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SOUND WAVES IN THE ATMOSPHERE GENERATED BY A SMALL EARTHQUAKE†

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In previous papers[1–5] theoretical and experimental results on the coupling of atmospheric compressional waves to various types of surface waves in the underlying earth or ocean have been presented. Recently Benioff[6] presented a paper describing a remarkable instance of atmospheric waves received at Pasadena from the earthquake of January 24, 1951, 07-17-01, magnitude 5.6, 33° 07′N., 115° 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 $^3/_4$ second and ended at about 23:39:00 P.S.T. with periods of about 1 sec. (Fig. 1). Benioff had noticed a similar disburbance following a small tremor several years earlier.

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.[4–5] 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, and group U/β, velocity curves of Rayleigh waves propagated through an earth whose layering is described below, neglecting coupling to the atmosphere. The dashed lines represent the corresponding curves with the inclusion of coupling to atmospheric compressional waves. The constants used in computing these curves are as follows:

$$\alpha_0 = 1070 \text{ ft./sec.} \quad \beta_1 = 800 \text{ ft./sec.} \quad \alpha_1 = \sqrt{3}\beta, \quad \alpha_2 = \sqrt{3}\beta_2$$
$$\rho_2/\rho_1 = 1.39 \quad \rho_0/\rho_1 = 0.001 \quad \mu_2/\mu_1 = 13.77$$

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.

The group velocity curve in figure 2 is divided into branches I, II and III, each of which represents a different train of waves. Branch I represents the ordinary dispersive Rayleigh waves. These waves first appear as long period oscillations, traveling with the speed of Rayleigh waves in the bottom layer, $U = 0.9194\ \beta_2$. Succeeding waves gradually increase in period, since the group velocity decreases as KH increases. Waves represented by branch I predominate if the source of waves and the detector

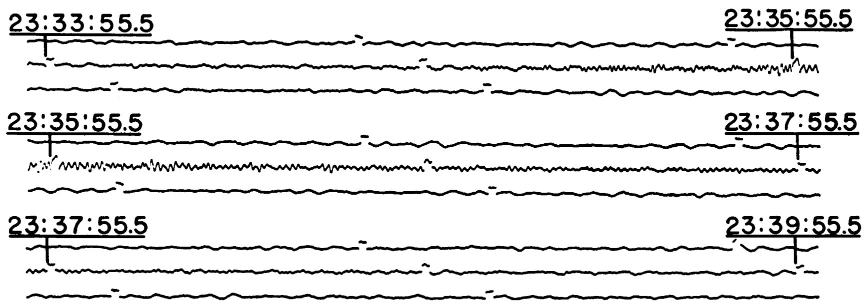

FIGURE 1

Copy of a 35-mm. film record taken with Benioff electromagnetic microbarograph, galvanometer period 0.15 sec., recording speed 0.25 mm./sec.

are located in the earth. Branch II represents a dispersive train of waves beginning with high-frequency oscillations propagated with the speed of Rayleigh waves in the surface layer. The frequency of these waves decreases as time progresses until the waves of both branches have a common frequency, forming an Airy phase[7] which is propagated at the minimum group velocity. Branch III represents an additional train introduced by coupling of the Rayleigh wave to atmospheric compressional waves. The beginning of this train is propagated with the speed of sound in air, and includes all frequencies from zero to that given by KH approximately equal to 2. In the neighborhood of KH = 2, the group velocity curve drops steeply, giving a long train of waves with almost constant frequency, and with phase velocity nearly equal to the speed of sound in air. Branch III governs transmission when the source is in the earth and the detector is in the air, or vice versa.

From figure 2 the depth of the weathered layer required to produce air coupling at a period of 0.9 sec. may be calculated as approximately 100 meters, using the equation

$$H = T(KH)(C/\beta_1)\beta_1/2\pi$$

A more complete discussion has been given previously.[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 0.10 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. (The lowest speed is that of the minimum group velocity.) Thus the first airborne waves started for Pasadena at about 07-17-01 G.C.T., a distance of 265 km., while the last ones started at about 07-26-11, a distance of 210 km. From the results of Crary[8] we may approximately consider that these sound waves go vertically to a height of 40 km. with a mean velocity of 0.305 km./sec. and travel the horizontal distance to Pasadena at a speed of 0.326 km./sec. before descending. One can roughly calculate the arrival times as follows:

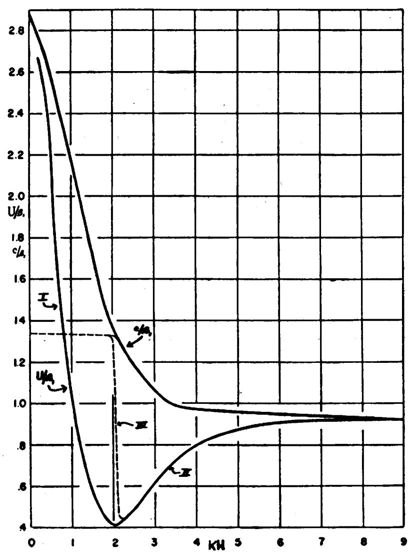

FIGURE 2

Phase and group velocity curves for air coupled Rayleigh waves.

	FIRST WAVE	LAST WAVE
Vertical travel time:	2 × 40/0.305 = 262 sec.	2 × 40/0.305 = 262 sec.
Horizontal travel time:	265/0.326 = 813 sec.	210/0.326 = 644 sec.
Total travel time:	17 min. 55 sec.	15 min. 6 sec.
Origin time in air:	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 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 uncertainty of the elastic constants used in the theoretical curves 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. The conditions necessary for its occurrence are not uncommon and one may expect that additional data will be forthcoming.

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