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WAVE GENERATIONS FROM CONFINED EXPLOSIONS IN ROCKS

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In order to record P- and S-waves generated from confined explosions in rocks in the laboratory, a method is developed based on the interactions between incident P- and SV-waves and free-surfaces of rocks. The relations between particle displacements of incident P- and SV-waves, and the strains measured using strain gauges attached on free-surfaces of rocks are analytically derived. P- and SV-waves generated from confined explosions in Bedford limestone are recorded.

INTRODUCTION

Virtually all the methods that have been proposed for discrimination of underground explosions ($m_b \leq 4$) from earthquakes and mining explosions(1 and 2) are based on various P-to-S amplitude ratios. Although there are many previous studies of seismic radiation patterns from decoupled explosions(3 - 6), it is still unclear what controls the radiation pattern of S-waves in tamped and decoupled explosions (5). Therefore, study of P- and S-wave generation from confined explosions is important for discrimination purposes. In order to investigate waves generated from small-scale laboratory explosions in rocks, a measurement method is required to monitor both P- and S-waves. Conventional seismic recording systems and methods for laboratory scale high strain rate experiments(7) can not be utilized. Based on the analysis of the interactions between P- and SV-waves and free surfaces, we have developed a method to monitor P- and SV-wave profiles using two perpendicular strain gauges attached to the free-surfaces of samples. The method and some initial experimental data are presented below.

MEASUREMENT METHOD

When elastic P- and S- waves generated from explosions in rocks reflect at free surfaces, these generate different displacement-time histories. We determine P- and SV-wave displacements using the strains measured along two perpendicular directions at a series of stations on free-surfaces of the rock samples.

Data reduction method

The strain gauges are attached at positions along the intersection of the plane containing the axis of the spherical wave front and the sample free-surface as shown in Fig.1. The strains recorded by the gauges include the contributions from incident P- or S-waves and reflected P- and S-waves. The relation between the measured strains and incident P- and S-wave particle displacements are derived as follows:

P-wave reflections at free surfaces

The displacement reflection coefficients for incident planar P-waves at free surfaces (8) are $PP = (B - A)/(B + A)$, $PS = 2\frac{\beta}{\alpha}\sin(2\theta)\cos(2j)/(A + B)$, where PP and PS are reflection coefficients of P- and SV-wave displacements due to incident P-waves, and α and β are P- and S-wave velocities, respectively. $A = \cos^2(2j)$ and $B = (\frac{\beta}{\alpha})^2\sin(2j)\sin(2\theta)$, where θ and j are P-wave incident angle and S-wave reflection angle, respectively (Fig.1).

The displacements of particles on free surfaces after P-wave reflections are

$$u^p_{par} = u^I_p[(1 + PP)\sin\theta + PS\cos j] = H_{par}u^I_p, \quad (1)$$

$$u_{per}^p = u_p^I[(1-PP)\cos\theta + PS\sin j] = H_{per}u_p^I, \quad (2)$$

where u_p^I is the particle displacement of incident P-waves; u_{par}^p and u_{per}^p are the particle displacements along the directions shown in Fig.1, respectively. Having substituted PP and PS into Eqs.(1) and (2), the two coefficients are $H_{par} = 2\cos\theta\sin(2j)/(A+B)$ and $H_{per} = 2\cos\theta\cos(2j)/(A+B)$.

SV-wave reflections at free surfaces

For incident SV-waves, the reflection coefficients for P-waves (SP) and SV-waves(SS)(8) are $SP = \frac{\beta}{\alpha}\sin(4\theta)/(A_s+B_s)$, $SS = (A_s - B_s)/(A_s+B_s)$, where $A_s = \cos^2(2\theta)$, $B_s = (\frac{\beta}{\alpha})^2\sin(2\theta)\sin(2j)$. θ and j are SV-wave incident angle and P-wave reflected angle, respectively.

