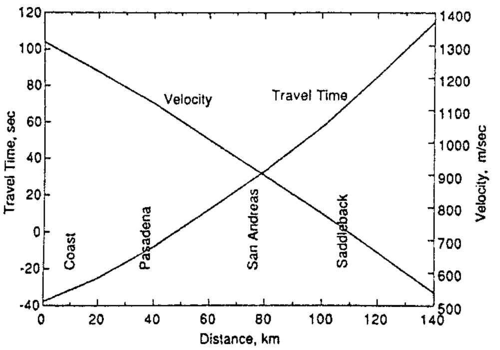

Fig. 5. Smoothed travel time and the velocity of the space shuttle Columbia as a function of distance across the LA basin. Approximate locations of four representative geographical points are shown

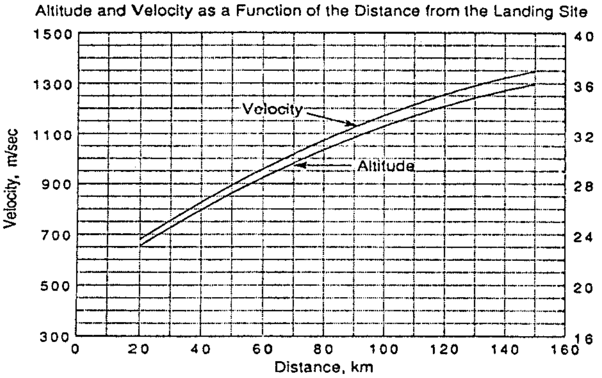

Fig. 6. The velocity and altitude from a nominal entry flight profile calculated from the data published by NASA

LA basin which are simultaneously hit by the space shuttle shock wave.

Figure 7c shows the record at SBC during the re-entry of Atlantis. The shock wave is barely seen on the displacement record. Large amplitude (approximately 5μm) signals are seen on this record both before and after the arrival of the shock wave indicating a complex pattern of acoustic coupling. The station SBC is located very close to the ocean, only 5 km away, and a very steep mountain range, Santa Ynez Mountains, is just behind (5 km) the station, as schematically shown in Fig. 8c. The velocity of space shuttle Atlantis just offshore Santa Barbara is comparable to the minimum phase velocity of Rayleigh waves in the ocean, about 1.5 km/s. Hence, some acoustic energy is expected to couple to the ground as Rayleigh waves. Also several large oil drilling platforms are located just offshore Santa Barbara which could have enhanced acoustic coupling. We will show later that the waves arriving after the shock wave can be interpreted as Rayleigh waves reflected from the Santa Ynez Mountains located behind SBC.

4. N wave

The shock wave excited by a supersonic aircraft is called an N wave for its distinct N shaped pulse (Carlson and Maglieri 1972). Cook and Goforth (1972) describe two kinds of seismic effects of sonic booms: (1) a moving strain field in the immediate vicinity of the surface loads from the N wave overpressure pulses, and (2) coupled seismic waves, which follow the passage of the N wave. The waveform recorded at ISA (Fig. 7a) shows a typical N wave of the first kind.

The magnitude of the overpressure, Δp, and the duration τ of an N wave can be approximately estimated from the speed, altitude and the size of the space shuttle, using equations (9.77) and (9.78) of Whitham (1974, pp 335-336, *a superscript 1/2 is missing in (9.77)*).

Let c, U, M, γ and H be the sound speed in the air (here assumed to be 300 m/s), space shuttle velocity, Mach number, the ratio of specific heats (= 1.4) and the altitude,

