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Influence of rock properties on methods for the verification of underground nuclear explosions

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ABSTRACT: A limestone for which mechanical behavior is well determined is used as a basis for a study of the effects of mechanical property variations on apparent seismic yield for contained nuclear explosions. The resulting variations in apparent seismic yield, up to 25% for this study, form an irreducible lower limit on the accuracy of seismic yield determination if further event-specific information on the mechanical properties is unavailable.

1 INTRODUCTION

The need for understanding the methodologies used for verifying nuclear testing treaties has been increasing. The two predominant methods for estimating yield from foreign underground tests both rely on measurements of the stress waves created by an explosion and transmitted through rock or soil. The hydrodynamic method measures shock radius versus time near the explosion in the region where peak stresses are greater than a few GPa (King, et. al 1989). In this regime, the shock radius versus time curve can be scaled to a curve for known yield giving the unknown yield from the scaling factor. In this regime, where strength effects are negligible, only the pressure-volume response of the rock at high pressures influences the results. In contrast, the seismic methods measure the elastic wave at large ranges. Not only does the response of the rock in the high stress regime affect the outgoing wave, but the final signal is influenced by the rock response in all regimes down to the low stress levels where linear elasticity applies. In this paper we explore the sensitivity of the seismic signal to various aspects of rock's mechanical behavior.

2 REDUCED DISPLACEMENT POTENTIAL

The fundamental measure of yield for seismic yield estimation is the late time value of the reduced displacement potential (RDP) (Denny and Goodman 1990, Patterson 1966). For a spherically symmetric wave in a linear elastic medium, the solution can be described by the RDP defined by:

$$u = \frac{\partial}{\partial r}\frac{f(\tau)}{r} = \frac{1}{c}\frac{1}{r}\frac{\partial f(\tau)}{\partial r} - \frac{1}{r^2}f(\tau) \qquad (1)$$

where u is the displacement, r is the radius, c is the longitudinal sound speed, and $\tau = t - r/c$ is the retarded time (Timoshenko and Goodier 1970). The RDP has had the geometric spreading removed by the $1/r$ term in equation 1 and so, in the absence of attenuation, it is independent of location at distances great enough that only linear elastic response is exhibited.

Typical RDP's (see Fig. 2) may be crudely approximated as a step function with some oscillations superimposed at early retarded time. The amplitude of the higher frequency seismic waves will be primarily determined by the early retarded time behavior, while the lower frequency amplitudes will be determined primarily by the late retarded time behavior. Because of preferential attenuation of the higher frequencies the amplitude of a seismic signal in the far field is proportional to the value at large retarded times of the RDP calculated in the linear elastic regime near the explosion (Latter, Martinelli, and Teller 1959; Haskell 1961, Patterson 1966). Although the higher frequency components of the seismic signal give important information about the size of the non-linear region around an explosion, the apparent yield is proportional to the low frequency amplitudes which are in turn proportional to the asymptotic value of the RDP at late retarded time (Denny and Goodman 1990).

In this paper, the late retarded time RDP is used to indicate the influence of changes in rock behavior on the apparent seismic yield. In a series of calculations where the rock behavior is changed, the RDP will be evaluated at locations where the material response is linear. It is sometimes thought that only where peak stresses, particle velocities and displacements vary as $1/r$ is the material response linear. This is not true. As equation 1 and the corresponding equations for stress in Timoshenko and Goodier (1970) show, higher order terms in $1/r^2$ and $1/r^3$ are present in the linear material problem. Only in the far field does the amplitude vary as $1/r$. The correct identification of the linear response region is where the RDP is independent of location.

