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DEVELOPMENT OF THE BRINELL SANDWICH PASSIVE TRANSDUCER

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INTRODUCTION

Passive stress gages can provide a cost-effective method of measuring peak stress in soil and on a soil-structure interface. Ideally, the deformation characteristics of a soil stress gage should match the soil as closely as possible. However, a flat, disc-shaped gage whose stiffness is greater than that of the soil is not very sensitive to variations in soil properties (1). Since pretest predictions of peak stress resulting from nuclear and high-explosive detonations are often very inaccurate, the widest possible sensing range is clearly advantageous. For maximum usefulness when dealing with pulses of different rise times and durations, the gage should be free of rate effects over as broad a range of pulse shapes as possible.

DESCRIPTION OF THE BRINELL SANDWICH SOIL STRESS GAGES

The Brinell Sandwich consists of a layer of small hardened steel balls between softer materials. The balls may be closely packed or separated from each other by a spacer. Indentations in the softer materials (their diameters are measured by a microscope), indicate the maximum compressive force that has been exerted at the location of each ball.

A cross section is shown in Figure 1. The gage body package serves to seal off the space around the balls from external pressure, and to provide protection against shear in the plane of the sandwich.

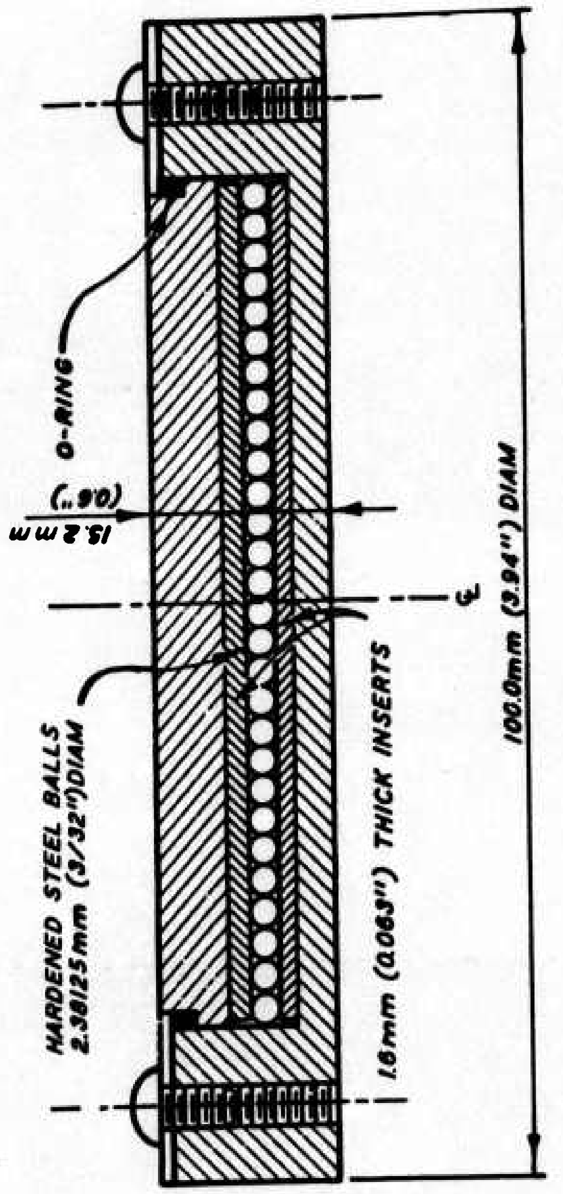

Figure 1. Brinell Sandwich soil stress gage. The hardened steel balls may be closely packed or separated by a spacer, depending on desired range and stiffness.

Two versions of the Brinell Sandwich soil stress gage have been used to date. In the high-ranged gage, the balls are closely packed, forming a plane hexagonal array except at the edge. Measured mean density in the hexagonal array (at the gage center) was 20.305 balls per square centimeter (131.00 per square inch). In the lower-ranged version, the balls are separated by a 1.27 millimeter (0.050 inch) thick spacer into an array with 3.875 balls per square centimeter (25 per square inch); this is a square array except at the edge, but the ball density there is very nearly the same as at the center.

CHOICE OF MATERIALS

The choice of insert materials is critical. A partial search of published literature on strain rate sensitivity (the dependence of plastic flow stress on strain rate) was conducted. The aluminum alloys 7075-T6 and 6061-T6 have the lowest strain rate sensitivity in compression of any materials on which published data were found in this search (2). Consideration was also given to the possibility of obtaining information on the pulse rise time by having one of the inserts made of a strain rate sensitive material, with the other made of a material insensitive to strain rate. However, this approach was not pursued. All laboratory testing was done with one insert of 7075-T6, installed on the bottom in Figure 1, and the other of 6061-T6 aluminum alloy.

The choice of material for the gage body is considerably less critical. The density of aluminum is much closer to media densities than that of steel, hence use of aluminum minimizes acceleration sensitivity. The alloy 7075-T651 is used because of its high strength and stress-relieved temper.