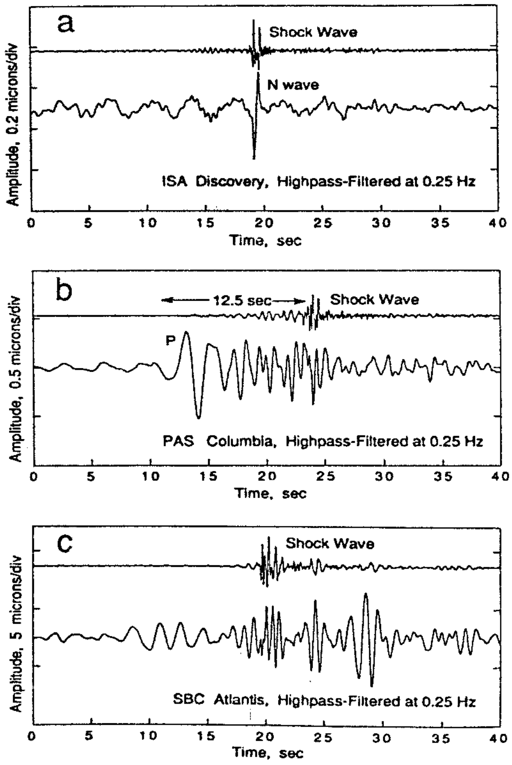

Fig. 7a-c. The displacement records (high-pass filtered at 0.25 Hz) obtained at the three TERRAscope stations for the space shuttles; **a** Discovery, **b** Columbia and **c** Atlantis. The arrival of the shock wave is indicated by the high-pass filtered trace above each displacement record

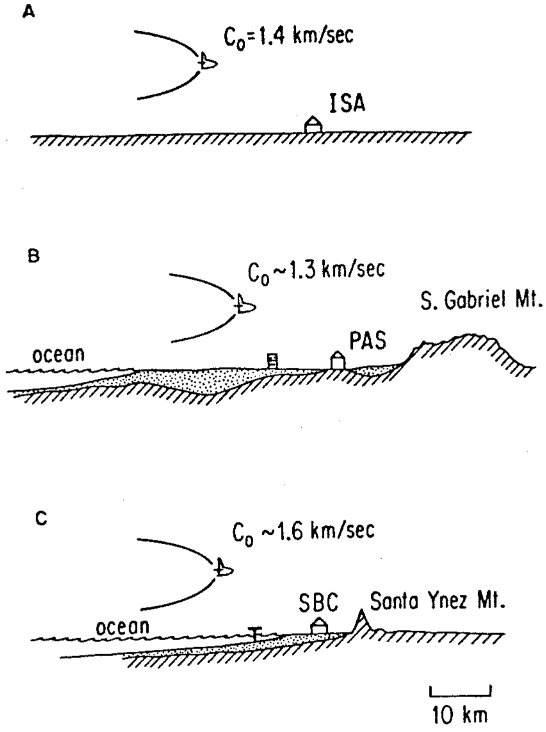

Fig. 8a-c. A schematic diagram showing the surface conditions near the three stations; **a** ISA, **b** PAS and **c** SBC

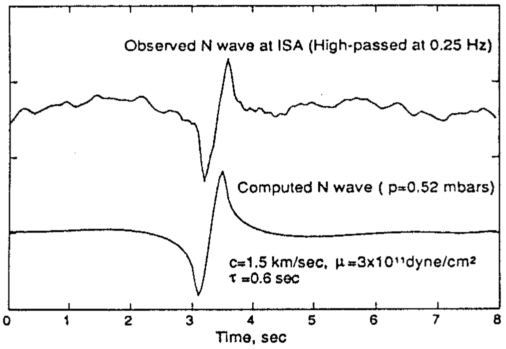

Fig. 9. Comparison of the shock wave (N wave) observed at ISA for Discovery and the waveform computed using (3)

Table 2. The pressure and the time separation of N waves estimated from the space shuttle parameters

		d (km)	y (km)	H (km)	U (m/s)	M	Δp (mbar)	τ (s)
PAS	(Col)	80	12	31	1,100	3.7	1.0	0.39
MWC	(Col)	70	18	30	1,000	3.3	0.93	0.39
CFL	(Col)	55	15	28	930	3.1	0.98	0.37
ISA	(Dis)	100	15	33	1,200	4.0	0.96	0.40

Col: Columbia, Dis: Discovery

respectively. Then the overpressure Δp is asymptotically given by

$$\frac{\Delta p}{p} \approx k_1 K H^{-3/4} \tag{1}$$

and τ is approximately given by,

$$\tau \approx 2\sqrt{2k_2} K H^{1/4}/U \tag{2}$$

where k_1 and k_2 depend on the properties of air and the shuttle velocity,

$$k_1 = \frac{2^{1/4}\gamma}{(\gamma+1)^{1/2}}\left(M^2-1\right)^{1/8} \qquad k_2 = \frac{(\gamma+1)M^4}{2^{1/2}(M^2-1)^{3/4}}$$

and K depends on the dimensions of the shuttle,

$$K \approx \delta l^{3/4}$$

where l is the length of the shuttle, and δ is the ratio of the maximum effective radius of the shuttle, r, to the length l.

