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Airblast Environments From Buried HE Charges

H. Reichenbach K. Behrens A. Kuhl

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E 1/93

Airblast Environments From Buried HE Charges

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SUMMARY

Laboratory experiments were conducted to measure the airblast environment generated by the detonation of buried HE charges. Spherical 0.5-g charges of Nitropenta were used as the HE source. Three ground materials were used: (1) a porous, crushable grout (YTONG, $\rho = 0.4 \text{ g/cm}^3$); (2) a water-saturated grout ($\rho \approx 0.7 \text{ g/cm}^3$) to investigate the effects of density increase; and (3) a clay-loam material ($\rho \approx 1.8 \text{ g/cm}^3$) to simulate some of the previous field tests conducted in clay. Diagnostics consisted of 13 flush-mounted pressure gauges, and single-frame schlieren photography. A special shock isolation system was used to eliminate the acceleration effects on the gauges that were induced by the cratering process. Analysis of the pressure measurements resulted in an experimental definition of the airblast environment as a function of ground range (GR) and depth-of-burst (DOB). Synthesis of these results allowed one to construct airblast DOB curves (i.e., iso-environment curves in GR-DOB space), similar to the airblast height-of-burst curves that we published previously for Nitropenta charges. Variables analyzed were: peak pressure, arrival time, positive phase duration and impulse. As in field tests, we found that the airblast waveforms changed character with increasing DOB: for small DOBs ($-0.25 < \text{DOB (m/kg}^{1/3}) < 0.1$), the waveforms had a classical blast wave character; for intermediate DOBs ($0.1 < \text{DOB m/kg}^{1/3} < 0.25$), a "front-porch" waveform was observed; while for deeper bursts ($\text{DOB} < 0.35 \text{ m/kg}^{1/3}$), only compressional waveforms were found. The crater characteristics (e.g., depth, radius and volume) were also measured. The cube-root-scaled crater volume was in qualitative agreement with data from field tests (e.g., charge weights up to 10^4 lbs.). Since the present scaled results compare well with data from large-scale HE tests, we conclude that the present experimental technique provides a useful tool for parametric investigations of explosion effects in the laboratory.

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SECTION 1

INTRODUCTION

While much airblast data were available for height-of burst (HOB) effects (e.g., References [1] to [4] systematic airblast data for depth-of-burst (DOB) effects are much more limited (e.g., References [5] to [13]). The legitimate question has therefore been asked whether the 0.5-g NP charges that proved to be successful for HOB tests are also suitable for DOB tests. As demonstrated in exploratory DOB experiments (Ref. [13]) airblast DOB tests can be performed at laboratory scale. Of course, not all physical quantities (e.g., gravity) can, on a model scale, be chosen in accordance with requirements of the similarity laws. This is true especially for the study of crater formation processes.

It was decided to use our laboratory test equipment to investigate blast wave data in order to be able to extend the isobaric HOB curves to cover DOB cases. The main interest was therefore to measure the airblast environment generated by the detonation of buried and aboveground HE-charges. The data recording concerning crater depth and crater volume are of secondary importance.

In the present report, the test setup will be described and results for three different simulated soil materials will be presented.

SECTION 2

EXPERIMENT DESIGN

Because the exploratory DOB experiments (Ref. [13]) produced remarkably good results, the previous experimental setup was maintained. In particular, the measuring system installed in the roof plate of the explosion chamber remained basically the same as used for our HOB tests. That means the DOB experiments were carried out upside down. For a more detailed description of the explosion chamber see Ref. [1].

2.1 SOIL MATERIAL.

Because of the geometrical arrangement, the simulated soil had to be cohesive. Three soil materials were used:

- (1) a porous, crushable aerated grout (German trade name: YTONG)
specific weight: $\rho = 0.40 \text{ g/cm}^3$ (25 lbs/ft³)
- (2) a water saturated grout (wet YTONG)
specific weight: $\rho = 0.73 \text{ g/cm}^3$ (45 lbs/ft³)
- (3) a clay/loam material
specific weight: $\rho = 1.8 \text{ g/cm}^3$ (113 lbs/ft³)

These materials were chosen to investigate the effects of density increase and to simulate some previous field tests.

