Origins of Displacements Caused by Underground Nuclear Explosions*

by

John S. Rinehart
ESSA Research Laboratories, and
Department of Mechanical Engineering, University of Colorado
Boulder, Colorado 80302

ABSTRACT

Elastic theory has been used to calculate the relative displacement that will occur between the two sides of a loose boundary when a plane wave strikes the boundary obliquely. The calculations suggest that the displacements produced along loose fractures and faults close in to the underground nuclear explosions are a direct consequence of reflection of the transient stress wave at this loose boundary. Quantitatively the results agree fairly well with the limited data that are available.

INTRODUCTION

A common effect of an underground nuclear explosion is the development at the time of the explosion of displacements along jointed rock structures and preexisting faults as illustrated for the Boxcar event in Fig. 1. Such displacements have been extensively described (Barosh, 1968; Buckman, 1969; Dickey, 1968; Dickey, Jenkins, McKeown, and Lee, 1967; Dickey, McKeown, and Ellis, 1968; Hamilton, McKeown, and Healy, 1969; McKeown and Dickey, 1969). Both vertical and right lateral displacements occur out to a few thousand meters from ground zero, the displacements being of the order of tens of centimenters.

The purpose of this paper is to show that these displacements are the anticipated consequence of the interaction of the generated elastic transient stress wave with a loose interface obliquely inclined to the front of the wave.

*Work partially supported by a grant from the American Petroleum Institute to the University of Colorado.

PARTICLE VELOCITY MAGNITUDES

Consider two flat blocks of similar material juxtaposed and loosely connected. When a transient compressional stress wave strikes obliquely such a boundary, the interface, considered perfectly lubricated, can sustain no shear stress. Only normal stresses can be transmitted. The four boundary conditions that must be met at all times during the interaction of the wave with the boundary are: continuity of normal stress across the interface; continuity of normal particle velocity, or displacement, across the interface; and zero shear stresses on both surfaces forming the interface.

When these conditions are applied to an advancing elastic dilatational compression wave, the five waves shown in Fig. 2 become involved in the interaction: the incident longitudinal wave (A); a reflected longitudinal wave (C); a reflected shear wave (D); a transmitted longitudinal wave (E); and a transmitted shear wave (F).

If the particle velocity in the incident is V_A (Fig. 2), the particle velocities in the four new waves will be given by

$$V_B/V_A = (\sin 2\alpha \sin 2\beta) \,/\, (K^2 \cos^2 2\beta \sin 2\beta)$$

$$V_C/V_A = (K \cos 2\beta \sin^2 \alpha) \,/\, (K^2 \cos^2 2\beta + \sin 2\alpha \sin 2\beta)$$

$$V_D/V_A = (K \cos 2\beta \sin 2\alpha) \,/\, (K^2 \cos^2 2\beta + \sin 2\alpha \sin 2\beta)$$

$$V_E/V_A = (K^2 \cos^2 2\beta) \,/\, (K^2 \cos^2 2\beta + \sin 2\alpha \sin 2\beta)$$

where α is the angle of incidence of the advancing wave (Fig. 2) and β is the angle the two shear waves make with the interface. The constant K is the ratio of the longitudinal wave velocity C_L to the shear wave velocity C_S. The angles α and β and K are related by the expression

$$\sin \alpha / \sin \beta = C_L/C_S = K = \left[2\,(1-\nu)/(1-2\nu)\right]^{\frac{1}{2}}$$

where ν is the Poisson's ratio. Thus the respective particle velocities in the several waves are functions both of the angle of incidence and Poisson's ratio.

Relative particle velocities for each of the five waves are plotted as a function of angle of wave incidence for several Poisson's ratios in the series of curves, Figs. 3 through 6. At low Poisson's ratios, proportionately more of the momentum of the original wave ends up in the reflected and transmitted shear waves, which in accordance with the above equations are equal.