CALIBRATIONS IN HYDRAULIC FLUID

Static and dynamic calibrations were performed in a dynamic fluid chamber. A representative of the group of dynamic pulses obtained by normal operation of the fluid chamber is shown in Figure 2a. However, it was found that by operating the fluid chamber with a volume of nitrogen immediately above the fluid and by minimizing chamber volume, considerably shorter pulses could be obtained, especially with the higher peak pressures. One of the fastest pulses from this group is displayed in Figure 2b. The rise time was defined as in Figure 2 because the beginning shoulder of the pulse is both poorly defined and unimportant in checking for possible strain rate effects.

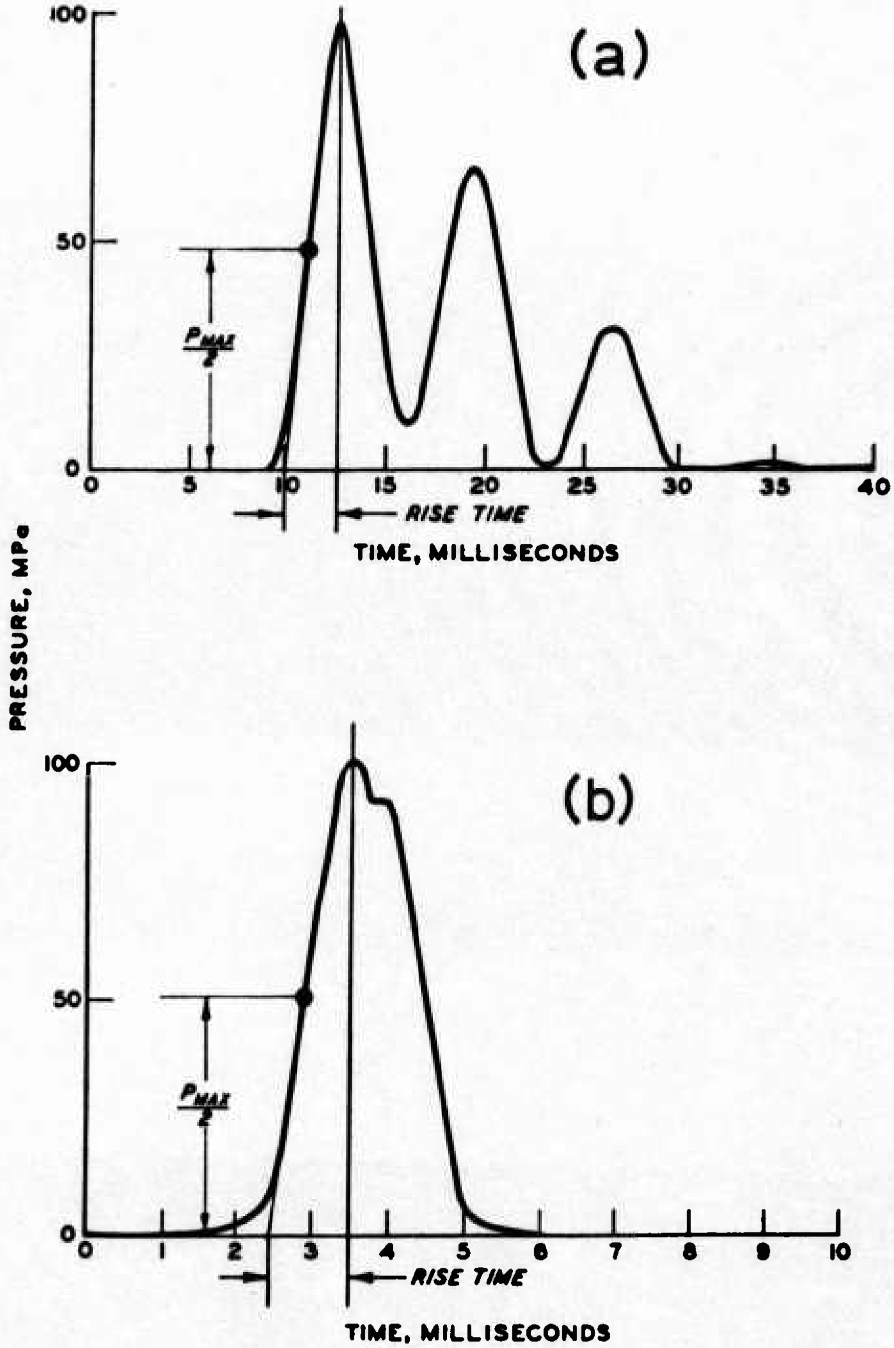

Figure 2. Representative pulses from calibrations in a dynamic fluid chamber. (a) Representative of the dynamic pulses obtained by normal operation of the fluid chamber, (b) One of the fastest pulses, rise time 1.0 millisecond, obtained by operating the chamber with a volume of nitrogen over the fluid.

