SOIL STRAINS AND HORIZONTAL PROPAGATION VELOCITIES OF STRONG GROUND MOTIONS OBSERVED DURING THE 1979 IMPERIAL VALLEY, CALIFORNIA, EARTHQUAKE

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SUMMARY

Strong ground motions caused by the 1979 Imperial Valley earthquake (M_s = 6.9) at the El Centro differential array, 5.6 km from the ground rupture, were caused primarily by direct P and S body waves originating from the fault at depth. Vertical and horizontal ground motions had propagation slownesses (1/velocity) of 0.11-0.19 s/km and 0.19-0.33 s/km, respectively, after near-surface perturbations were removed. These correspond to vertical and horizontal strains less than 4.5×10^{-3} and 0.22×10^{-3}, respectively.

INTRODUCTION

Part of the deformations suffered by large foundations and bridges during earthquakes may be caused by strains which occur in the soils in which the structures are embedded. In order to predict the size of these soil strains, it is necessary to know whether they are caused by body waves or surface waves, what the angle of incidence of these waves is to the earth's surface, and what their wavelengths and propagation velocities are when measured along the earth's surface. Measurements (Ref. 1) made at a site 5.6 km from the surface rupture of the M_s = 6.9 1979 Imperial Valley, California, earthquake answer many of these questions. From these measurements we may estimate the soil strains which occurred at the site.

OBSERVATIONS

The 1979 Imperial Valley earthquake was recorded by 5 elements, DA1-DA5, of a linear, 6-element array of 3-component digital accelerometers (Ref. 2) whose positions with respect to the fault are shown in Figure 1. Peak accelerations of about 0.65 g, 0.35 g, and 0.48 g were recorded in the vertical, east-west, and north-south directions, respectively. The array data and performance have been discussed extensively elsewhere (Refs. 1, 3); however, an important malfunction was that absolute time was not recorded on any array element. Time was established on each array element by using the P waves from the main shock hypocenter and an aftershock as synchronizing events, since their theoretical propagation velocities along the array were known. This fact will have an important effect on the interpretation of the strains we derive below.

Ground motions in the 1.6 to 25 Hz band observed on the array during the first 11 s of shaking (which includes the strongest shaking) were

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composed mostly of direct P and S waves from the ruptured portion of the fault (Ref. 1). Horizontal propagation velocities of the strong motions were also obtained. By measuring the time of arrival of a seismic wave at each element of the array, the component of the wave's propagation slowness (1/velocity) along the array could be obtained by dividing the arrival time difference by the spatial separation of the array elements (slowness is a more convenient quantity to use than velocity because it is linearly related to the observed time difference, and never becomes infinite). This procedure was applied to successive overlapping time windows of the array data (Ref. 1) to produce running records of the slowness (inverse velocity) of seismic arrivals along the direction of the array during the earthquake. The slownesses observed on the vertical and horizontal components of motion during the event are shown in Figures 2 and 3, respectively. The interpretation of these diagrams is simple; in Figure 2 we see that during the first second of motion the seismic arrivals travelled along the array with a 0.1 s/km slowness (or 10 km/s velocity) from south to north. About 6 s into the event the seismic waves arrived at all array elements simultaneously, leading to a 0.0 s/km slowness (infinite velocity along the array), and at 9 s the seismic waves were propagating from north to south along the array at 0.14 s/km (7 km/s). In Figure 3 the slowness observed in the horizontal ground motions was very erratic until about 6 s, when the strong horizontal motions began. It changed fairly smoothly during the period of strong horizontal shaking, showing a progression from northward to southward energy propagation, as did the vertical ground motions. The observed slownesses are quite consistent with the hypothesis that the ground motions in the 1.6 - 25 Hz band are caused by direct P and S waves radiated by the earthquake rupture front as it propagated northward along the Imperial fault from the event's hypocenter (Ref. 1). Little surface wave energy was observed at the array.

AN IMPORTANT WARNING

Because of the method used to set time on the differential array, the slownesses measured above and the strains derived below lack the effects caused by very near-surface variations in the soil's P and S velocities under each array element (Ref. 1). P wave velocity variations may be caused by differing depths to the water table (Refs. 1, 4,), and may be confined to the top 10 m of the soil. The effect of these velocity variations at each array element is to advance or retard the arrival time of a wavefront initially incident on the near-surface zone. Thus, the measured slownesses are those of the waves incident on the near-surface zone before being advanced or retarded, and the strains derived later in this paper are those which would have been observed if the very shallow soil structure had been identical under each array element.

