Seismological Laboratory

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NOTE ON "SOUND WAVES IN THE ATMOSPHERE GENERATED BY A SMALL EARTHQUAKE"

by

Hugo Benioff

Maurice Ewing

Frank Press

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ABSTRACT

Sound waves from the Imperial Valley earthquake of 24 January 1951 are interpreted as the result of coupling between Rayleigh waves crossing the valley and the atmosphere. An order of magnitude calculation based on the theory of air coupled Rayleigh waves satisfactorily explains the duration, travel time, period, and path of the sounds.

In previous papers 1-5 theoretical and experimental results on the coupling of atmospheric compressional waves to various types of surface waves have been presented. Recently Benioff[6] presented a paper describing a remarkable instance of sound waves received at Pasadena from the earthquake of 24 January 1951, 07-17-01, Magnitude 5.6, $33^{\circ}07'$N, $115^{\circ}34'$W, $\Delta = 265$ km. The microbarograph recorded a train of waves which commenced gradually at about 23:34:00 P.S.T. with periods of about 3/4 sec. and ended at about 23:39:00 with periods of about 1 second. (Figure 1)

About 55 km of path, starting from the epicenter in the Imperial Valley, crossed valley sediments before reaching intrusive rocks of the mountains. For the valley part of the path we may expect, by analogy with the results of a study of air coupling to Rayleigh waves in the weathered layer in northeast Texas, that the group and phase velocities are given by curves similar to the dimensionless curves in Figure 2. These curves are only useful for an "order of magnitude" calculation when applied to the Imperial Valley.

In this figure the heavy lines represent the dimensionless phase (c/β_1) and group (U/β_1) velocity curves of waves propagated without coupling to the atmosphere which would be recorded by a seismograph. The dashed lines represent the corresponding curves for Rayleigh waves coupled to atmospheric compressional waves. The constants used in computing these curves are as follows:

$\alpha_0 = 1070$ ft/sec $\beta_1 = 800$ ft/sec $\alpha_1 = \sqrt{3}\,\beta_1$ $\alpha_2 = \sqrt{3}\,\beta_2$

$\rho_2/\rho_1 = 1.39$ $\rho_0/\rho_1 = .001$ $\mu_2/\mu_1 = 13.77$

where α is compressional wave velocity, β is shear wave velocity, ρ is density, μ is shear modulus and the subscripts 0, 1, 2 refer respectively to air, surface unconsolidated sediments and bedrock. These values were chosen as representative of near surface conditions often encountered in seismic prospecting. A depth of the weathered layer of about 100 meters is required to obtain the observed period of 0.9 sec. by the following equation:

$$H = T\,(kH)(c/\beta_1)\,\beta_1/2\pi$$

where H is the depth, T is the period, k is the wave number.

This curve shows that waves of period about 0.9 sec. will be coupled to the atmosphere, that the corresponding phase velocity is equal to the speed of sound in air and that the group velocity ranges from the speed of sound in air to .31 times that value. A more complete discussion of this curve is given elsewhere.[4,5]

An approximate interpretation of the propagation of sound to the microbarograph is that the Rayleigh waves of period 0.9 sec. crossed the valley at a speed of 0.100 km/sec. radiating compressional waves into the air as they went. The time required for these Rayleigh waves to cross the valley was about 550 sec., after which time no Rayleigh waves of sufficiently slow speed to radiate into the air could exist. Thus the first airborne waves started for Pasadena at about 07-17-01 GC a distance of 265 km, while the last ones started at about 07-26-11 at distance of 210 km. From the results of Crary[7] we may approximately consider that these sound waves go vertically to a height of 40 km with a mean velocity of .305 km/sec and travel the horizontal distance to Pasadena at a speed of .326 km/sec. before descending. One can roughly calculate the arrival times as follows:

	First Wave	Last Wave
Vertical travel time:	$2\times\frac{40}{.305} = 262$ sec.	$2\times\frac{40}{.305} = 262$ sec.
Horizontal travel time:	$\frac{265}{.326} = 813$ sec.	$\frac{210}{.326} = 644$ sec.
Total travel time:	17 min 55 sec	15 min 6 sec
Origin time:	07-17-01	07-26-11
Computed arrival time:	07-34-56	07-41-17
Observed arrival time:	07-34-00	07-39-00

The values deduced for computed arrival time of the first and last waves by this order of magnitude calculation agree reasonably well with the observed values in view of the gradual nature of the beginning and end of the signal, the approximate applicability of the theoretical waves and the simplification of the aerial path.