The impressions formed by the balls were measured with a binocular microscope calibrated with a stage micrometer, at 160X, 80X, and 56X nominal magnifications, depending on impression size. A photomicrograph of an impression representative of the mid-range is shown in Figure 3. Impression edge definition becomes a problem only with impressions smaller than 0.3 millimeter diameter; this is due to the small change in slope at the edge. Nevertheless, impression diameters as small as 0.17 millimeter could be measured, although with reduced accuracy. Each impression was measured in mutually perpendicular directions. The mean impression diameter at the gage center was based on a sample pattern of seven impressions for the high-ranged gage, and five impressions for the lower-ranged gage.*

The results are plotted in Figures 4 and 5, and the parts of these plots involving the higher peak pressures and correspondingly large impressions (which are the most sensitive indicators of possible strain rate effects) are expanded in Figures 6 and 7. In the absence of detectable rate effects, all three sets of points should lie along the same line (within random point scatter) irrespective of pulse rise time and duration. This is indeed true for the alloy 7075-T6. However, large impressions in the alloy 6061-T6 appear to involve a barely detectable rate effect, as indicated in Figure 7. Of course, this is easily avoided by always installing at least one 7075-T6 insert in the gage, and not utilizing large impressions in 6061-T6 as readout. Small impressions in 6061-T6 may be used for better resolution near the lower end of the sensing range. By contrast, with the copper-ball-crusher gage often used for measuring gun chamber pressure, peak pressures applied with a half-sine pulse of 3 millisecond rise time are 1.1 to 1.3 times the static pressures needed to produce the same deformations (3).

High pressures close the radial clearance just below the O-ring. However, the effect of edge friction is mitigated by the low flexural stiffness of the gage body faces. There are indications that under normal conditions, the effect of edge friction upon impressions at the center is negligible for the two gage versions tested. Tests with the more friction-sensitive lower-ranged gage designed to simulate effects of extreme variation in edge friction resulted in only 1.3 to 4.0 percent changes in impression diameters at the center.

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*ASTM Standard E10-66, "Standard Method of Test for Brinell Hardness of Metallic Materials," specifies a minimum of five impressions in calibrating standardized hardness test blocks whose test face area is less than 100 square centimeters.