The displacements of particles on free surfaces after SV-wave reflections are

$$u_{par}^{sv} = u_{sv}^I[(1+SS)\cos\theta + SP\sin j] = G_{par}u_{sv}^I, \quad (3)$$

$$u_{per}^{sv} = u_{sv}^I[(SS-1)\sin\theta - SP\cos j] = G_{per}u_{sv}^I, \quad (4)$$

where u_{par}^{sv} and u_{per}^{sv} are particle displacements after reflection along the directions shown in Fig.1, and u_{sv}^I is the particle displacement of incident SV-waves. The two coefficients are determined to be $G_{par} = 2\cos(2\theta)\cos\theta/(A_s+B_s)$, $G_{per} = -2\frac{\beta}{\alpha}\cos j\sin(2\theta)/(A_s+B_s)$.

Particle displacements of incident P-waves

Because u_{per}^p is perpendicular to free surfaces, and incident waves are assumed to be spherical, the strain due to u_{per}^p along direction 1, ε_1^{per}, is simply expressed as

$$\varepsilon_1^{per} = H_{per}u_p^I/r_0, \quad (5)$$

where r_0 is the distance between the center of explosive source and the free surface of samples at $\theta = 0$.

u_{par}^p does not result in any strains along direction 1, so the total strain induced by the incident P-waves is determined to be $\varepsilon_1^p = H_1 u_p^I/r_0$, where $H_1 = H_{per}$. Therefore, the strain along direction 1 yields the particle displacement of incident P-waves as

$$u_p^I = r_0\varepsilon_1^p/H_1. \quad (6)$$

Since both u_{per}^p and u_{par}^p have contributions to strains along direction 2, we need to consider the resultant displacements. The length of the gauge after reflection, Δs, is equal to $(r_n^2 + (\frac{\partial r_n}{\partial\theta})^2)^{\frac{1}{2}}\delta\theta$, where $\delta\theta \approx \frac{l_s\cos\theta}{r_n}$, l_s is the initial length of the strain gauge, r_n is the distance between the explosive source center to the position of a gauge upon P-wave reflection. Here r_n can be expressed as $r_n \approx r + u\cos(\eta-\theta)$, where r is the distance between the explosive source center and the gauge before P-wave reflection, u is the resultant displacement of the point at θ on the free surface and η is the angle between u and u_{per}^p. u and η are given by $u = u_p^I 2\cos(\theta)/(A+B)$ and $\eta = 2j$.

From the expressions above, Δs is given as

$$\Delta s \approx (r_n + \frac{1}{2r_n}(\frac{\partial r_n}{\partial\theta})^2)\delta\theta. \quad (7)$$

Because $\frac{u_p^I}{r} \ll 1$, Δs is rewritten as

$$\Delta s = (r(1+\frac{\tan^2(\theta)}{2}) + u_p^I(W(\theta)(1-\frac{\tan^2(\theta)}{2}) + \tan(\theta)\frac{dW}{d\theta}))\delta\theta, \quad (8)$$

where $W(\theta) = 2\cos(\theta)\cos(\eta-\theta)/(A+B)$.

From the definition of strains,

$$\varepsilon_2^p = \frac{\Delta s - l_s}{l_s} = \frac{H_2 u_p^I}{r_0}, \quad (9)$$

where $H_2 = \cos(\theta)(W(1-\tan^2(\theta)/2) + \tan\theta\frac{dW}{d\theta})/(1+\tan^2(\theta)/2)$.

The particle displacement of an incident P-wave determined from a gauge along direction 2 is

$$u_p^I = r_0\varepsilon_2^p/H_2. \quad (10)$$

Particle displacements of incident SV-waves

Using the same above formulation, the relations between incident SV-wave particle displacements and strains along the two directions are obtained.