Using values from these curves, it is a straightforward matter to calculate the relative velocity with which the two faces of the interface move with respect to one another. The right hand face (cd, Fig. 7) will move only perpendicular to itself. Its velocity will be the vector sum of V_D and V_E (Fig. 2). The face ab will also have the same component of velocity in the same direction but in addition will have a

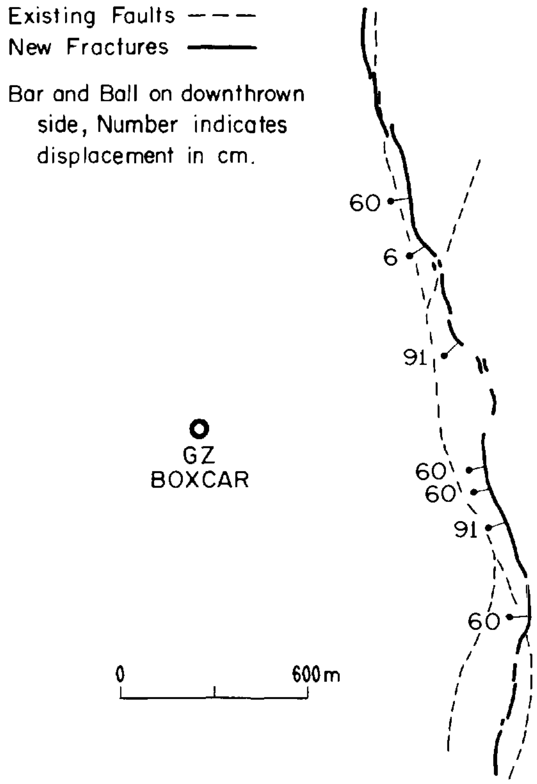

Fig. 1. Fractures generated along existing faults by Boxcar event (after Dickey, McKeown and Ellis, 1968).

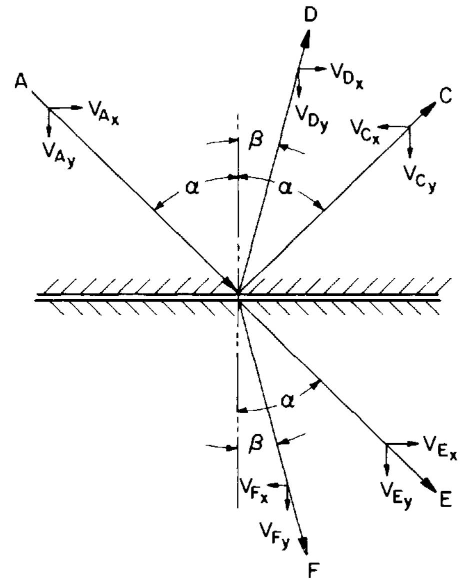

Fig. 2. Waves involved in interaction of a longitudinal wave at a loose interface. A, C, and E are longitudinal waves; D and F are shear waves.

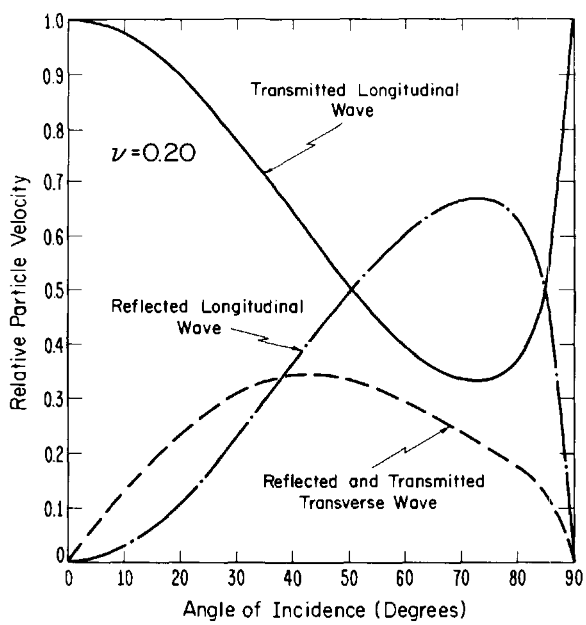

Fig. 3. Particle velocities associated with the five waves shown in Fig. 2 as a function of angle of incidence. ν = 0.20.

