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SOME ASPECTS OF COUPLING BETWEEN EXPLOSIVES AND ROCKS

by

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ABSTRACT. This report is a summary of the work done in the field of explosive coupling. Generally, three zones of material behavior are considered when an explosive is detonated in contact with a material. These are the hydrodynamic zone, transition zone, and elastic zone. In seismic studies the term coupling refers to the production of strong seismic signals while decoupling refers to methods of decreasing the amplitudes of seismic signals such as detonating the explosive in an underground cavity larger than the explosive charge. The decoupling factor for such experiments is defined as the ratio of the seismic signal amplitude for a fully tamped shot to the signal amplitude of a shot of the same size in the given cavity. A similar ratio has been defined for peak particle velocities. When explosive performance is related to rock breakage both dynamic shock effects and expansion effects of the explosion gases must be considered. United States Bureau of Mines investigators have defined two decoupling factors: the ratio of charge diameter to hole diameter; and vice versa. They have related the amplitude and period of the strain pulse in rock to these decoupling factors.

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FOREWORD

This report discusses material pertaining to the general problem of coupling explosive energy into solid bodies. It is part of a continuing applied research program in earth and rock mechanics in support of explosive ordnance problems at the U. S. Naval Ordnance Test Station.

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INTRODUCTION

This report summarizes a literature survey carried out to see how much and what type of work has been done in the area of coupling between explosives and rocks. The purpose of this survey is to determine what various investigators mean when they speak of coupling and how they approach the problem.

It appears that some of the differences in what various investigators mean by coupling depends on what effect they are interested in obtaining. The geophysicist, for example, is concerned with the amplitude of the strain wave transmitted through the rock and is not much concerned with the fracturing of the rock other than that caused by the primary compression pulse. The mining engineer, on the other hand, is interested in breaking rock so he is interested in the strain pulse from the standpoint of reflection breakage and in the slow expansion of the explosion products which also affects comminution.

MATERIAL BEHAVIOR UNDER EXPLOSIVE LOADING

When an explosive is detonated in contact with a solid material, the material experiences an extremely high pressure and temperature for a very short period of time. The pressures in the explosive are of the order of 300 kilobars (kb) and the temperatures are of the order of 4000°C. Under these conditions, the material no longer reacts as an elastic solid in the region near the explosion. Instead, the material which is stressed to a pressure of the same order as that in the explosive is thought to behave essentially as a fluid and can be treated hydrodynamically.

Grine (1959) investigated the fracturing of rock by high-amplitude explosively-generated pulses and the effects of such fracturing on pulse propagation. In his analysis he discusses three zones of rock behavior surrounding the explosive: the hydrodynamic zone; the transition zone; and the elastic zone. The existence of these different zones of behavior has also been recognized by many other investigators. Grine describes the three zones as follows:

The hydrodynamic zone is one in which the rapid, high-amplitude loading of the solid material transforms the solid material into an essentially fluid state. It is assumed that the material does not melt (the temperatures reached in the severely compressed rock will be only a few hundred degrees centigrade, a temperature well below the melting points of most rocks) but that the pressures are so high that rigidity becomes negligible. This assumption is valid if the pressure range considered is much greater than the dynamic yield strength of the material being considered. It is also generally assumed in analyses that the experimentally determined states are states of thermodynamic equilibrium. This assumption is fulfilled, for the usual scale of experimentation, if thermodynamic equilibrium is attained in 10^{-7} seconds or less. Just how one would go about determining if this condition were fulfilled is not immediately evident and was not discussed by Grine. Grine feels that if hydrodynamic theory does apply, pressure-density curves obtained from shock wave experiments should connect smoothly with results of Bridgman's hydrostatic experimentation at lower pressures.