3 EQUATION OF STATE EFFECTS ON RDP

For the purposes of studying the effects of material response changes on the RDP, I use a baseline calculation of a 1 kt explosion in a nearly saturated limestone. The behavior of the limestone is described by the effective stress model described in Dey (1990) and Dey and Brown (1990). For material which has been exposed to peak stresses greater than 5 GPA, a tabular equation of state from the SESAME EOS library is used. At this pressure, the effective stress model response merges smoothly into the EOS table. The mechanical response of the limestone is based on unpublished data for Salem, Indiana limestone by S. Blouin of Applied Research Associates and J. Zelasko of Waterways Experiment Station. These experimental data were digitized and converted into tables of shear strength versus effective stress and porosity versus effective stress. The porosity table also contains the hysteretic behavior caused by pore crushing. The baseline limestone has 13.5% porosity and is 95% saturated which leaves 0.67% air-filled void space. Longitudinal sound speed is 3585 m/s. This material shows brittle behavior with the accompanying strain softening for mean stresses below roughly 75-100 MPa. Above this level, the material behaves ductily and is well represented by a strain hardening model. In addition, the data shows shear-enhanced void collapse behavior and this, too, has been incorporated into the model.

Figure 1 shows the peak stress as a function of range while Figure 2 shows the apparent RDP calculated at 100 m intervals from the explosion. The RDP's calculated at 300 m and greater range are all identical while the apparent RDP at 200 m is only slightly greater indicating that the range at which linear elastic material response is reached, and a true RDP is being determined, is between 200 and 300 m. Notice that the peak stress attenuation at this point and out beyond 1000 m is not $1/r$ but closer to $1/r^{1.5}$, illustrating that $1/r$ attenuation is not a necessary condition for linear response. The asymptotic value of the RDP for ranges of 300 m and greater is about 395 m^3.

Figures 3 and 4 show the RDP and the cavity radius for the baseline calculation together with results from four variations of the material models. The oscillations in the RDP correlate with the cavity oscillations. With the exception of variation 4, a smaller cavity radius corresponds to a lower RDP.

The equation of state of the rock or soil around the device influences the how much of the device energy can be converted into expansion of the melted and vaporized rock in the cavity and into driving the stress wave. The dashed lines labelled "1" in Figs. 3 and 4 result from a calculation where only the tabular equation of state was changed. The only significant differences are in

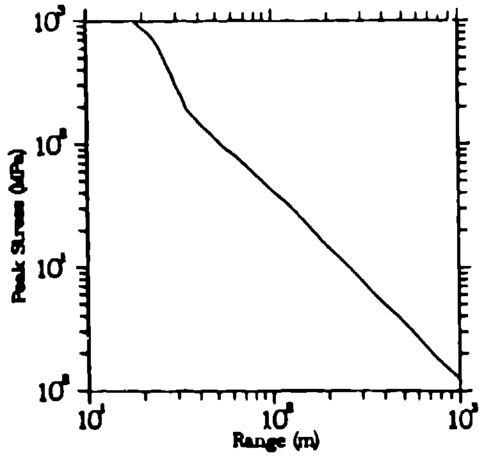

Figure 1. Peak stress versus range for the baseline 1-D 1kt calculation.

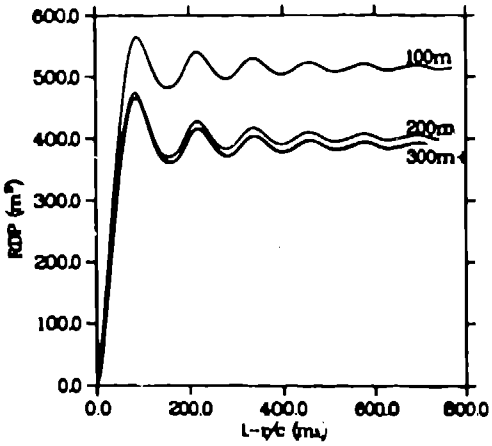

Figure 2. RDP calculated at a number of ranges for the baseline calculation. The top line is at 100 m range, the next at 200 m range, and the bottom line shows results for 300 m, 400 m, 500 m and 600 m which are all identical.