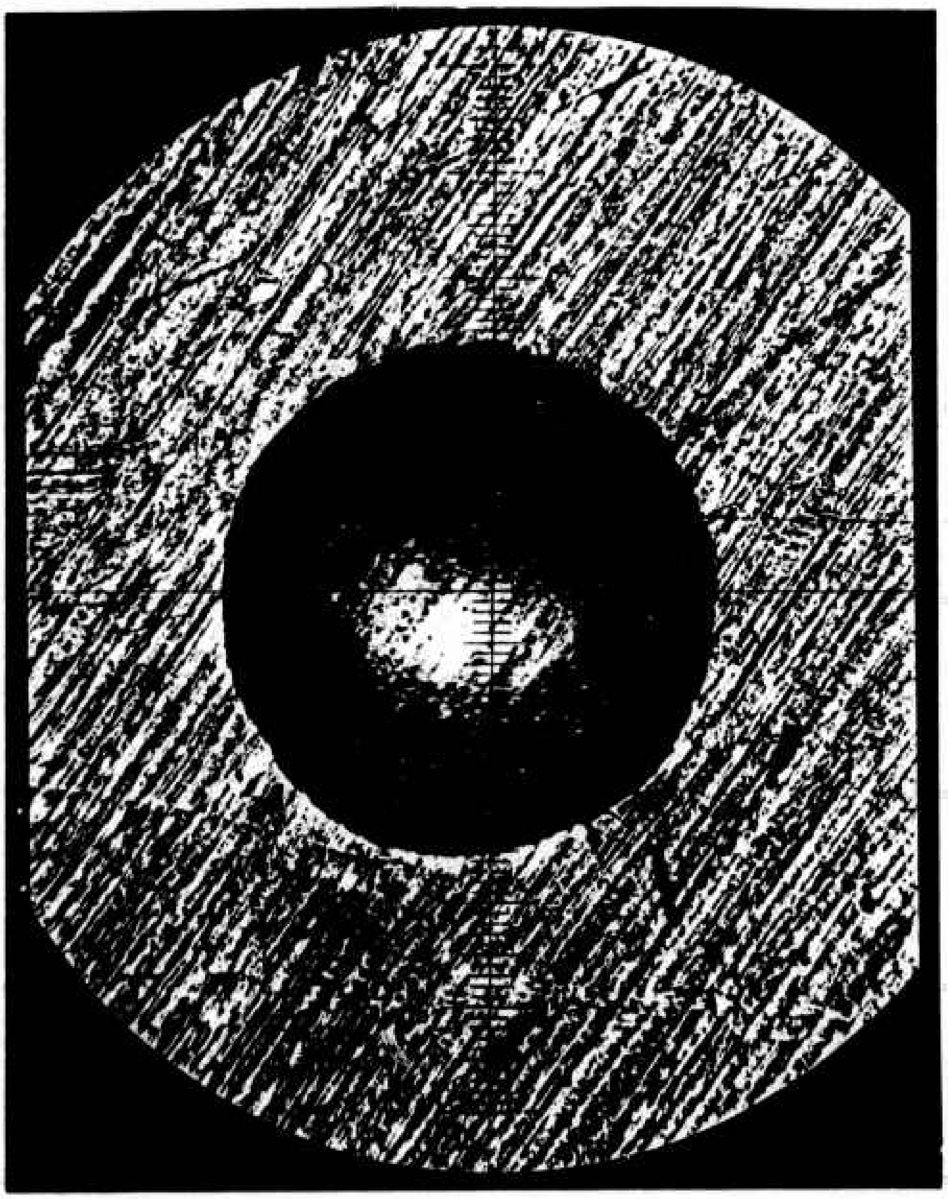

Figure 3. Photomicrograph of an impression. Each scale division is approximately 16 microns.

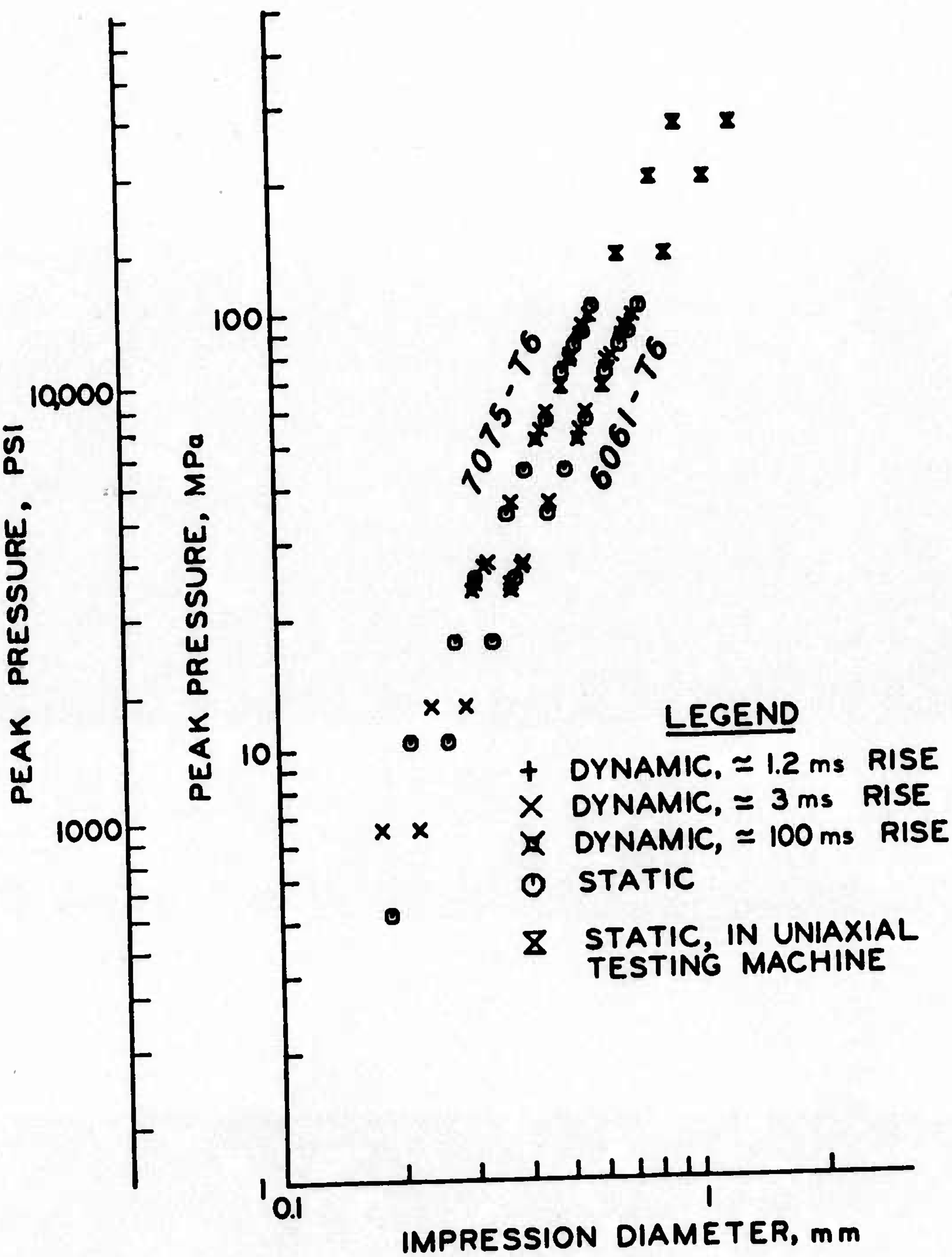

Figure 4. Calibrations in hydraulic fluid for the high-ranged Brinell Sandwich soil stress gage, with the steel balls closely packed.