We estimated Δp and τ for the space shuttles Columbia and Discovery using (1) and (2), and the results are summarized in Table 2. In this calculation, we used l = 35 m, r = 4 m, and the altitude H and the velocity U in Fig. 6 corresponding to the distance between the station and Edwards Air Force Base, d were used. The off-axis distance y was measured from the trajectory, and the effective altitude $(H^2+y^2)^{1/2}$ was used for H in (1) and (2). These values are obtained with many simplifying assumptions, and are meant to be used for comparison purposes only.

We can estimate the shock wave pressure amplitude from the observed N wave. We approximate the shock front by a

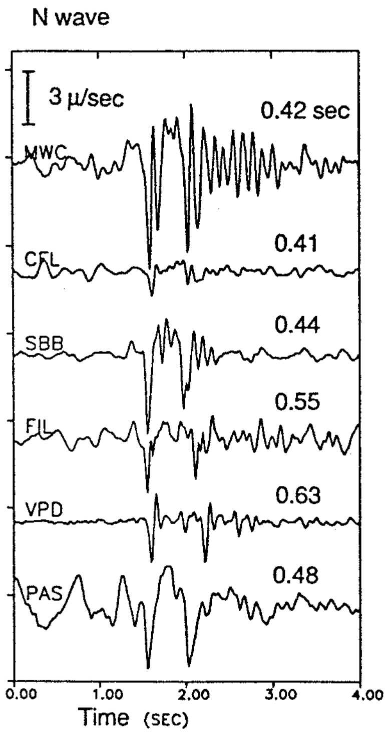

Fig. 10. N Waves observed for Columbia. The records represent ground motion velocity in a frequency range of 1 to 10 Hz. The numbers written on the right end of the records are the separation between the two pulses of an N wave

plane wave incident on a halfspace with an incident angle $i = \sin^{-1}(1/M)$. Following Ben Menachem and Singh (1981), when the horizontal phase velocity (i.e. the velocity of the space shuttle) is much smaller than the seismic P velocity in the halfspace, which is the case for the stations on hard rock sites like ISA and PAS, the vertical displacement of the free surface for an incident shock wave $\Delta p\, exp[i\omega(t - x/U)]$ is given by

$$u_z = \frac{-U\Delta p}{2\omega(\lambda+\mu)}\left(\frac{\lambda+2\mu}{\mu}\right)e^{i\omega(t-x/U)} \qquad (3)$$

where Δp is the pressure, U is the space shuttle velocity, and λ and μ are the elastic constants of the halfspace. Using the expression, we computed the response of an elastic halfspace to an N wave, compared it with the observed seismogram, and estimated the pressure. Figure 9 compares the observed record at ISA for Discovery and the computed waveform. The positive pressure causes downward ground motion near the seismograph. The result is summarized in Table 3. The shock wave pressure, Δp and the N wave separation, τ, are estimated to be 0.52 mbars and 0.6 s respectively. The good agreement between the observed and computed waveform suggests that the plane wave assumption used here is reasonable.

Figure 10 shows the N wave recorded for the space shuttle Columbia, recorded at the SCSN stations. Unlike Figs. 7a or 9, these records represent ground motion velocity in a frequency range of 1 to 10 Hz. The amplitude calibration is accurate to 5% at Pasadena, and 30% at the other stations. The ground motion velocity ranges from 1.9 to 9.4 μm/s.