The transition zone is the zone immediately surrounding the hydrodynamic zone. It is in this zone that behavior ceases to be purely hydrodynamic and becomes substantially elastic with increasing remoteness from the area of application of the explosive. This zone has been studied very little. The behavior of aluminum under explosive loading agrees with hydrodynamic theory down to a pressure of about 18 kb. On the other hand, elastic waves of 11 kb pressure have been observed in 1020 steel. The extent of the transition zone appears to be related to the material under consideration. For instance, in some materials such as 1020 steel the transition zone is essentially non-existant, either hydrodynamic theory or elastic theory being adequate to cover the whole range of wave amplitude. In other substances rigidity and non linear effects such as fracturing may be more important and as a result neither hydrodynamic theory nor elastic theory applies in some regions of the material. Grine believes that the outer limit of the transition zone may be taken at the point where fracturing ceases. Crushing and fracturing in the transition zone produces new surface area. This process absorbs energy and has a large effect on pulse attenuation and pulse shape. The extent of this fracturing is believed to depend on rock strength, ambient pressure, amount of void space in the rock, the geometry of the front of the pulse, and the pulse amplitude and its shape.

The elastic zone is the region farthest from the explosive. In this region the material may be treated as an elastic solid. Most attention has been focused on this zone in the past since it lends itself to straightforward mathematical treatment. Elastic theory can explain several observed fractures, such as spalling and corner fractures, in rock having low ratios of tensile strength to compressive strength.

Grine also concluded that high porosity leads to fracture at low dynamic stresses. Nonporous rocks were observed to withstand compressive stresses six times the static compressive stress without damage while porous media were destroyed by compressive stresses less than twice their static strengths.

SEISMIC COUPLING

Several investigators have been working on the problem of seismic coupling and decoupling. Here the emphasis is on the seismic signal, the nearly elastic disturbance observed in the earth at a relatively large distance from the source, usually an explosion. In this work the term coupling is generally used in connection with problems relating to the production of strong seismic signals while the term decoupling refers to methods of decreasing the amplitude of the seismic signal. The idea of decoupling was introduced in an attempt to avoid detection of large underground nuclear blasts.

Latter, Le Levier, et al. (1961) show theoretically that the seismic signal from an underground nuclear explosion can be reduced by a factor of 300 by carrying out the explosion in a cavity much larger than the dimensions of the explosive. The decoupling factor is defined to be:

$$\text{decoupling factor} = \frac{16\pi}{3(\gamma-1)} \frac{c_h}{c} \mu_h \frac{r_o^2 d_o}{W}$$

where γ is the ratio of the specific heats applicable to an explosion in a cavity, c_h is the velocity of sound in the medium around the cavity, c is the velocity of sound in the medium around the tamped shot, μ_h is the shear modulus of the medium around the cavity, r_o is the distance from the tamped explosion at which the permanent displacement d_o is measured in the elastic zone, and W is the explosion energy released. Herbst, et al. (1961) present an analysis of an experiment designed to test the theory of seismic decoupling proposed above. The test series is known as Project Cowboy. The theory was verified by the experiments. Seismic signals from explosions in cavities so much larger than the explosive that they yield elastically are very small compared to those from cavities completely filled with explosive. An explosion in a sphere which is smaller than necessary to insure elasticity will still be somewhat decoupled. Another verification of decoupling theory was made by Murphey (1961). He measured peak particle velocities and displacements at different distances from tamped (coupled) and cavity (decoupled) explosions in halite. These experiments showed that decoupling in halite of from 40 to 100 can be obtained for high explosives. Here the decoupling factor is defined as the ratio of peak displacement for a fully tamped shot to peak displacement for a decoupled shot and a similar ratio is defined for peak particle velocities.

Latter, Martinelli, et al. (1961) studied theoretically the possible effects of plasticity and work hardening on seismic decoupling of underground explosions in large spherical cavities designed to give maximum decoupling and in small (overdriven) cavities designed to give partial decoupling. They concluded that plasticity should play no role in explosions in large cavities, even at great depths. For small cavities at great depth plasticity could affect the decoupling factor by an amount depending upon the degree of overdriving, the depth, and the detailed stress-strain relation of the medium.