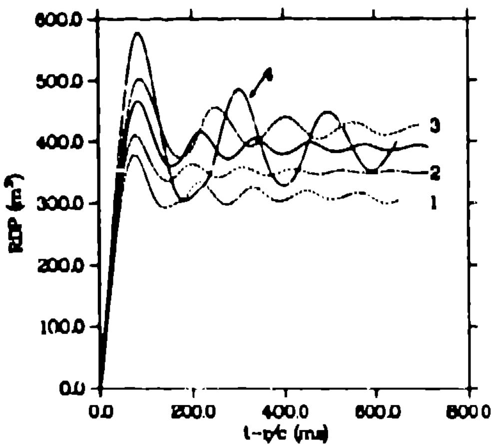

Figure 3. RDP's for baseline calculation and the four variations. The solid unlabeled line is the baseline calculation, and the other four lines are: 1 - change tabular EOS, 2 - increase strength, 3 - increase porosity, and 4 - increase saturation.

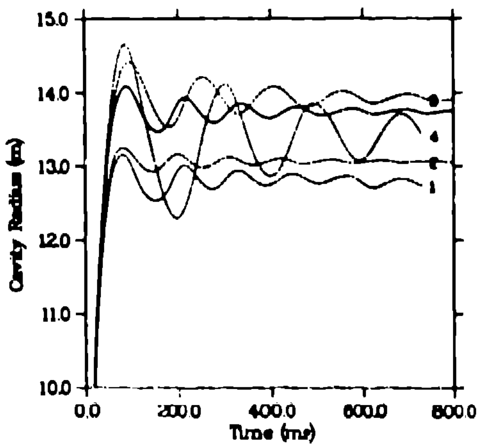

Figure 4. Cavity radii for baseline calculation and the four variations. The solid unlabeled line is the baseline calculation, and the other four lines are: 1 - change tabular EOS, 2 - increase strength, 3 - increase porosity, and 4 - increase saturation.

the portion of the table for material exposed to peak stresses of 10-100 GPA which leads to the conversion of the liquid water in the pores to steam as it expands. The table differences correspond to a halving of the water content. A lower water content means that there will be less expansion of the rock-steam mixture and less of the energy deposited in the material around the device is transmitted through work to the material at greater ranges. The late time RDP shows a drop of about 25% to about 300 m^3 while the final cavity radius is reduced by 8% to 12.8 m due to this change.

Shear strength has long been known to affect coupling to seismic waves. Since the late time RDP is proportional to the permanent displacement, the more fluid-like the material the greater will be the coupling (Latter et. al 1961). Haskell (1961) worked out a theory of this for a Mohr-Coulomb material and showed greater coupling with lower strength. Results for this limestone, with its more complex behavior, are similar. The dashed lines labelled "2" in Figs. 3 and 4 show results for a calculation where the strength has been uniformly increased by 25%. The late time RDP approaches 350 m^3 representing a 10-15% drop in apparent seismic yield while the final cavity radius is about 13.1, a 5% drop compared to baseline. Greater shear strengths resist the growth of the cavity and reduces the amount of work the cavity gases can do on the surrounding material leading to a smaller seismic signal.

Porosity changes from location to location within a site are common. Modulus and strength are typically correlated with porosity. Since the effect of strength changes was already demonstrated, the next calculation contains only a porosity change. The porosity was increased from 13.5% to 20% while keeping the total air-filled void fraction the same by increasing the saturation. The effective pressure-porosity table was scaled to the increased porosity so that, for either porosity, half the total porosity is closed by the same effective pressure. The longitudinal sound speed is reduced to 2865 m/s with this modification. The strength versus effective pressure relation is unchanged, but, since the effective pressures stay lower in the higher porosity material, the strength of the material at any given time tends to be lower. The lines labelled "3" in Figures 3 and 4 show results for this calculation. The RDP has increased over the baseline case to about 420 m^3 while the final cavity radius is larger by one percent. The greater compressibility of the material, together with a lower apparent strength because of effective pressure effects, is allowing a greater final displacement.