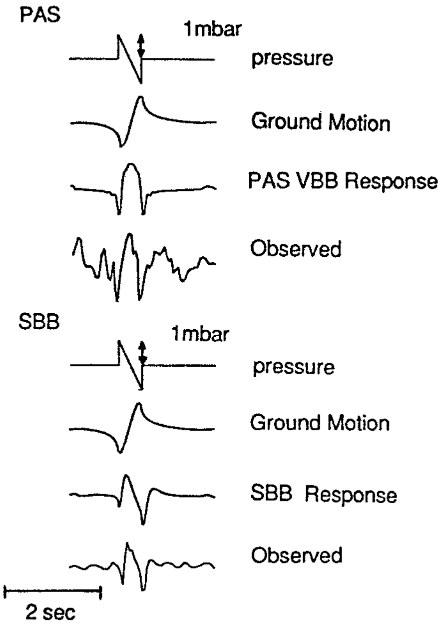

Fig. 11. N wave (pressure), the ground motion excited by N wave, the synthetic seismogram of N wave and the observed seismogram for stations PAS and SBB. The ratio of the observed to synthetic seismograms gives the estimate of the pressure

Note that the separation of the two pulses of an N wave varies from station to station. This is probably due to the difference in the distance of the stations normal to the space shuttle path. We estimated the pressure amplitudes from these records using (3). Figure 11 shows the result for the stations PAS and SBB, and the results are summarized in Table 3 for the stations located near the axis of the Mach cones. The estimated pressure changes are from 0.6 to 2.2 mbar. The relatively high value for Mt. Wilson (MWC) may be due to the interaction between the San Gabriel Mountain and the shock front. These values of Δp and τ thus estimated are in good agreement with those estimated from (1) and (2) and those measured directly by pressure gauges for the earlier space shuttles (Garcia et al. 1985).

5. Excitation of seismic waves

As mentioned earlier, the displacement record at PAS exhibits a very distinct long period (about 2 to 3 seconds) pulse at 12.5 s before the arrival of the shock wave. This pulse is recorded on all the components (vertical, N-S, and E-W), with a peak-to-peak amplitude of about 1 μm, Fig. 12. The initial horizontal particle motion is NE, and is in phase with the vertical motion, indicating that this pulse is a compressional P wave arriving at the station from the southwest. We rotated the two horizontal components in NE-SW (radial) and NW-SE (transverse) directions, which are shown in Fig. 12. From the time difference, 12.5 s, between the shock wave and the P pulse we determined that the origin of the P pulse is located near downtown LA, 14.5 km southwest of the Pasadena station (see Fig. 3 inset). In this calculation an average velocity of 4.5 km/s is used for the P wave.

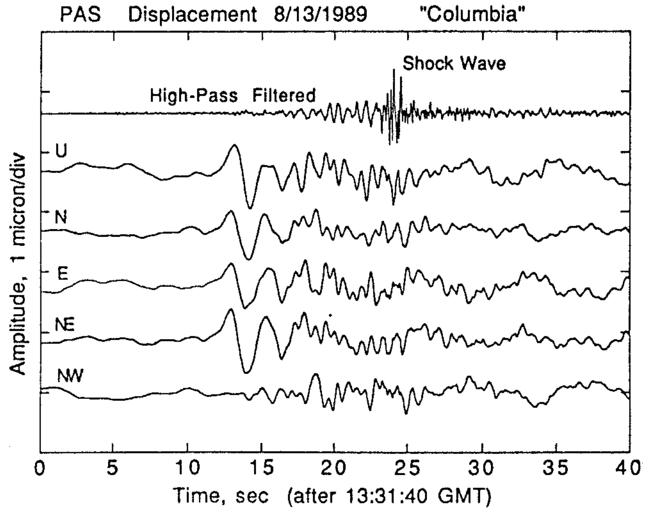

Fig. 12. The displacement records obtained at PAS for Columbia. The top trace is a high-pass filtered record showing the shock wave. The bottom two traces are the rotated traces obtained from the N-S and E-W components. Note the absence of energy on the transverse component

Table 3. The pressure and the time separation of N waves estimated from seismic data

Station		U (km/s)	μ (kbar)	Δp (mbar)	τ (s)
ISA	(Discovery)	1.5	300	0.52	0.60
PAS	(Columbia)	1.1	100	0.7	0.48
SBB	(Columbia)	0.7	300	0.8	0.44
MWC	(Columbia)	1.0	300	2.2	0.42
CFL	(Columbia)	1.0	300	0.6	0.41