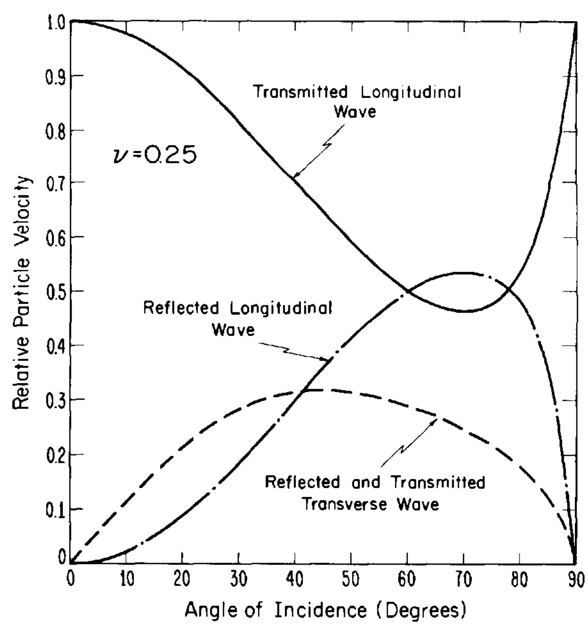

Fig. 4. Same as Fig. 3 except ν = 0.25.

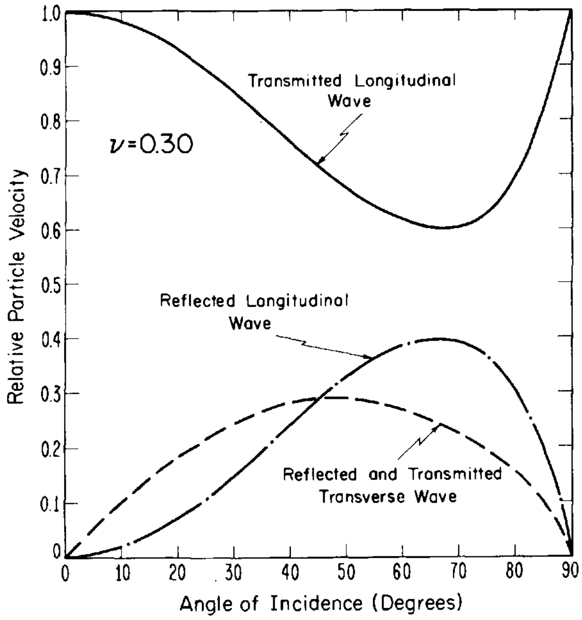

Fig. 5. Same as Fig. 3 except ν = 0.30.

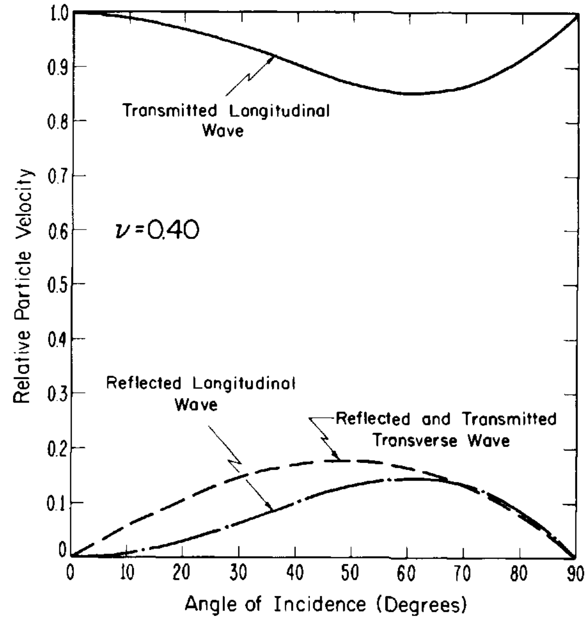

Fig. 6. Same as Fig. 3 except ν = 0.40.

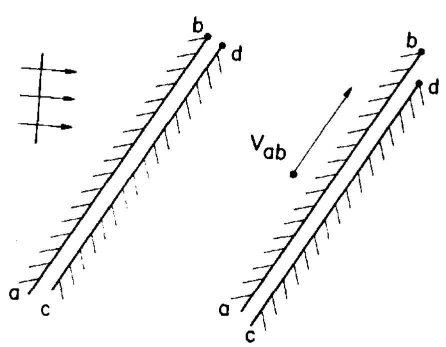

Fig. 7. Movement generated by interaction of transient stress wave with loose boundary.