DEDUCING SOIL STRAINS

A rough estimate of the size of the strains associated with the observed slownesses and ground motions may be obtained from the following analysis. Let the displacements caused in the x-y plane by a propagating plane wave be $\mathbf{u}(x-ct)$, where c is the velocity of phase fronts along the x-y plane in the x direction. Note that the direction of plane wave propagation need not lie in the x-y plane. If the wave propagates in a direction normal to the x-y plane, c will be infinite; if the wave propagates in the x direction, c will be the wave propagation velocity. We then have that the spatial derivative of displacement $\partial_x \mathbf{u} = -\partial_t \mathbf{u}/c = p_x \mathbf{v}$, where $\mathbf{v}$ is the particle velocity and $p_x = 1/c$ is the slowness of the wave in x-y plane. Hence, the spatial derivative of displacement (strain) is proportional to slowness times particle velocity.

From arguments such as these, we may determine the following approximate expression for spatial derivatives of ground displacement:

$$\begin{bmatrix} u_{x,x} & u_{x,y} & u_{x,z} \\ u_{y,x} & u_{y,y} & u_{y,z} \\ u_{z,x} & u_{z,y} & u_{z,z} \end{bmatrix} = \begin{bmatrix} p_x v_x & p_y v_x & p_z v_x \\ p_x v_y & p_y v_y & p_z v_y \\ p_x v_z & p_y v_z & p_z v_z \end{bmatrix}$$

where $u_{x,y} = \partial_y u_x$, v_x is the x component of ground velocity, and p_i is the i component of slowness, with

$$\frac{1}{V} = \sqrt{p_x^{\,2} + p_y^{\,2} + p_z^{\,2}}$$

where V is the compressional or shear velocity of the soil.

These relations would be easy to apply to the differential array measurements, except for the fact that we only have measurements of the north-south component of slowness. To deduce the true slowness p_t of the ground motions along the earth's surface, we must introduce seismological evidence about the rupture mechanism of the Imperial Valley earthquake. Most of the energy radiated from the fault appears to have come from depths of 4 km or greater (Refs. 1, 5, 6). If we assume that all the observed energy came from a line on the Imperial fault at a fixed depth, then each observed slowness can have come from only one point on that line, which can be uniquely identified (Ref. 1). Once such a point is identified, it is possible to calculate p_{ts} the true slowness P and S waves generated by that point would have at the array, knowing the local velocity structure. Using this procedure we have converted the observed slowness of vertical and horizontal motions into true slowness, assuming 3 source depths, 4, 7, and 10 km (Figures 2 and 3), and assuming the vertical and horizontal motions are caused by P and S waves, respectively (see Ref. 1 for a discussion of this assumption). The figures show that the true slownesses of vertical motions lie between 0.11 and 0.19 s/km, and for horizontal motions the slownesses lie betwen 0.19 and 0.33 s/km.

We may set upper bounds on strain by using the largest possible values of p_x, p_y, p_z, and observed ground velocity at the array (Ref. 7) in the expressions for the strains. For the maximum p_x and p_y we use the largest true slownesses shown in Figures 2 and 3, and to maximize p_z we use the above equation and the minimum true slownesses in Figures 2 and 3. The values used and the results are shown in Table 1, in which we presume that the vertical motions consists of P waves and the horizontal motions sist of S waves, and in which v_n, v_e, and v_z are the peak north, east, and vertical components of ground velocity at the differential array.

Table 1. Determination of Strain

	P waves	S waves	Comment
V (km/s)	0.34	0.15	Ref. 1
max. p_t (s/km)	0.19	0.33	
max. p_z (s/km)	2.9	6.7	
peak v_n (cm/s)	0.0	42.5	
peak v_e (cm/s)	0.0	67.8	
peak v_z (cm/s)	20.0	0.	
$p_t v_n$ (unitless)	0.	1.4×10^{-4}	$u_{n,n}$; $u_{n,e}$
$p_t v_e$ (unitless)	0.	2.2×10^{-4}	$u_{e,n}$; $u_{e,e}$
$p_t v_z$ (unitless)	0.38×10^{-4}	0.	$u_{z,n}$; $u_{z,e}$
$p_z v_n$ (unitless)	0.	28.4×10^{-4}	$u_{n,z}$
$p_z v_e$ (unitless)	0.	45.4×10^{-4}	$u_{e,z}$
$p_z v_z$ (unitless)	5.8×10^{-4}	0.	$u_{z,z}$