Haskell (1961) presents a static theory for seismic coupling of a contained underground explosion. The theory states that the amplitude of the distant seismic signal from a completely contained explosion is determined by the permanent displacement produced in the neighborhood of the source. A Coulomb-Mohr type of yield condition is used to determine the stresses in the near zone where the stresses are beyond the elastic limit and the internal friction is treated as a parameter. Reasonably good agreement was found between the predictions of this theory and the relative amplitudes of the seismic signals observed in the Project Cowboy tests and in the Ranier test.

EXPLOSIVE PERFORMANCE

Brown (1956) did some work relating some of the properties of explosive to their effects on rock breakage. He discusses methods of computing detonation velocity, pressure, and energy of an explosive. The expansion properties of the gases are outlined. He believes that the important effects of an exploding charge on a medium are those due to shock waves and expansion of the bubble of detonation gases. For large confined charges, the detonation pressure is of primary importance in the shock effects. For smaller unconfined charges the shock effects depend more on the impulse $I = \int P\,dt$. The acoustic impedance of the explosion gases is thought to be important in the transmission of the shock from the explosive into the medium. The expansion effects depend on the energy content of the explosion gases and on the law governing their expansion. Thus, for breaking rock, it is believed that explosives should be rated for both "shock" and "expansion" effects.

The Trauzl lead block test has been used in the past to obtain a measure of explosive performance. Gordon, et al. (1955)

describe a comprehensive study made of the merits of the tests. A charge is placed in the center of a cylinder of lead. The charge is then stemmed with sand according to a standardized procedure. The amount of expansion of the cavity in the lead produced by the exploding charge is measured. The expansion volume is a measure of the work of plastic deformation, which in turn is found to correlate with the calculated quantity, nRT, of the explosive.

In the lead block test as described by Gordon, illustrated in Fig. 1, some very interesting results were obtained which verify Brown's contention that both shock effects and expansion effects should be considered in the rating of an explosive. For example, corner fracturing which occurred was not closely related to the expansion of the cavity; it depended rather, upon the nature of the explosive. A charge of six grams of an RDX-tetranitromethane mixture caused corner fractures, although it produced a cavity of only 290 cc. However, ten grams of a TNT-tetranitromethane mixture do not cause corner fractures, although the cavity was 596 cc, more than twice as large. The small charge of RDX mixture generated a higher intensity compressive stress pulse than the larger charge of TNT mixture. The proportions used in the explosive mixtures is not given, however if we compare the detonation pressures of RDX and TNT, we find that the detonation pressure of RDX is 337.9 kb and of TNT, 189.1 kb. Since these pressures greatly exceed the compressive strength of lead, one is led to believe that the peak stress generated in a material by an