2.2 INSTALLATION OF THE CHARGE.

The installation of the 0.5-g charge is sketched in Figure 1. The soil material was embedded in a steel tube (length: 300 mm; inner diameter: 100 mm). Different procedures were applied:

2.2.1 Aerated Grout (YTONG; materials (1) and (2)).

With the help of a core drill, cylinders were bored out of YTONG-blocks and finished on a lathe. Thus the aerated grout, despite its granular structure, achieves a relatively smooth surface. During the drilling and turning water is added. YTONG absorbs the moisture. To achieve reproducible results, for tests with dry YTONG, the cylinders were stored and dried in the laboratory for several days. For tests with wet YTONG the cylinders were saturated in water for several hours. They were only used when there were no further changes in the weight checks in both cases.

To install the charge (diameter: 10 mm), a hole with a diameter of 10.4 mm is drilled concentrically into the YTONG cylinder. The bore depth is chosen in such a way that the required overburden remains undisturbed. With the help of a special tool, a hemispherical deepening with a radius of 5 mm is made at the end of the bore. The charge is inserted through the bore channel and the correct position of the charge is controlled with the length of the supply wires. The remaining hollow space in the bore channel is filled with pulverized aerated grout to obtain the necessary backfilling. Finally, the bore opening is closed with an adhesive.

This procedure guarantees that the overburden remains in the original material condition and is not altered, as it is generally the case with free field DOB experiments. There the charge is usually sunk into the soil from the earth surface.

After the YTONG cylinder was prepared as described, it was inserted into the steel tube so that the plane face ends flush with the rim of the tube.

2.2.2 Clay/Loam (material (3)) .

It was not possible to apply the same procedure as with YTONG. Therefore the steel tube containing the simulated soil material was direct filled with the clay/loam mixture to such a height that the charge could be placed in the desired position. Then the overburden was filled in so that the clay/loam soil ends flush with the rim of the tube. The material was carefully and slightly compacted to achieve a cohesive connection between overburden and the first filled-in material. The supply wires of the charge led sideways through the overburden.

2.3 INSTALLATION INTO THE EXPLOSION CHAMBER.

To reduce the transmission of acceleration pulses created by the detonation of the charge and the cratering processes, the steel tube containing the soil material was installed with shock isolation mechanism to decouple it from the explosion chamber (see Figure 1). A shock isolation system was also used on the gauge to eliminate the acceleration effects.

Figure 2 gives a general view showing not only the construction of the steel cylinder but also of the shielding of the high-voltage ignition circuit that runs in a type of Faraday cage. This isolation technique was necessary to keep the electromagnetic interferences, coming from the ignition circuit, as far away from the pressure gauges and their supplies as possible.

The position of the pressure gauges in relation to ground zero (GZ) is depicted in Figure 3. Gauge MK1 is 90 mm away from GZ. The distance between gauges MK1 to MK13 is 60 mm each. Gauges MK14, MK15, MK16 are arranged in a distance of 85 mm, 99.4 mm and 150 mm, respectively, but they are not on the same radial as gauges MK1 to MK13.

The recording equipment and the optical arrangement for shadow and schlieren single photographs are the same as described in Reference [1].

SECTION 3

TEST MATRIX

The test matrix is presented in Table 1. Included are also the tests documented in Reference [13]. We found that experiments with $DOB > 5 \text{ cm}$ ($= 0.63 \text{ m/kg}^{1/3}$) did not create significant pressure pulses in air. Note that DOB is counted positive from the surface to the installation point (center of charge), so that $DOB = -0.5 \text{ cm}$ (at a charge diameter of $D = 1.0 \text{ cm}$) indicates a charge tangent above surface, which is identical with $HOB = +0.5 \text{ cm}$.