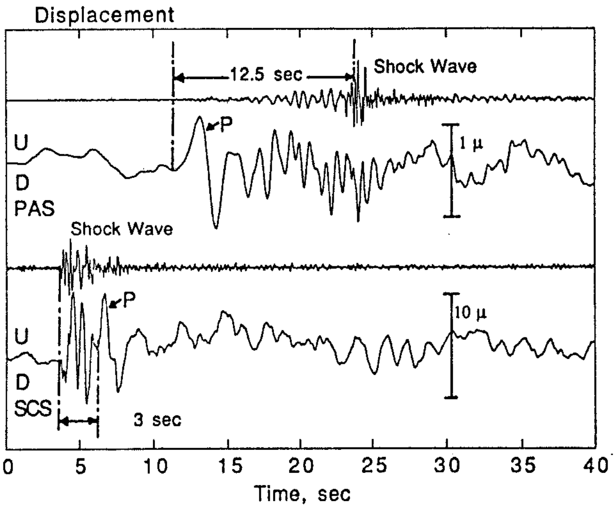

Fig. 13. Comparison of the displacement records for Columbia obtained at PAS and SCS (for the station locations, see Fig. 3) displayed on a common time scale. A high-pass filtered record is shown above the displacement record for each station to indicate the arrival time of the shock wave. Note that at PAS the long period P pulse is arriving 12.5 s before the shock wave while at SCS it is 3 sec after the shock wave

A broadband instrument (vertical component only) at the station SCS of the University of Southern California located slightly south of downtown LA also recorded this pulse as well as the shock wave. Figure 13 compares this record with the Pasadena record. Unlike the Pasadena record, the SCS record shows the P pulse (period is about 2 s) arriving about 3 s after the shock wave. The peak-to-peak amplitude is 10 μm, about 10 times larger than at Pasadena. Considering the geometry of the shock front and the locations of PAS and SCS (Fig. 3 inset), this observation is consistent with the hypothesis that the P pulse originated from downtown LA. The slight difference in the period between USC and Pasadena could be due to attenuation during propagation. (This pulse was also recorded in Monrovia, 27 km N60°E of Los Angeles (Lehner 1990).

The observation that the epicenter (the origin of the P pulse) is in downtown LA requires that the shock wave energy must have been transferred to the ground there by some coupling mechanism. The most prominent feature on downtown LA is the group of high rise buildings (natural period 1 to 6 s). This leads us to believe that the P pulse was excited by the high rise buildings which were simultaneously hit by the shock waves. According to the data provided by the Los Angeles City Fire Department (Borden 1989), there are about 100 buildings taller than 20 stories in downtown LA and the Wilshire district.

The damping of the buildings is very small (about 2% in damping constant) so that the oscillation of the individual building hit by a shock wave will last for a long time. The ground motion thus excited will be a long damped oscillation instead of an impulse. However, if many buildings with different periods are excited simultaneously, the first cycle will constructively contribute to excitation of ground motion, but the later cycles will destructively interfere with no significant net contribution. Consequently, the resulting ground motion will be impulsive, as observed. This situation may be viewed as an inverse Fourier transform of a delta function. The harmonic oscillations of the buildings with different periods correspond to the harmonic components of a delta function.

The natural period of the basin is about 2 to 3 s, so that the excitation by the buildings having this period range is more effective due to the matching periods between the buildings and the ground. This explains the dominant period of the P pulse at 2 to 3 s.

The excitation of seismic waves by the shaking of buildings has been demonstrated by Jennings (1970). Shaking of the 9 story Millikan Library building on the Caltech campus excited seismic waves which were observed with a seismograph at Mount Wilson, 11 km away. In this experiment the observed acceleration on the roof of the Millikan library is 2% of g, and the observed amplitude at Mount Wilson was 0.02 μm, which is 1/25 of the amplitude of the P pulse observed at Pasadena for the space shuttle.