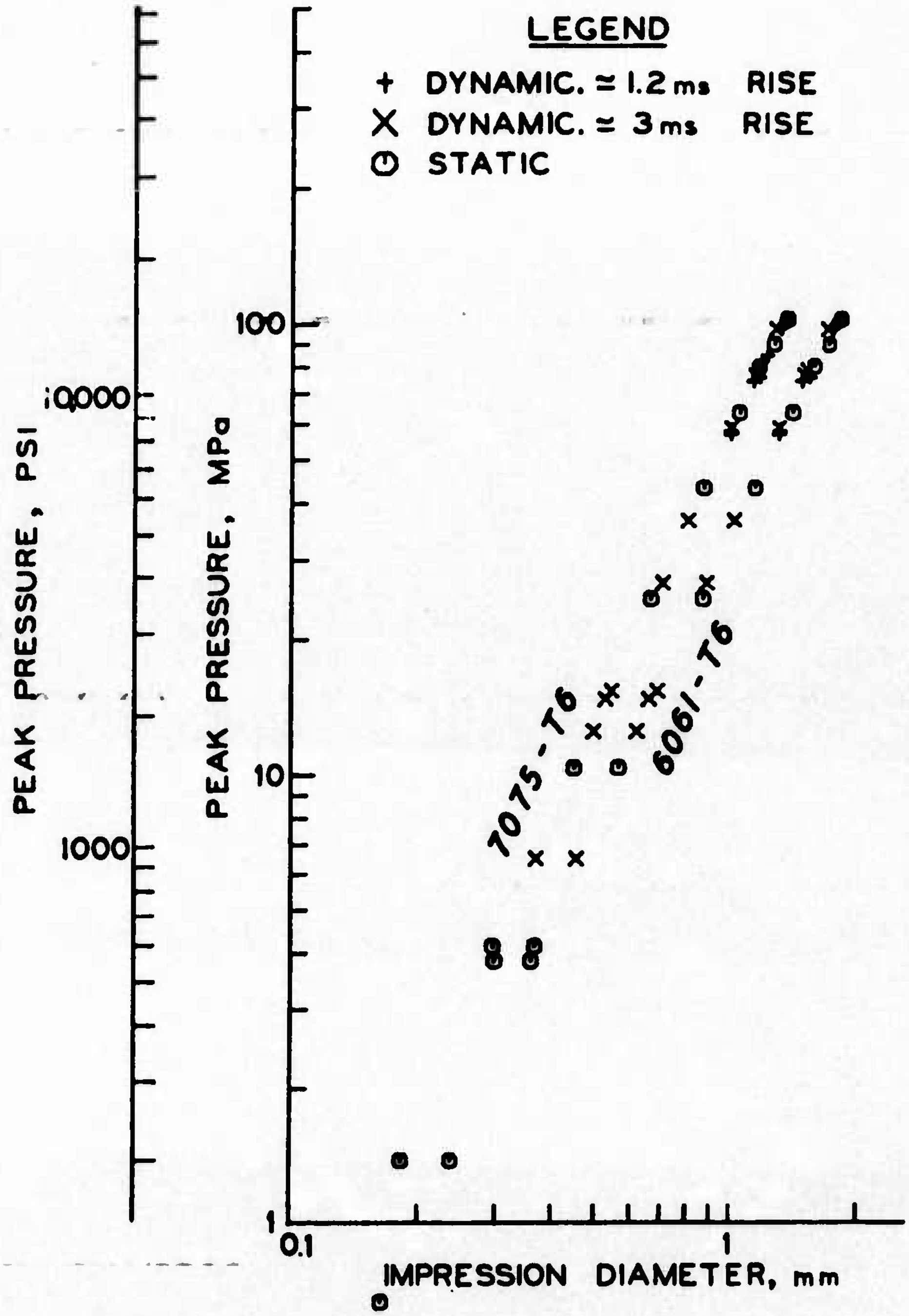

Figure 5. Calibrations in hydraulic fluid for the lower-ranged Brinell Sandwich soil stress gage, with 3.875 balls per sq cm (25 per sq in.), separated by a spacer.

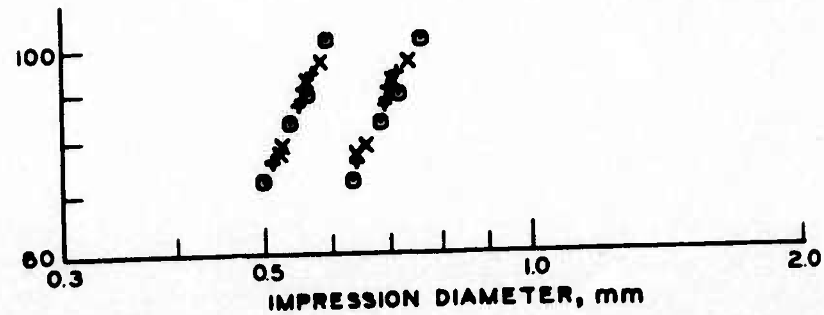

Figure 6. Part of Figure 4 expanded for clearer display of comparisons between different pulse rise times and durations.