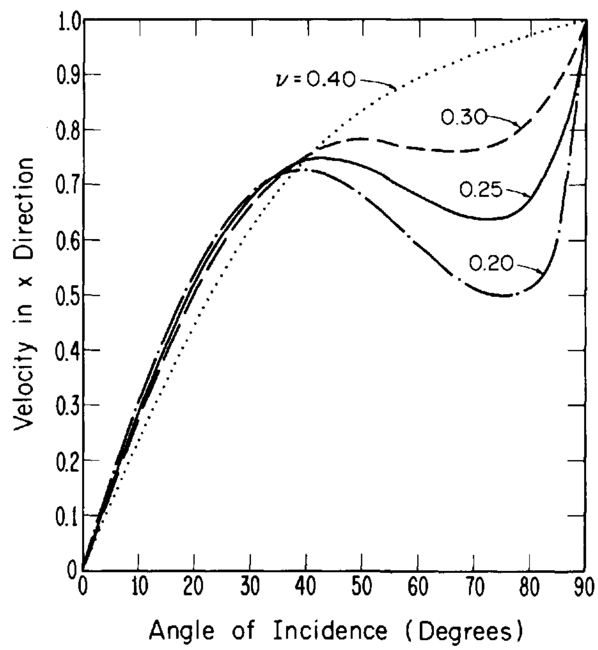

Fig. 8. Velocity of face ab (Fig. 7) with respect to face cd (Fig. 7) for several Poisson's ratios as a function of angle of incidence.

component of velocity parallel to the interface. This parallel component V_{ab} will be given by the expression

$$V_{ab} = V_A \sin\alpha + V_D \cos\beta - V_C \sin\alpha$$

where the right hand side is the sum of the particle velocity components along the interface of each of the three waves involved in the interaction. The velocity V_{ab} has been plotted in Fig. 8 for several Poisson's ratios as a function of angle of incidence.

For a transient compressional wave, the total displacement d of the face ab with respect to the face cd will be given by

$$d = \int V_{ab}(t)\, dt \qquad (1)$$

where the integration is taken over the duration of the wave. Assuming that the transient wave is square topped and of unit duration, the relative surface displacements that would accompany the impingement of the wave against a loose fracture or fault at various angles of incidence are illustrated for several Poisson's ratios in Figs. 9 through 12. Only a few cases are shown and these are ones in which the fault has a negative dip and its near side is thrown downward. When the dip of the fault is positive, the near side will be thrown upward.

In the examples shown thus far, it has been assumed that the wave front is plane and parallel to the plane of the interface. Usually neither is the case. For a non parallel plane wave front, the slippage can be resolved into components at right angles, one relating to vertical displacement and the other to horizontal displacement. At a ground surface, the displacements would manifest themselves at combined right lateral and vertical slips.

SOME SAMPLE CALCULATIONS

Unfortunately very little quantitative data have yet been made available on the magnitudes and durations of the particle velocities developed around underground nuclear explosions so that it is not possible to make accurate and detailed calculations regarding the displacements to be expected along fractures and faults. However, it is known that the observed particle velocity versus time distributions are generally "N" shaped, which at distances of 1000 to 2000 m from the explosions have durations of the order of one quarter to one second and maximum amplitudes of a meter or two per second (Perrett, personal communication). While the Poisson's ratios of the materials in which the detonations were set off is not known precisely, they are in the neighborhood of 0.20.

As an example, consider an explosion located at a one kilometer distance from a vertical fault and buried at a one kilometer depth. The angle of incidence between the wave front and the plane of the fault near the ground zero would be 45°. From Fig. 8 it is seen that at ground level the near surface of the fault would move upward with respect to the far surface at a velocity of 0.75 times the particle velocity in the incident wave. Applying