The particle displacements of incident SV-waves from the strains along direction 1 and 2 are

$$u_{sv}^I = r_0\varepsilon_1^{sv}/G_1, \quad (11)$$

and

$$u_{sv}^I = r_0\varepsilon_2^{sv}/G_2, \quad (12)$$

where $G_1 = G_{per}$,

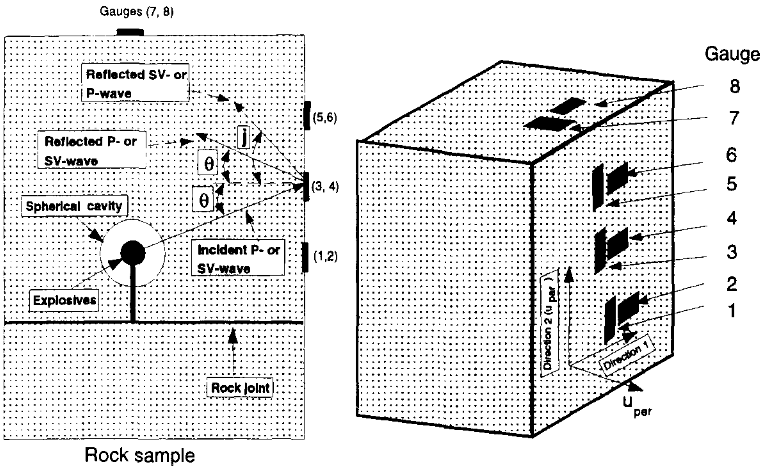

Figure 1. Schematic arrangement of experiments

$$G_2 = \cos(\theta)(W_s(1 - \frac{\tan^2(\theta)}{2}) + \tan\theta \frac{dW_s}{d\theta})/(1 + \frac{\tan^2(\theta)}{2}),$$

$$W_s = \frac{2\cos(\eta - \theta)\cos(\theta)}{A_s + B_s}(\cos^2(2\theta) + 4(\frac{\beta}{\alpha})^2 \cos^2 j \sin^2(\theta))^{\frac{1}{2}},$$

and $\tan\eta = -\alpha\cos\theta/(\beta\cos j)/\tan(2\theta)$.

Characteristics of strains in different directions

Figure 2 shows the dependence of H_1, H_2, G_1 and G_2 on incident angle that were calculated using the equations derived above. For incident P-waves, the constant, H_1, is relatively insensitive to θ, and H_1 changes from 2.0 at $\theta = 0^o$ to 1.4 at $\theta = 60^o$ for Bedford limestone. The constant, H_2, is very sensitive to θ, and it varies from 2 to -0.4 when θ varies from 0 to 60^o. It can be seen that the strains induced by compressional P-waves along direction 1 are always positive, but the strains along direction 2 are positive when θ is less than 47^o and negative when θ is larger than 47^o. This change in polarity is controlled by the ratio of the projection of P-wave displacements along direction 1 to that along the direction that is perpendicular to the free surface. If the strain induced by the displacement along direction 2 is less than that due to the displacement along the perpendicular direction, the strain is positive, otherwise, the strain is negative.

From the above calculation, the gauges along direction 1 are not sensitive to an incident SV-wave, however, the gauges along direction 2 are very sensitive to an incident SV-wave. The polarities of the strains along direction 2 are always negative, and the polarities of the strains along direction 1 are determined by the direction of SV-wave particle motion .

Eqs.(6), (10), (11) and (12) give the relations between strains along the two directions and incident P- and SV-wave particle displacements. If strains along the two directions can be recorded, the P- and SV-wave amplitudes can be determined experimentally.

EXPERIMENTS AND RESULTS

The method described above was used to monitor P- and SV-waves generated from confined explosions in rocks. The rock sample (Bedford limestone) was assembled with two blocks as shown in Fig.1. The rock sample with strain gauges was placed inside a tank that was pressurized to 10 bars.

The recorded strains for one of the experiments are shown in Figs.3 and 4. The characteristics of the strains recorded by the gauges are the same as predicted from our derived equations. The strains along direction 1 induced by incident P-waves are always positive, while the strains along direction 2 change polarities as P-wave incident angle increases (Figs.3 and 4). The strains induced by incident SV-waves along direction 2 are negative and are much larger than that along direction 1.