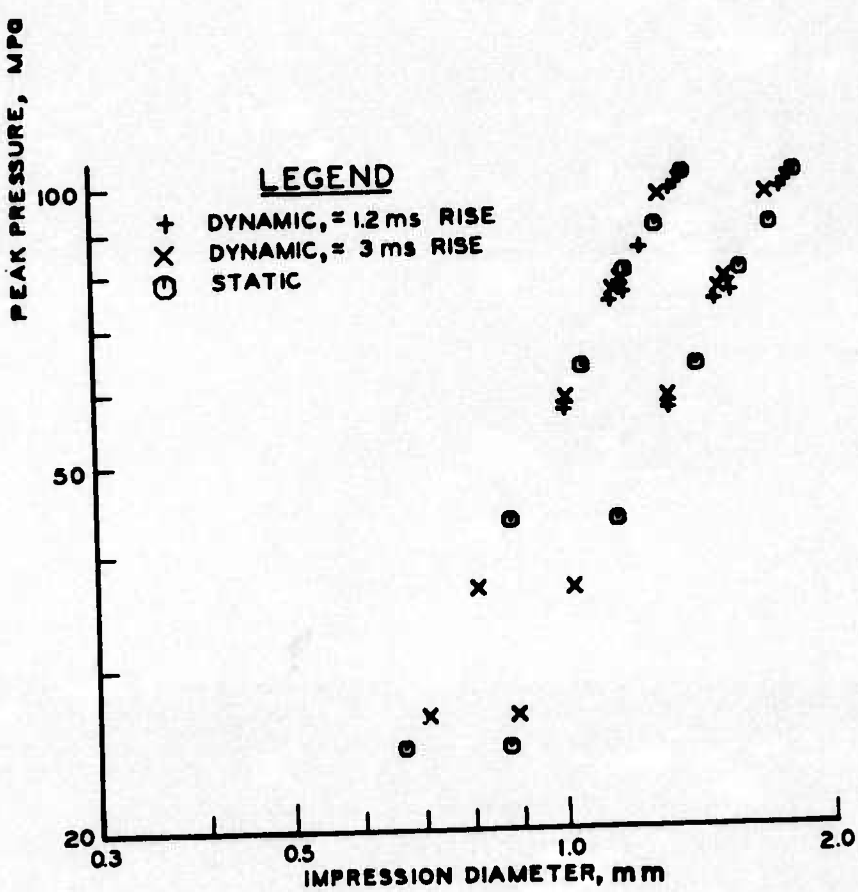

Figure 7. Part of Figure 5 expanded for clearer display of comparisons between different pulse rise times and durations.

Calibrations in hydraulic fluid between peak pressures of 100 MPa and 400 MPa were also attempted. Due to problems with the reference transducer, the quality of the resulting data could not be considered sufficient for calibration purposes. The pressure threshold at which the inserts bottom on the spacer in the lower-ranged gage was found to be between approximately 130 MPa and 180 MPa. The threshold for permanent deformation of the gage body parts was found to be approximately 200 MPa, but the gages could always be easily disassembled. Absence of any O-ring failures was encouraging.

Some calibrations of the high-ranged gage, with balls closely packed, were performed with a uniaxial static testing machine. The gage bodies used in these tests had been machined for extra radial clearance. The load was distributed over the entire active face of the gage. The equivalent pressure was computed by dividing the total load by the total number of balls, then multiplying by the ball density in a close packed hexagonal array. Root-mean-square impression diameters were computed from a sample pattern covering the insert face. The results are included in Figure 4.

The most convenient calibrations would be with a single ball, using an appropriate hardness testing machine with different load settings. A set of points generated in this way could serve to anchor a calibration curve for a new batch of insert material of the same alloy, its general shape having already been well defined.

STRESS VERSUS STRAIN CHARACTERISTICS

No attempt was made to measure axial gage strain directly. Calculated stress-strain relations for initial loading are depicted in Figure 8. The actual stiffness is expected to be somewhat greater. The offset at zero stress corresponds to the maximum discrepancy permitted between the measured thickness of the assembled gage at the center and the sum of the measured thicknesses of the parts.

With very short rise times, gage performance will depend on frequency response as well as possible strain rate effects. If the stress versus strain behavior of the high-ranged gage, with balls closely packed, were to be characterized by a modulus of 7500 MPa (≈1100000 psi), and the lower-ranged gage by a modulus of 1400 MPa (≈200000 psi), then their response times to a step function in external stress applied to both gage faces simultaneously would be 15 microseconds and 35 microseconds, respectively. These correspond to half-periods of equivalent elastic systems, which would have natural frequencies of 33 kHz and 14 kHz, respectively.