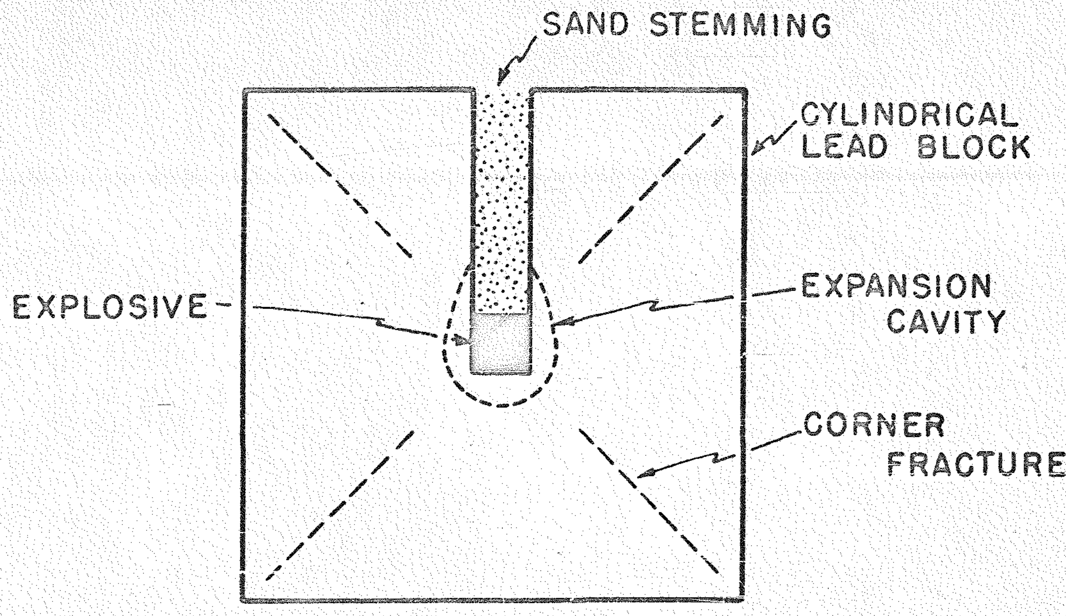

FIG. 1. Trauzl Lead Block Test.

explosive may be related to the detonation pressure of the explosive and not so much on the dynamic compressive strength of the material as many people now believe. The larger expansion volume corresponds to the larger charge. This indicates that the expansion volume is a function of the volume of gas produced.

Another result of the Trauzl test indicates the importance of confinement. For the standard test the explosive is stemmed with sand. When the charge was stemmed with a close-fitting lead plug, it took several minutes for the explosion gases to escape. The increase of expansion volume over that with sand was about 32 percent. This indicates that the permanent displacement of the cavity wall is related to the degree of confinement of the explosion products.

BUREAU OF MINES INVESTIGATIONS

The United States Bureau of Mines has been studying explosive coupling for a number of years at their College Park, Maryland station. They have developed a dynamic strain gage and a companion amplifier and recording camera (Obert and Duvall, 1949). The apparatus is designed to detect and record the strain waves produced in rock by a nearby explosion. Resistance strain gages are cemented to cores of the rock which are in turn placed in drill holes and cemented into place. The tests are made with a few pounds of explosive and the strain pulse is measured at points ranging from a few feet to about a hundred feet from the explosion.

Duvall and Petkof (1959) present some results of tests made with the above described apparatus. Strain pulses were measured for five different rock types and ten different types of explosives. Analysis of the data showed that the experimental peak strain satisfies the exponential decay propagation law;

$$\frac{\epsilon}{W^{1/3}} = K e^{-\alpha \frac{R}{W^{1/3}}}$$

where ϵ is the strain in the rock as measured by the strain gage; R, the distance from charge to the point at which strain is measured; and W is the weight of the charge. The constant K was found, for a particular rock, to be a linear function of the calculated energy density of the explosive. Also K was found to be a linear function of the elastic parameter of the rock, ρc^2, for a particular explosive. The decay constant, α, was found to be independent of type of explosive but dependent on rock type.

In another series of tests Fogelson et al. (1959) tested six explosives in a granite gneiss. The results showed that the percentage of explosive energy transferred to the rock increased linearly as the ratio of the characteristic impedance of the explosive to that of the rock increased toward unity. From five to nine percent of the calculated total energy released by the explosive was transferred to the rock as radial strain energy.

Duvall and Atchison (1957) discuss data on crater formation in four rock types. They note that crushing takes place near the charge hole because of the high amplitude of the strain pulse. The fracture characteristics of the crater are explicable in terms of reflection of the primary compression wave at the free surface, it being assumed that the rock fails in tension. It seems more likely that this explanation will hold only for hard brittle rocks where a high ratio exists between compressive strength and tensile strength but not for a material for which the compressive strength and tensile strength are nearly equal.

Atchison (1961) studied the effect on the strain pulse in rock produced by varying the explosive diameter and the hole diameter. This is in a sense a study of decoupling. The purpose of such a study was to determine just how important it is to have the explosive in intimate contact with the rock. In these experiments Atchison defines the percent of coupling as the ratio of charge diameter to hole diameter. He found the strain to be approximately proportional to the 1.5 power of the ratio of the charge diameter to the hole diameter.