These results show that by far the largest strains are associated with derivatives of displacement with respect to depth. These strains may go as high as 4.5×10^{-3} (5.5 inches/100 ft). However, strains in the horizontal direction are much smaller, reaching an upper bound of 2.2×10^{-4} (0.26 inches/100 ft). The reason why vertical derivatives overwhelm horizontal derivatives in this case is because the near-surface P and S wave velocities at the array are so slow that P and S waves travel nearly vertically in the near-surface material.

DISCUSSION

As mentioned earlier, the small horizontal strains and larger vertical strains derived above are those that would have been observed at the array had the soils under each element been identical. Since they were not, the strains actually observed at the array are different and still unknown. What, then, is the relevance of our results?

Our observations and results provide a useful mechanism for site-specific predictions of soil strain. In this and our earlier work, we have shown for this earthquake and observation site that the strong motions are caused by direct P and S body waves which travel predictable paths, except possibly in some thin near-surface zone. The effect of this zone is to advance or delay wavefronts. These delays are probably independent of the earthquake source. Thus, at this or any other site they can probably be estimated by measurement of soil velocity or measured directly by recording small earthquakes at the site. Knowledge of these delays then provides the necessary information for the prediction of horizontal propagation velocities of strong motions and the resulting strains, given a hypothetical earthquake source.

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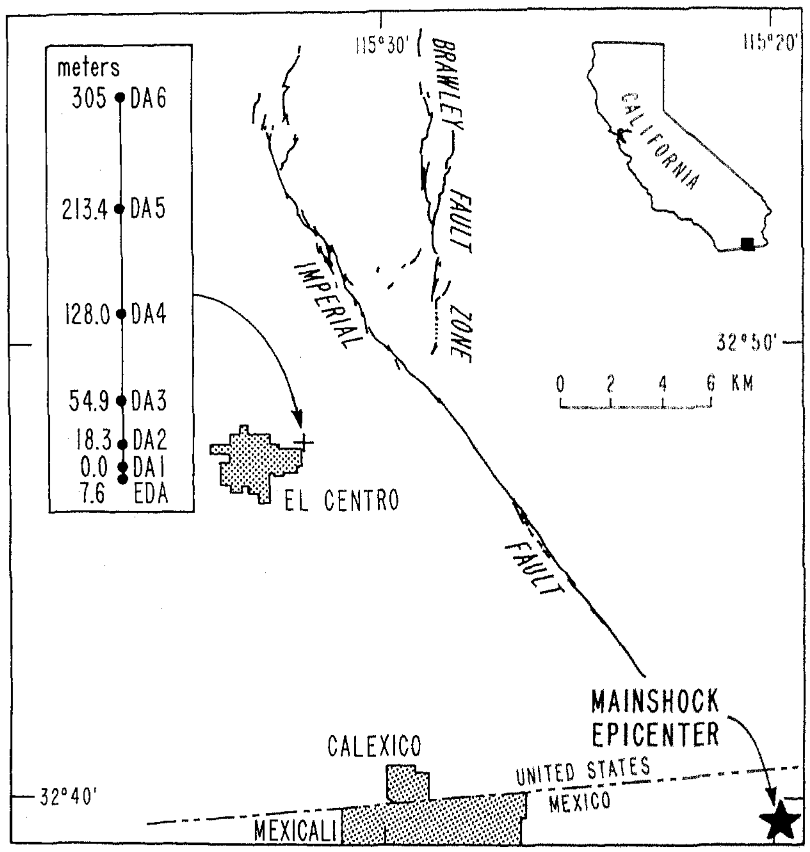

Figure 1. Location and layout of the array elements, and surface rupture associated with the earthquake. EDA was an analog SMA-1 accelerograph.