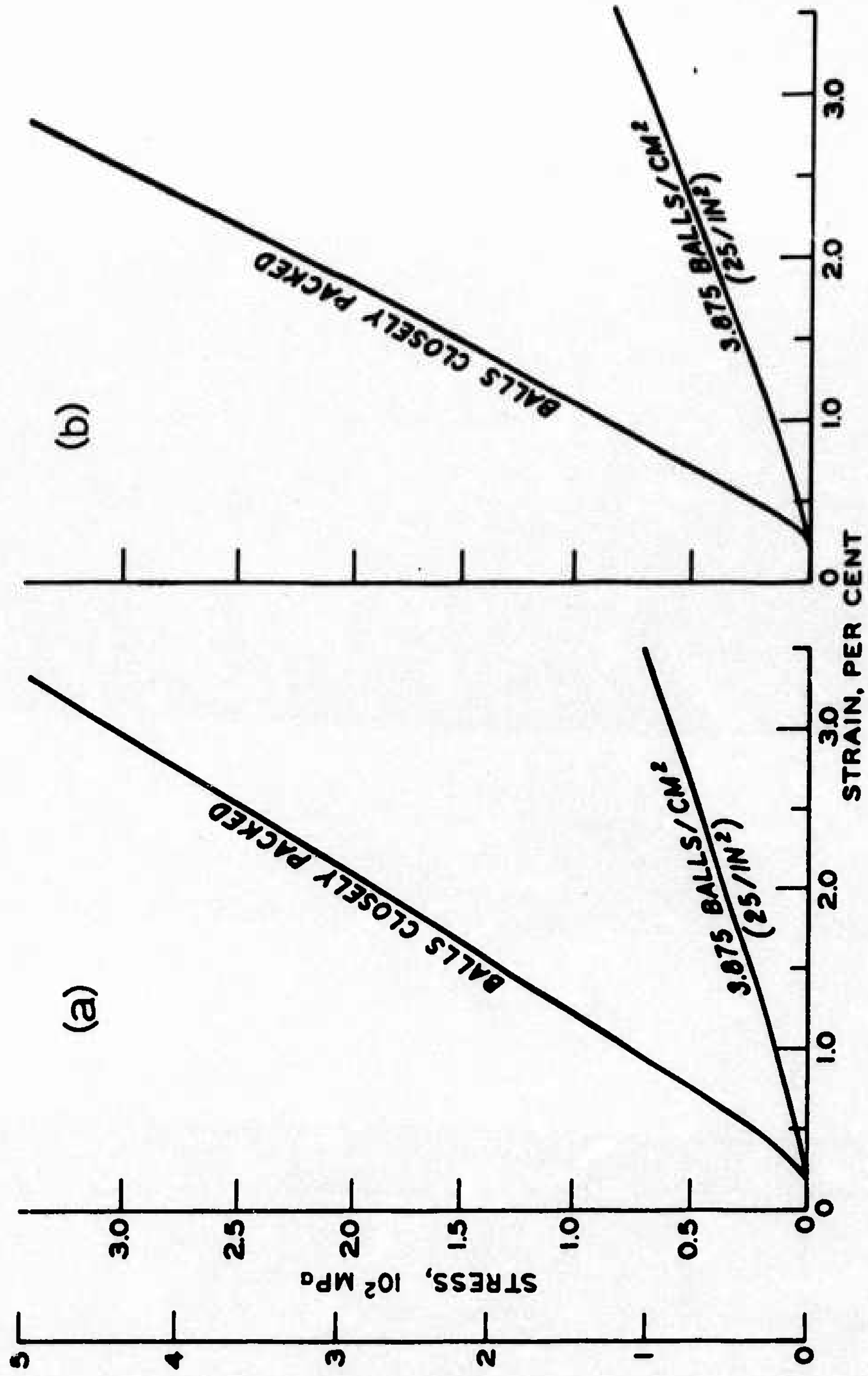

Figure 8. External compressive stress versus calculated axial strain at the gage center. (a) One insert 7075-T6, other insert 6061-T6. (b) Both inserts 7075-T6.

LABORATORY TESTS IN SAND

The test fixture was the same dynamic fluid chamber that was used for calibrations in hydraulic fluid. The specimen volume, 13.34 cm diameter and 6.35 cm high, contained Reid-Bedford sand, with a gage embedded in the middle. Properties of Reid-Bedford sand have been described elsewhere (4). The sand was sprinkled in place, with a nominal density of 1.65 gm/cc (103 pounds per cubic foot). A rubber membrane separated the specimen volume from the hydraulic fluid above it. The results are plotted in Figure 9. Both the high-ranged and lower-ranged gage consistently overregistered, which is not surprising. The overregistration is greatest at the lowest test pressure (Figure 9b).

SUMMARY OF CHARACTERISTICS

The following table summarizes the characteristics of Brinell Sandwich soil stress gages tested, with one insert of 7075-T6, and the other of 6061-T6 aluminum.