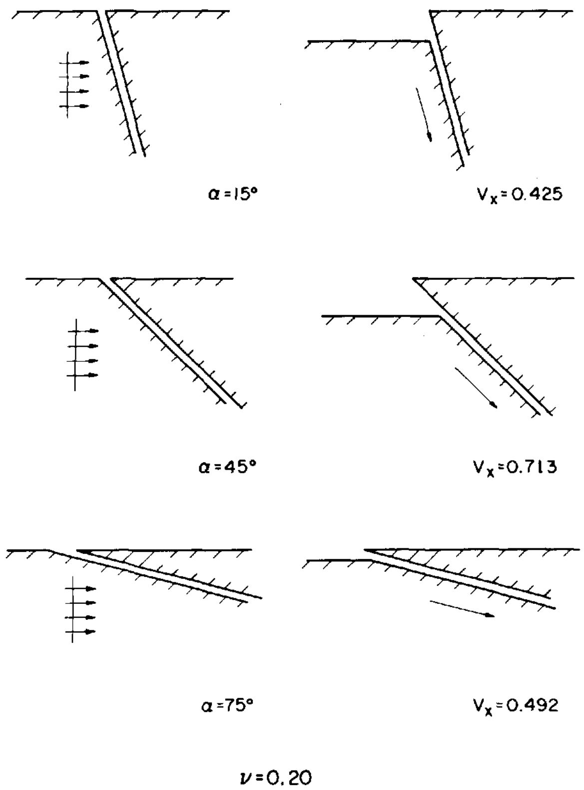

Fig. 9. Surface displacements caused by a square topped transient stress wave impinging against a loose fracture or fault. $\nu = 0.20$.

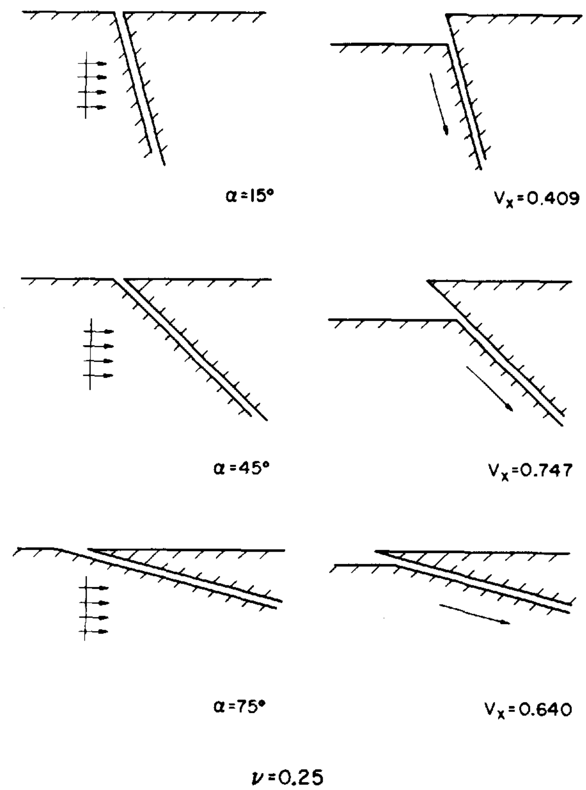

Fig. 10. Same as Fig. 9 except $\nu = 0.25$.

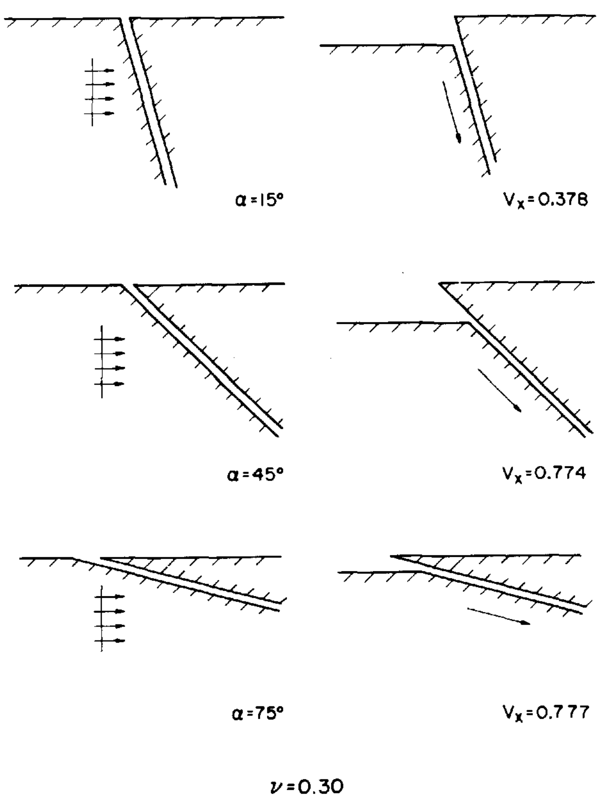

Fig. 11. Same as Fig. 9 except $\nu = 0.30$.