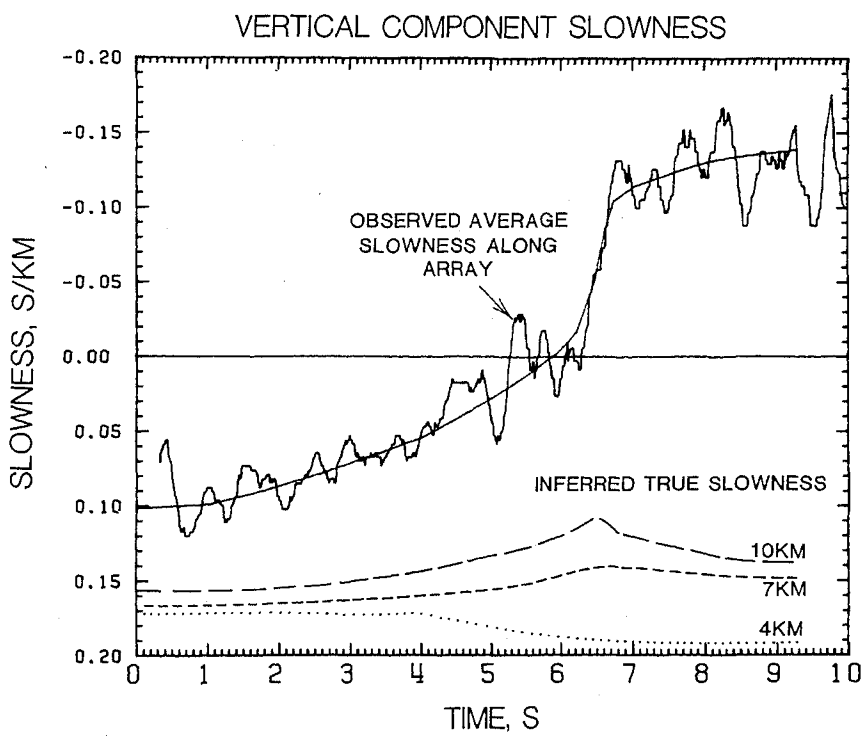

Figure 2. Jagged line is observed slowness of vertical ground motions along the array during the earthquake, and smooth line is fit visually through the observations. Dashed and dotted lines are true slownesses inferred from the smoothed observations, based on indicated source depths. Negative slownesses indicate energy travelling in a southerly direction, positive indicate northerly propagation.

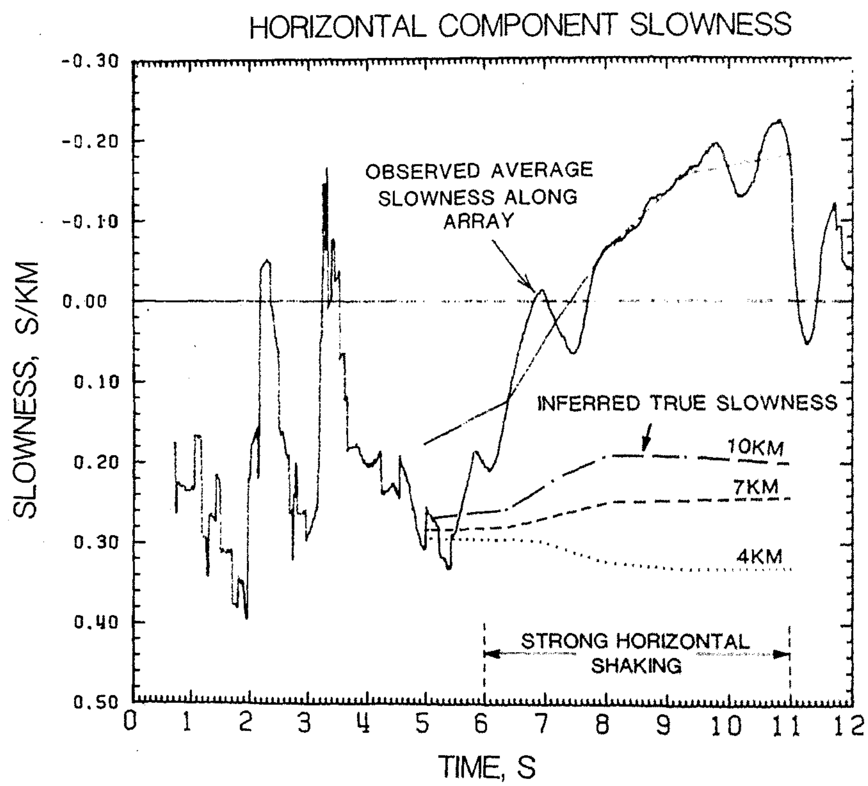

Figure 3. Observed and true slowness of horizontal ground motions. See Figure 2 for details.