Feature	Balls Closely Packed, 20.305/cm^2	3.875 Balls Per cm^2	Determination Method
Range lower limit	4 MPa (≈600 psi)	0.67 MPa (≈100 psi)	Experiment
Range upper limit	Not determined (>400 MPa)	>130 MPa <180 MPa	Experiment
Stiffness modulus at center	≈7500 MPa (≈1100000 psi)	≈1400 MPa (≈200000 psi)	Calculation
Response time to a step function	≈15 μs	≈35 μs	Calculation
Error band over most of range, ≈ 95% conf. level	± 4% of reading		Experiment
Strain rate effects	No influence on measurements with pulses ranging from static to half-sine with ≈1 ms rise		Experiment
Acceleration sensitivity	≈100 Pa/g (≈0.015 psi/g) in soil of 1.7 gm/cc density		Calculation

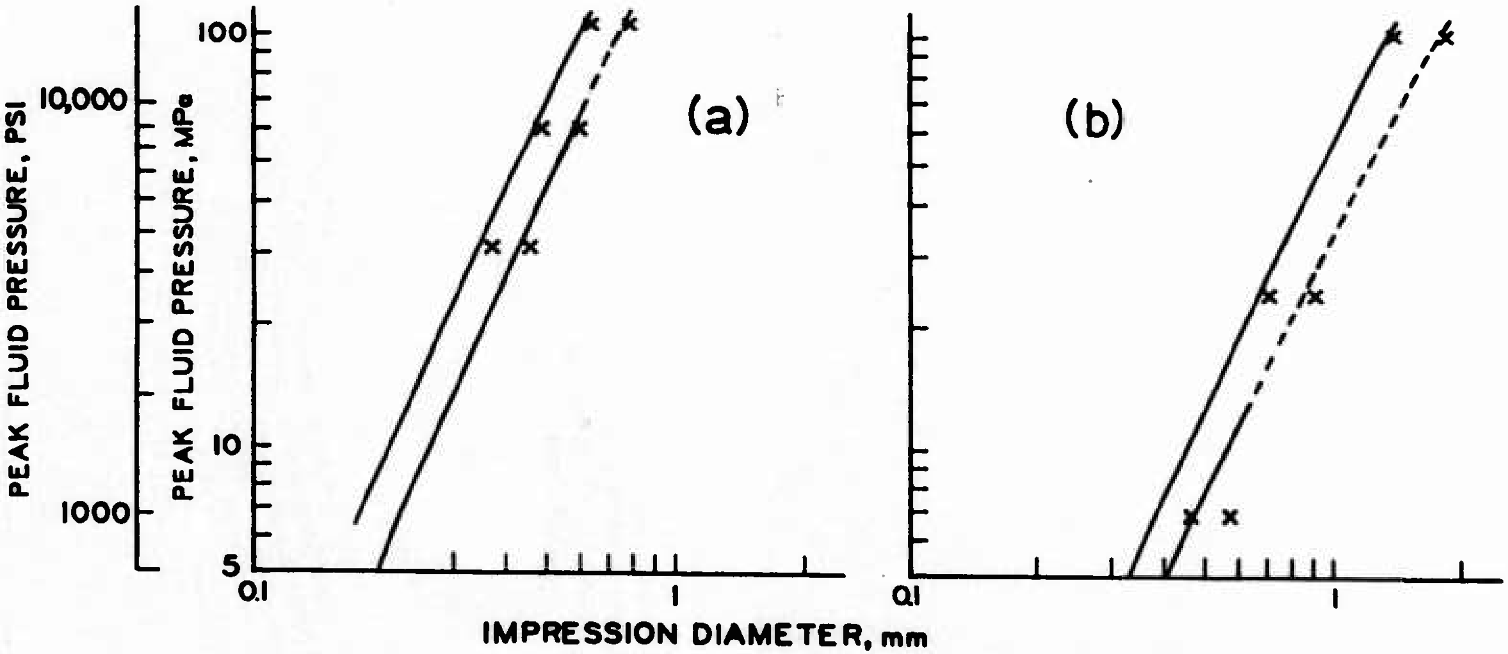

Figure 9. Dynamic tests of the Brinell Sandwich soil stress gage in Reid-Bedford sand. (a) High-ranged gage, with balls closely packed, (b) lower-ranged gage, 3.875 balls per sq cm (25 per sq in.), separated by a spacer. The lines are from calibrations in hydraulic fluid (Figures 4 and 5).

These gages can also indicate local anomalies in the external stress field. For example, the presence of voids or soft inclusions near the gage is indicated by regions of low impression sizes on the recovered inserts. This diagnostic capability is important in excluding misleading readings from the data.

OTHER APPLICATIONS OF THE BRINELL SANDWICH

A slightly modified version of the lower-ranged Brinell Sandwich soil stress gage was used to measure peak impact force in a battle tank suspension simulator subjected to ground motion. The contact time was estimated from the impacting mass and the calculated deformation characteristic of the gage. Since this estimated contact time was approximately 0.2 millisecond, a possible strain rate effect was not ruled out and the indicated peak impact force was considered a lower limit.

The Brinell Sandwich could readily be packaged to optimize location and distribution of impact forces over a wider area. This may make it useful in crash testing.

Use of a Brinell Sandwich peak reading uniaxial accelerometer is presently being attempted in measuring peak deceleration of a projectile upon impact.

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(4) Kennedy, T. E., Albritton, G. E., Walker, R. E., "Initial Evaluation of Free-Field Response of the Large Blast Load Generator," USAE Waterways Experiment Station Technical Report 1-723 (1966), Appendix A.