As mentioned above, the periods within the train are erratic, but show a predominant value of about 3/4 sec. at the beginning and 1 sec. at the end. The most probable explanation of this change is a variation in the dispersion properties of the sediments across the valley.

Regarding the depth of 100 meters, chosen to represent the "weathered layer", it must be pointed out that the Rayleigh wave velocity is essentially controlled by the vertical variation in shear velocity, which may be quite different from that of compressional wave velocities. In a general way the former depends on the degree of lithification and the latter on the water table.

These results illustrate a fundamental reciprocity principle of observation of air coupled waves through the fact that the Pasadena seismographs did not register this wave train. For a disturbance in either medium, the air coupled waves are detected in the other medium. Thus a disturbance in the air could produce a similar train of waves in the earth.

This example is believed to represent the first analyzed case of air coupled waves from a natural earthquake. It may be expected that a variety of others will now be found.

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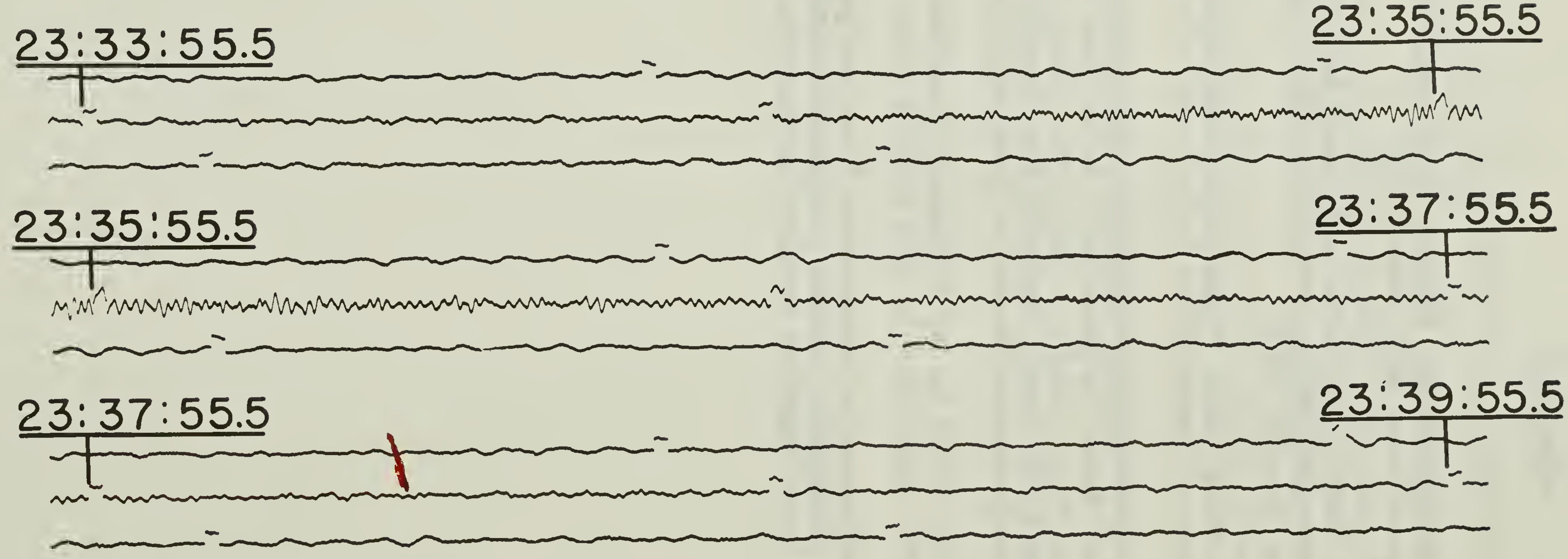

Figure 1. Copy of a 35 mm film record taken with Benioff electromagnetic microbarograph, galvanometer period 0.25 sec., recording speed 0.25 mm/sec.

Figure 2. Phase and group velocity curves for air coupled Rayleigh waves.