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IMPROVED ONE-DIMENSIONAL CALCULATIONS
OF THE EFFECTS OF FOUR NUCLEAR EXPLOSIONS
IN ALLUVIUM

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ABSTRACT

In a previous paper, we used early quasi-static measurements of the pressure-volume relationship and a manufactured pressure - maximum-deviatoric-stress relationship to calculate the effects of nuclear events in alluvium. The threshold pressure for pore collapse was either held constant or varied in layers. Recently, new measurements of pressure versus volume and versus maximum possible deviatoric stress have become available. Calculations using these data and the same treatment of threshold disagreed badly with field measurements. By permitting the threshold for pore collapse to vary with overburden (much more realistic physically) and making the unloading behavior more realistic than in the previous calculations, agreement with experiment was generally improved over the original work. This tends to confirm the idea that threshold pressure for pore collapse is an indication of the maximum overburden stress experienced by the material.

INTRODUCTION

In the hope of increasing our understanding of seismic source functions, we are continuing our work of calculating the effects of underground nuclear explosions in alluvium. In particular, we are attempting to develop a suitable equation of state for use in the one-dimensional elastic-plastic-brittle failure code SOC.^{1,2} In addition, we are attempting to determine whether the SOC model is suitable for alluvium or whether one of the other published models²⁻⁶ or a new one would be significantly more suitable.

The work described below was performed on a version of SOC in use in 1972. A later version, SOC73,⁷ has not proved more useful in this work so far; however, it will be briefly discussed below. Good free-field particle-velocity-vs-time data were available from four explosions, two of which were in essentially the same material, and the basic idea of this work is to compare calculations with those data.

In a previous paper,⁸ we obtained an equation of state by fitting a smooth curve to data from quasi-static measurements on small samples a few cubic centimeters in volume. We then constructed an arbitrary failure envelope and adjusted it until agreement between the calculation and the measurement was as good as seemed feasible. Now we have better data.

NEW DATA

In late 1970 undisturbed alluvium core samples were obtained from one site (Ue3ct) at the Nevada Test Site. Using these samples, quasi-static pressure-volume measurements were made on pieces about 1 liter in volume.⁹ There were two interesting results. First, data from these samples showed much less compressibility than the earlier data. Second, data from the undisturbed samples agreed fairly well with those from reconstituted samples!

From the measurements and from data reported elsewhere by many authors,¹⁰⁻¹⁴ a new pressure-volume curve was prepared (Fig. 1). The shape of this curve was far more constrained by data than that of the curve in our previous work. However, there were still difficulties. The "average" pressure-volume curve reported in Ref. 9 was based on an initial density of about 1.57 g/cc, and for the shots to be calculated the in situ densities were between 1.65 and 2.14 g/cc. Therefore, a correction had to be made for initial density.

The low-pressure part of the corrected pressure-volume curves were constructed for densities of 1.65 through 1.85 by starting with an initial slope corresponding to the field-measured acoustic velocity at the field-measured density in question, continuing that slope to an overburden pressure, and then fairing to the measured curve. This initial steep slope rising to a "threshold" pressure will be discussed below.

From these pressure-volume curves, pressure - volumetric-strain ($P-\mu$) curves were constructed. Figure 2 shows these curves. Note that a curve at an initial density of 2.03 g/cc is shown. This was obtained from data on saturated samples - probably not corresponding to the real case, but the best available. The unloading curve, also obtained from Ref. 9, is also shown in Fig. 2. For the $P-\mu$ curves at densities of 1.65 and 1.75 g/cc, unloading was to the measured final unloading specific volume. Thus the difference between the two is treated as air-filled porosity.

Since alluvium is very compressible, and since we used data from an initial density of 1.57, we decided to use the $P-\mu$ curves developed for densities of 1.65 and 1.75 for all materials with initial density less than 2.0. Had we not done this, but instead had constructed curves for high density from the 1.57 data in the same way as those for 1.65 and 1.75 (as shown in Fig. 1), the resulting curves would not have been compressible enough to represent alluvium. Then, since alluvium is very variable, and samples were taken from only one hole, we performed two calculations for each nuclear event, one with the 1.65 $P-\mu$ curve for all materials with density above 1.65 and less than 2, and one with the 1.75 $P-\mu$ curve. For densities above 2, the 2.03 $P-\mu$ curve was used. Thus, we had a range of probable $P-\mu$ curves for the materials. In each case, however, the initial density and slope corresponded to the field-measured values for the particular site.

The failure envelope was constructed from data in Ref. 9, and shows a maximum possible deviatoric stress of 250 bars at confining pressures of 5 kb and above (Fig. 3). This is much weaker than the envelope used in the past, but is required by the data.

Fig. 1. Measured (solid) and constructed (dashed) pressure-volume curves for Nevada alluvium. Points are data (gathered by T. R. Butkovich).

Fig. 2. Pressure-compression curves constructed from the pressure-volume curves of Fig. 1.

Fig. 3. Maximum permissible deviatoric stress (shear strength) vs confining pressure for Nevada alluvium, constructed from Ref. 9.