The last variation reducing the air-filled void. The saturation was increased from 95% to 98%, which decreases the air-filled void from just under 0.7% to under 0.3%. Less air-filled void should result in less energy dissipation due to pore crushing. The effective pressure should tend to be lower since the pore water begins sharing the load earlier, and this should also result in lower shear strengths since the strength increases with effective pressure. Cavity growth may be greater because of the lower shear strength or may be less because less permanent compaction can be obtained. Results are given by curves labelled "4" in Figs 3 and 4. Both the RDP and the cavity radius show larger oscillations since less dissipation is available from the lower strength and smaller compaction. The lower air-filled void appears to have the greater effect on the cavity radius since the final value should be less than the baseline case. The reduced strength appears to have the greater effect on the RDP since the final RDP should be slightly greater than the baseline case. This calculation is an exception to the correlation of greater cavity radii with greater RDP.

4 DISCUSSION

The variations of the material models performed in this study result in variations of the late-time RDP of up to 25%. The apparent seismic yield should also vary by the same amount. If explosions of the same yield were done at a site where material properties varied from place to place by the extent explored in this paper, then, without event specific information, the apparent seismic yield would vary randomly by up to about 25% due to the material property changes. Additional variation would occur due to background noise at the seismic station. This variation will represent an irreducible error in seismic yield determination based on the low frequency amplitudes as long as the event specific information on the material properties in the non-linear regime is unavailable.

The variations that were chosen here, although applied to a rock which is certainly not from a nuclear test site, should be reasonable indicators of what may occur in real sites. A site specific analysis would need to be done for each such area and may well give a substantially larger or smaller irreducible error in the apparent seismic yield.

5 SUMMARY AND CONCLUSIONS

A limestone whose mechanical behavior has been well determined has been used as a basis for a study of the effects of mechanical property variations on apparent seismic yield for contained nuclear explosions. The resulting variations in apparent seismic yield, up to 25% for this study, form an irreducible lower limit on the accuracy of seismic yield determination if further event specific information on the mechanical properties is unavailable. Studies specific to the actual testing areas need to be performed to evaluate the mechanical property variations present and assess the consequent variation in apparent seismic yield for those location.

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REFERENCES

Denny, M.D. & D.M. Goodman. 1990. A Case Study of the Seimic Source Function: Salmon and Sterling Reevaluated. *J. Geophys. Res.* 95:19705-19723.

Dey, T.N. 1990. Effective stress model for partially and fully saturated rocks. In *Shock Compression of Condensed Matter-1989*, S.C. Schmidt, J.N. Johnson, & L.W. Davison (eds). Elsevier Sci. Publ. 617-620.

Dey, T.N. & J.A. Brown. 1990. Liquifaction of fluid saturated rocks due to explosion-induced stress waves. In *Rock Mechanics Contributions and Challenges*, W.A. Hustrulid & G.A. Johnson (eds.), Balkema, Rotterdam. 889-896.

Haskell, N.A. 1961. A Static Theory of the Seismic Coupling of a Contained Underground Explosion. *J. Geophys. Res.* 66:2937-2944.

King, D.S., B.E. Freeman, D.D. Eilers, & J.D. Johnson. 1989. The Effective Yield of a Nuclear Explosion in a Small Cavity in Geologic Material: Enhanced Coupling Revisited. *J. Geophys. Res.* 94:12375- 12385.

Latter, A.L., E.A. Martinelli, J. Mathews, & W.G. McMillan. 1961. The Effect of Plasticity on Decoupling of Underground Explosions. *J. Geophys. Res.* 66:2929-2936.

Latter, A.L., E.A. Martinelli, & E. Teller. 1959. Seismic Scaling Law for Underground Explosions. *Phys. Fluids.* 2:280-282.

Patterson, D.W. 1966. Nuclear Decoupling, Full and Partial. *J. Geophys. Res.* 71:3427-3436.

Timoshenko, S.P. & J.N. Goodier. 1970. *Theory of Elasticity*. McGraw-Hill, New York. 508-513.