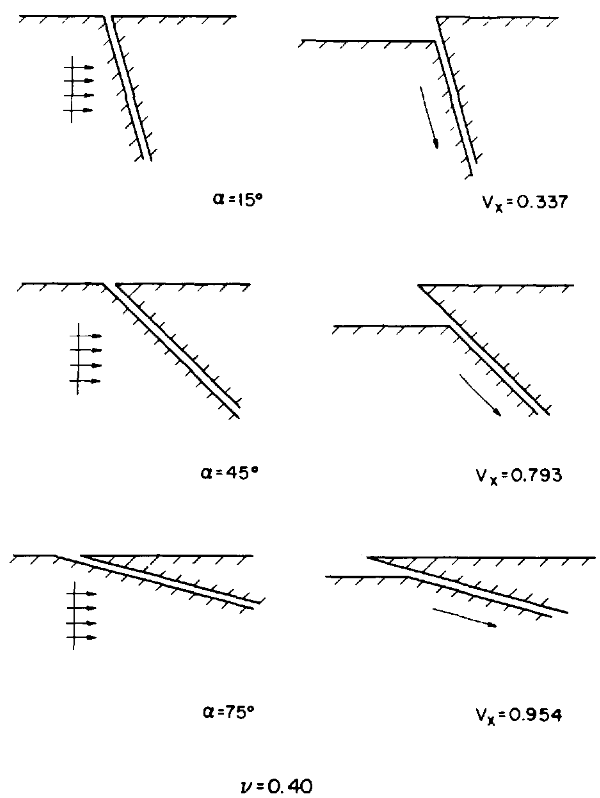

Fig. 12. Same as Fig. 9 except $\nu = 0.40$.

Eq. (1), the displacement produced by a wave of amplitude 3m/sec and the duration of positive phase of 0.25 sec results in 28 cm, a value quite compatible with those observed in the field (Fig. 1).

In a recent Amchitka Island event, an abrupt, about 30 percent, decrease in particle velocity occurred across the nearby Rifle Range Fault (Perrett, personal communication). This fault is so located with respect to ground zero that the wave inclination assuming that the fault is vertical, would be about 45°. However, the dip of the fault has not been established. The curve for $\nu = 0.20$ in Fig. 3 for the intensity of the transmitted longitudinal wave indicates that if the fault were vertical, the particle velocity should be reduced even more, by as much as 50 percent. The actual change in particle velocity suggests that the fault may have a positive dip of about 30°, making the angle of incidence 70°, and hence increasing the intensity (Fig. 3) of the transmitted wave to 70 percent of the intensity of the incident wave.

BIBLIOGRAPHY

Barosh, P.G., 1968. "Relationships of Explosion-Produced Fracture Patterns to Geologic Structures in Yucca Flat, Nevada, Test Site". Geol. Soc. Amer., Mem. 110, 199-217.

Bucknam, R. C., 1969. "Geologic Effects of the BENHAM Underground Nuclear Explosion". Bull. Seis. Soc. Amer. 59, 2209-2219.

Dickey, D.D., 1968. "Fault Displacement as a Result of Underground Nuclear Explosions". Geol. Soc. Amer., Mem. 110, 219-232.

Dickey, D.D., E.C. Jenkins, F.A. McKeown, and W.H. Lee, 1967. "Geologic Effects of the Greeley Event". Nevada Test Site Technical Letter: NTS-196, U.S. Geol. Surv. Open File Report.

Dickey, D.D., F.A. McKeown, and W.L. Ellis, 1968. "Summary of Geologic Effects of the Boxcar Event, Nevada Test Site". Technical Letter: Special Studies -65, U.S. Geol. Surv. Open File Report.

Hamilton, R.M., F.A. McKeown, and J.H. Healy, 1969. "Seismic Activity and Faulting Associated with a Large Underground Nuclear Explosion" Science 166, 601-604.

McKeown, F.A. and D.D. Dickey, 1969. "Fault Displacements and Motion Related to Nuclear Explosions". Bull. Seis. Soc. Amer. 59 2253-2269.