If the excitation by a building is proportional to $M\alpha$ (M: mass of the building, α: acceleration), the ground motion amplitude x is given by

$$x = cNM\alpha$$

where N is the number of buildings and c is a constant. Then, a simple scaling shows that

$$(\alpha_1/\alpha_0) = (x_1/x_0)(N_0/N_1)(M_0/M_1)$$

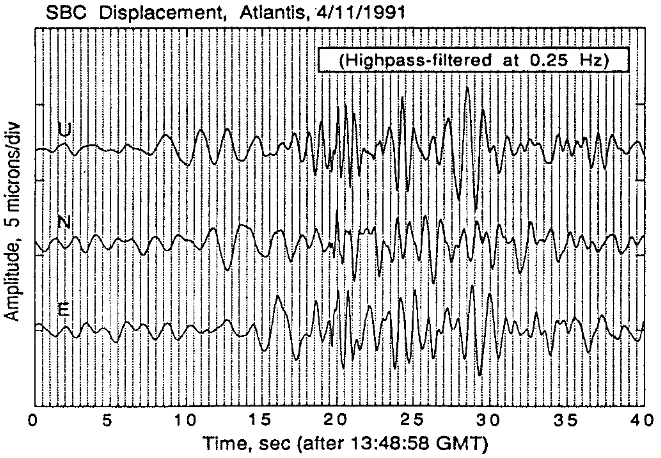

Fig. 14. The three component displacement seismograms recorded at SBC for Atlantis

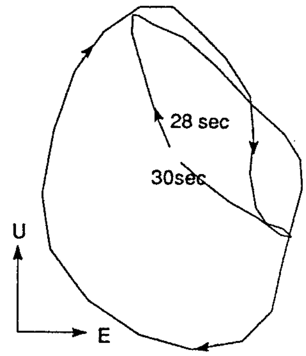

Fig. 15. The particle motion of the wave arriving at about 29 s on the record shown in Fig. 14, determined from the vertical and E-W components

where subscripts 0 and 1 refer to the Millikan Library and the space shuttle, respectively. Since 20 story buildings whose natural period is about 2 s are primarily responsible for excitation of the 2 s P pulse, we assume that $(N_0/N_1) = 1/10$. Here, $N_1 = 100$ is the approximate number of buildings taller that 20 stories, and (M_0/M_1) is assumed to be proportional to the cube of the height ratio of the buildings. Then, $\alpha_1 = 0.025 \times 0.02g = 0.0005g$ (i.e. 0.05% of g), a very small value. Even if we allow for the large bulk density of the Millikan Library building, α_1 is about 0.1% of g. Although no accelerograms are available from the buildings, this level of acceleration is plausible.

Figure 7b exhibits reverberations following the P pulse. As Fig. 2 shows, the stations located in or near the LA basin show similar reverberations, while stations outside the LA basin show only impulsive shock waves. We conclude that these reverberations are the response of the LA basin to the shock wave.

The record obtained at SBC for Atlantis (Fig. 7c) is similar to that of PAS for Columbia. However, the particle motion of this pulse is very complex, as shown in Fig. 14. The particle motion which is initially vertical becomes N-S and E-W subsequently. This is in contrast to the coherent particle motion between the vertical and NW-SW components of the PAS record for Columbia (Fig. 12). This difference suggests that the acoustic coupling of the shock wave of Atlantis occurred over an extended area near Santa Barbara, while it occurred at a localized area, downtown LA, for Columbia.

The complex pattern of the acoustic coupling seen for Atlantis is probably caused by two factors. First, the velocity of the space shuttle was large enough, larger than the Rayleigh wave phase velocity in the water, to cause efficient acoustic energy coupling between shock wave and seismic wave. Second, about a dozen large oil drilling platforms offshore Santa Barbara could have coupled the shock wave energy to the ground in a way similar to that by the high rise buildings in downtown LA. We could not determine the details with the single station data, however.

The large pulse arriving at about 29 s on Fig. 14 exhibits a distinct $\pi/2$ phase shift between the vertical and E-W components, as shown in Fig. 15. This suggests that this pulse is a Rayleigh wave propagating from east towards the station SBC. From the time difference between this pulse and the shock wave, we interpret it to be a Rayleigh wave originating from the Santa Ynez mountains which are hit by the shock wave after it propagated past SBC. This example suggests that the efficiency of acoustic coupling is very strongly controlled by the local topography near the station.