From the records, it is straightforward to determine P and SV-wave amplitudes for the experiment using the expression given above. From the P- and SV-wave velocities of Bedford limestone, the expected S-wave arrivals are labeled on the records. The time difference between the expected and the recorded is less than $2\mu s$ for the experiment.

CONCLUSIONS

In this work, a method has been developed for measuring P- and SV-wave amplitudes generated from explosions in rocks. The relations between the strains given by gauges placed on the free surfaces of rocks and incident particle displacements are derived analytically. The experimental results showed that the characteristics of recorded strains along the two directions are in good agreement with the predictions.

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REFERENCE

1. Blandford, R. R., AFTAC-TR-95-002, 1995.
2. Helmberger, D. V. and Woods, B., *Monitoring a Comprehensive Test Ban Treaty,* edited by Husebye, E.S. and Dainty, A.M., Kluwer Academic Publishers, the Netherlands, 1996, 365-383.
3. Glenn L. and Goldstein P., *J. Geophys. Res.*, **99**, 11,732 - 11,730(1994).
4. Glenn L., Ladd A., Moran B., and Wilson K., *Geophys. J. R. astr. Soc.,* **81**, 231- 241(1985).
5. Murphy J. , op. cit in Ref.(2), pp 247-293.
6. Sykes L., op. cit in Ref.(2), pp 225-245.
7. Kim S., Clifton R. and Kumar P., *J. Appl. Phys.*, **48**, 4132-4139(1977).
8. Aki, K. and Richards, P., *Quantitative Seismology Theory and Methods,* W. H. Freeman and Company, 1980, ch.5, 320.

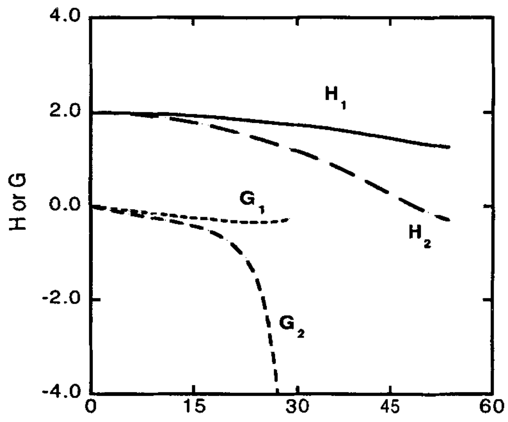

Figure 2. Incident angle (degree)

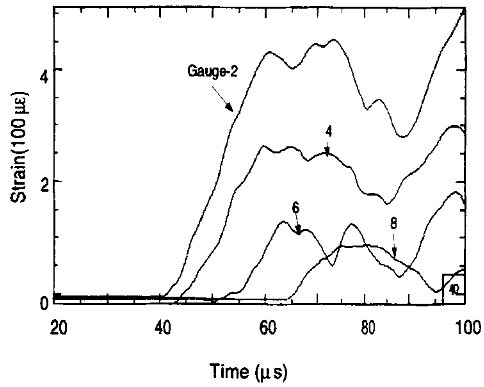

Figure 3. Strains induced by P-wave along direction 1

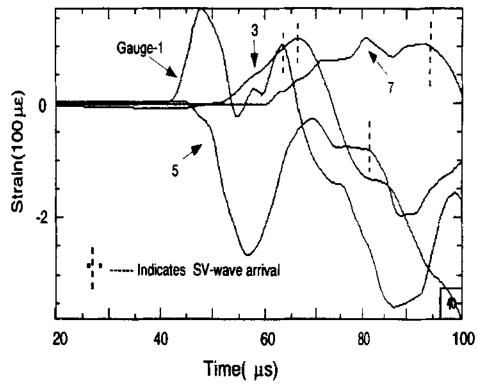

Figure 4. Strains induced by incident SV-waves along direction 2