CODE CHANGES

Modifications made to SOC for this work are illustrated in Fig. 4. The loading was modified so that the "threshold" for the steep slope of the $P-\mu$ curve, instead of being constant for a given material, varied with overburden pressure as shown in the figure. An arbitrary value of 5 bars above overburden for a given zone was used; small changes in that value made small changes in the result. A threshold, no matter how constructed, will give rise to a precursor in the stress wave; such a precursor is often observed. If there is no threshold, that is, no steep initial slope, the particle velocity will be much larger than if there is a threshold and the signal will arrive much later. Such a situation is often observed in the stemming in emplacement holes, where measurements indicate overburden pressure to be very small. Therefore, use of the threshold as a function of overburden is quite justified. In fact, a similar threshold is used by the oil industry to deduce ancient overburden. The threshold presumably builds up as the alluvium is laid down and compressed. Use of the variable threshold also avoids spurious reflections at material boundaries at very low pressure.

The unloading scheme in SOC was also modified. The version used here interpolates between the input loading and unloading curves at pressures well above threshold and interpolates between the steep slope to threshold and the lowest part of the unloading curve at pressures below threshold. Near threshold pressure, the two are faired. In the original version of SOC, similar interpolation was performed, but the change in slope took place at the compression corresponding to threshold rather than at the pressure. This permitted a discontinuity and was also not as steep above threshold.

RESULTS

Figure 5 shows the materials used in the various calculations. The 10-kt Merlin Event at site Ue3ct was unique in that there were not only two instrument holes above the explosive, but also a series of holes horizontally at shot depth. Therefore, both vertical and horizontal (constant overburden) calculations were performed. Figure 6 shows measured and calculated peak particle velocity vs radius for the vertical case. Agreement in general is quite good except near the surface. Note that measured data disagree among themselves beyond about 200 m, but that the calculation agrees with some of the measurements to 250 m. Beyond this, near the surface, the validity of a one-dimensional calculation is questionable. Since most of the material has a density below 1.75 g/cc, only the 1.65 $P-\mu$ curve was used in most of the calculation; therefore there is little difference whether the 1.65 or 1.75 $P-\mu$ curve was used in the 1.75 material.

Figure 7 shows some sample pulse shapes. Here the agreement between measurement and calculation is not as satisfactory, and more work is needed. The

Fig. 4. Illustrations of modifications to the SOC code. The light lines are modifications to the loading and unloading pressure-volume curves.

Fig. 5. Setup of the four problems.

Fig. 6. Measured and calculated peak particle velocities for the Merlin Event, vertically above the explosion.

Fig. 7. Sample measured (solid) and calculated (dashed) pulse shapes for the Merlin Event, vertically above the explosion.

problem is briefly discussed below. Note the presence of a precursor both in the measurement and in the calculation.

The calculated cavity radius of 38.5 m was larger than the measured value of 30 m. This is the one result that is not as good as the previous work, where the cavity radius was calculated quite well. However, the calculated radius is the upper half, larger than the measured downward half.¹⁵

The horizontal calculation of Merlin (Fig. 8) gave quite good agreement with observed peak particle velocity. Here, since all material has densities greater than 1.65 g/cc, both P- μ curves were used in the calculations, and substantial differences can be seen. However, it is not clear which curve is best.

The Hupmobile Event, at 7.4 kt, was fired 91 m south of the exploratory hole Ue2y and the 10-kt Packard Event was fired 178 m north of Ue2y. Since all geophysical data were taken from Ue2y, the two events were taken as one problem, and the Packard data were cube-root scaled to compare with Hupmobile. Peak particle-velocity data are shown in Fig. 9, and quite good agreement is seen when the 1.75 P- μ curve is used. However, closer in, the 1.65 curve seems better for Hupmobile. The variation may well be real. Again, calculated cavity radius (35 m) is considerably larger than the observed 32 m and 30 m (scaled) for the two events.

The instrumentation on the Vulcan Event was not as good as on the other three, nor were the in situ geophysical data. Figure 10, giving peak particle velocities, shows that the 1.75 P- μ curve is fairly satisfactory for Vulcan, especially considering the poor data.

DISCUSSION

We can calculate peak particle velocity vs radius fairly well if we are willing to make two calculations and accept a range. This seems reasonable since the calculations are made in the absence of pressure-volume data from the site of the event; we must recognize the variability of the alluvium.

Use of a variable threshold improves the calculations greatly, and this fact, coupled with our observations in stemming and the experience of oil companies, indicates that the variable threshold is probably physically real.

Calculated pulse shapes are still unsatisfactory. Attempts to improve pulse shape, using the new code SOC73,⁷ have been successful in that the new code eliminates the nonphysical jaggedness of the pulses. However, we have been unable, with SOC73, to approach the accuracy of the above calculations of the peaks.

We have also attempted to use the Butkovich¹⁶ method of construction of an equation of state for alluvium. This method gives a stiffer pressure-volume curve, at very low pressures, than used here (or observed for alluvium) and has, so far, proved less satisfactory.

We hope that as the model of a highly porous material in SOC is improved we will be able to improve our calculations of alluvium.

Fig. 8. Measured and calculated peak particle velocities for the Merlin Event, horizontally at shot depth.

Fig. 9. Measured and calculated peak particle velocities for the Hupmobile and Packard (scaled) Events.

Fig. 10. Measured and calculated peak particle velocities for the Vulcan Event.

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