6. Conclusions

Shock waves generated by space shuttles, and recorded with modern broadband seismic instruments proved useful for studying the seismic response of the Earth's surface with different surface conditions as well as for estimating the shock wave amplitudes.

The efficient excitation of the seismic pulse with a period of 2 to 3 s by the Columbia shock wave suggests a good mechanical coupling between the buildings and the LA basin with matching natural periods. This in turn suggests that seismic waves excited by earthquakes having significant energy in this period range will preferentially shake the buildings with similar natural periods.

Figure 16 shows the frequency spectrum of the vertical component of the P pulse recorded at Pasadena (Fig. 7b). Spectral peaks are observed at 0.76, 1.17, 1.62 and 2.00 Hz, which can be interpreted as the response of a soft superficial layer with a two way P wave travel time of about 2 s. For example, for a layer over halfspace model (a 2.22 km thick layer with a P wave velocity of 2 km/s), the spectrum of the vertical component of the ground motion at the surface due to a vertically incident P wave computed by the Thomson-Haskell method (Haskell 1962) exhibits similar spectral peaks (Fig. 16).

Amplification of seismic waves by soft sediments in the LA basin has been already demonstrated. Liu and Heaton (1984) and Vidale and Helmberger (1988) show that the ground motions from the 1971 San Fernando earthquake are significantly (a factor of 3 to 5) amplified in the LA basin. Although the seismic response of the LA basin is not known in detail, the efficient excitation of the 2 to 3 s seismic pulse by the shock wave points to the importance of investigating the long period response of the LA basin to earthquake generated seismic waves coming into the LA basin. The

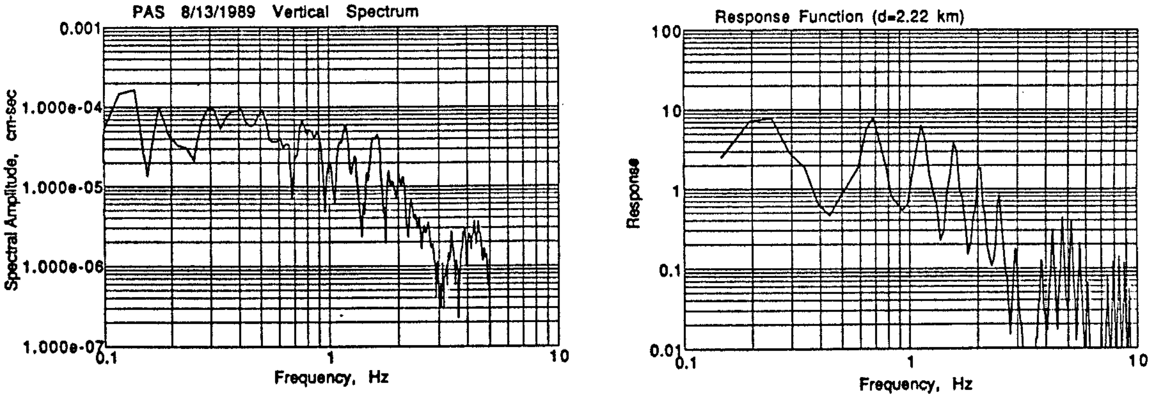

Fig. 16. **Left** The spectrum of ground motion at Pasadena (Fig. 7b), **Right** The response of a layer (P velocity = 2 km/s, S velocity = 1.4 km/s, density = 1.2 g/cm^3, thickness = 2.22 km) over halfspace (P velocity = 6 km/s, S velocity = 3.7 km/s, density = 2.5 g/cm^3). The spectrum of the vertical displacement at the surface caused by a vertical incident P wave at the bottom is shown

importance of site effects has been repeatedly demonstrated for the recent major earthquakes such as the 1985 Mexico earthquake and the 1989 Loma Prieta, California earthquake.

As many recent studies have suggested, large earthquakes with long fault lengths such as those expected on the San Andreas fault excite a very significant amount of energy at periods longer than 1 s. In view of the high probability of large ($M > 7.5$) earthquakes on the San Andreas fault in the next 30 years (Working Group 1988), and possible large earthquakes on the blind faults beneath the LA basin (Hauksson 1990), it is important to assess the long period response of the LA basin quantitatively so that more comprehensive hazard mitigation measures can be taken.

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