Table 1. Test Matrix

DOB/D	Test Number			Remarks
	dry YTONG	wet YTONG	Clay/Loam	
- 2.0	814	768 783	813	HOB/D = + 2.0
- 1.0	815	769	781	
- 0.5	723 726 747 802	800 801	780	tangent above surface
- 0.25	804	807	812	
0.0	722 803	805	777	half buried
0.15	736			
0.25	735	784 808		
0.5	737 738 809	806	767 776	tangent below surface
1.0	717	758 785	762 811	
1.5	740	786 787	766 796	
2.0	712 713 719	788 789	761 773 774 775 810	
2.5	741 742 816	790 791	765 797 798 799	
3.0	718 720	792 793	763	
3.5			771	
4.0	721	794 795	764	
5.0	724 725	759 760	772	

To get a better idea about how the measuring data fit in with previous full scale experiments, Table 2 presents some DOB tests, for which airblast data were determined. The charge weights were between 8 and 20 tons, i.e., about 7 orders of magnitude higher than for our 0.5-g charges. The EMI experiments have also been inserted in Table 2. The scaling was $W^{1/3}$.

Table 2. HE Events with Airblast Data

SDOB [ft/kt ^{1/3}]	HE Event	Yield	Soil	EMI Experiments	
				SDOB [ft/kt ^{1/3}]	Depth (Charge Dia.)
				- 56	- 2.0-D
				- 28	- 1.0-D
				- 14	- 0.5-D
				- 7	- 0.25-D
				0	0-D
				4	0.15-D
				7	0.25-D
				14	0.5-D
				28	1.0-D
36.4	Essex-I-3MS	11.5-T	LMD*		
39.2	Essex-I-3MU	9-T	LMD		
				42	1.5-D
54	Stagecoach-2	20-T	Alluvium		
				56	2.0-D
				70	2.5-D
73.3	Essex-I-6MWS	10-T	LMD		
74.4	Essex-I-6MU	10-T	LMD		
81	Buckboard-11	20-T	Basalt		
81.5	Essex-I-6MU	8-T	LMD		
				84	3.0-D
108	Stagecoach-3	20-T	Alluvium		
				112	4.0-D
135	Buckboard-12	20-T	Basalt		
				140	5.0-D
152.7	Essex-I-12MS	10-T	LMD		
152.7	Essex-I-12MPS	10-T	LMD		
186	Buckboard-13	20-T	Basalt		
253	Stagecoach-1	20-T	Alluvium		

*LMD = Layered Marine Deposits

SECTION 4

TEST RESULTS

4.1 CRATER.

The depth of the crater, d_k , which is formed at the detonation of the charge has been measured with a caliper rule. Note that, with our test set-up, the true crater depth is measured, because the loose crater material can no longer fall back into the crater, as it is the case with free field tests. A definition of apparent and true crater depths, respectively, is given in Figure 4 (Ref. [3]). The crater volume, V_k , was determined by several methods: (1) by difference in weight of the soil material before and after the experiment, (2) by weight of soil material found after the test in the explosion chamber, (3) by filling the crater with fine grained sand and determining its weight, ΔG . The last method proved to be the most accurate and was applied in most cases. Since the specific weight of the used sand, γ_{sand} , was determined before, we find:

$$(Eq.1) \quad V_k = \Delta G / \gamma_{\text{sand}}$$

In Tables 3 to 5 the crater depth and crater volume are given for the three soil materials under consideration.

4.1.1 Crater Form.

Some photographs of craters at different DOB have been compiled in Figure 5 for the porous, crushable aerated grout (dry YTONG) and in Figure 6 for the water-saturated grout (wet YTONG), respectively. It was not possible to extricate the clay/loam material from the steel tube without destruction of the form.

Figures 7 to 9 depict some typical crater cross sections, measured mostly according to eye judgement. The crater form turned out to be axially symmetrical in all experiments. It is remarkable that in about one third of the DOB an edge exists that is more or less distinct for dry YTONG and wet YTONG. For clay/loam material the crater is more trough-shaped. In contrast to the crushable YTONG the clay/loam material shows a more viscous behavior. It also has to be pointed out that the experiments at the same DOB show relative small scatter in the crater dimensions.