Atchison and Duvall (1962) performed another series of decoupling experiments involving nearly spherical charges detonated in rock. They were able to explain the results of their tests in terms of a simple mathematical theory. Their mathematical model is illustrated in Fig. 2 where R_c is the radius of the charge; R_h is the radius of the original hole; R_o is the radius of the transition zone. The radius R_o is considered to be the radius of the boundary between the inelastic and elastic

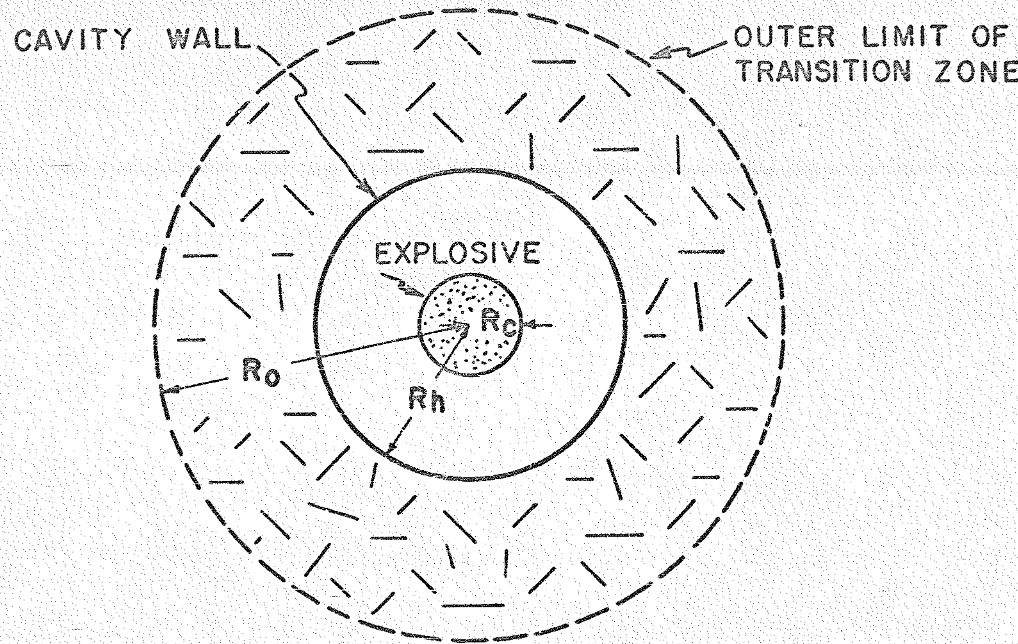

FIG. 2. Decoupling Model.

regions. They assumed that the following laws govern the pressures and stresses in the three respective regions: in the cavity

$$P = P_c \left(\frac{R}{R_c}\right)^{-3\gamma}$$

where P_c is the detonation pressure of the explosive and γ is the ratio of the specific heats of the explosion gases; in the transition zone

$$\sigma = \sigma_h \left(\frac{R}{R_h}\right)^{-m}$$

where σ_h is the stress (pressure) exerted on the cavity wall by the explosion gases and m is a constant which describes the stress decay in the transition zone; and in the elastic or seismic zone

$$\sigma = \sigma_o \left(\frac{R}{R_o}\right)^{-n}$$

where σ_o is the stress at the outer limit of the transition zone and n is a constant which describes the stress decay in the seismic zone. This method of analysis may prove to be very useful because it recognizes the existence of a non linear transition zone.

SUMMARY

The meaning which one attaches to explosive coupling depends on what effect he wishes to study. In seismic work efficient coupling is associated with the generation of a strong seismic pulse. In mining one is concerned with the breaking of rock so that both the dynamic shock effects and the expansion effects of the gases must be considered. Both effects are important and must be considered if one is to understand the processes by which an explosive breaks rock.

This report does not discuss all the literature available on explosive performance. However, it does include most of the pertinent literature on explosive coupling which is readily available.

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