Table 3 Crater Depth and Crater Volume for dry YTONG

Test No.	DOB [cm]	dk [cm]	Vk [cm ³]	SDOB [m/kg ^{1/3}]	Sdk [m/kg ^{1/3}]	SVk [m ³ /kg]
814	-2.0	0.6	4.26	-0.252	0.0756	0.0085
815	-1.0	1.2	8.33	-0.126	0.151	0.0167
723	-0.5	1.8	14.3	-0.063	0.227	0.0286
726		1.8	16.3		0.227	0.0326
747		1.95	15.6		0.246	0.0312
802		1.9	12.5		0.239	0.0250
804	-0.25	2.4	33.8	-0.0315	0.302	0.0683
722	0	2.7	32.2	0	0.340	0.0644
803		2.6	34.6		0.328	0.0692
736	0.15	2.9	70.9	0.0189	0.365	0.142
735	0.25	2.7	83.7	0.0315	0.340	0.167
737	0.5	3.1	76.7	0.063	0.391	0.153
738		3.0	85.7		0.378	0.171
809		3.2	85.1		0.403	0.170
717	1.0	4.0	-	0.126	0.504	-
740	1.5	5.0	163.1	0.189	0.630	0.326
712	2.0	5.3	-	0.252	0.668	-
713		5.3	-		0.668	-
719		5.0	177.1		0.630	0.354
741	2.5	5.9	179.1	0.315	0.743	0.358
742		6.0	194.9		0.756	0.390
816		4.9	165.4		0.617	0.331
718	3.0	6.4	197.1	0.378	0.806	0.394
720		6.2	193.0		0.781	0.386
721	4.0	7.2	223.2	0.504	0.907	0.446
724	5.0	8.5	307.4	0.630	1.071	0.615
725		9.0	315.8		1.134	0.632

Table 4 Crater Depth and Crater Volume for wet YTONG

Test No.	DOB [cm]	dk [cm]	V _k [cm ³]	SDOB [m/kg ^{1/3}]	Sdk [m/kg ^{1/3}]	SV _k [m ³ /kg]
768 783	-2.0	0.7 0.4	9.3 3.4	-0.237	0.083 0.50	0.019 0.0068
769	-1.0	1.5	13.7	-0.120	0.180	0.027
800 801	-0.5	1.7 1.85	10.4 10.7	-0.063	0.214 0.233	0.021 0.021
807	-0.25	2.7	29.9	-0.0315	0.340	0.060
805	0	2.4	41.4	0	0.302	0.083
784 808	0.25	2.8 3.4	98.0 86.4	0.0315	0.353 0.428	0.196 0.173
806	0.5	3.5	105.3	0.063	0.441	0.211
758 785	1.0	4.5 4.3	143.0 132.9	0.126	0.567 0.542	0.286 0.266
786 787	1.5	4.5 4.6	168.6 160.5	0.189	0.567 0.580	0.337 0.321
788 789	2.0	5.2 5.0	180.0 177.4	0.252	0.655 0.630	0.360 0.355
790 791	2.5	5.3 5.3	189.4 180.0	0.315	0.668 0.668	0.379 0.360
792 793	3.0	6.4 6.3	230.5 233.7	0.378	0.806 0.794	0.461 0.467
794 795	4.0	7.2 7.1	302.0 273.4	0.504	0.907 0.895	0.604 0.547
759 760	5.0	8.7 8.0	375.0 376.0	0.630	1.096 1.008	0.750 0.752

Table 5 Crater Depth and Crater Volume for Clay/Loam

Test No.	DOB [cm]	dk [cm]	Vk [cm ³]	SDOB [m/kg ^{1/3}]	Sdk [m/kg ^{1/3}]	SVk [m ³ /kg]
813	-2.0	1.3	9.4	-0.240	0.156	0.016
781	-1.0	2.6	40.2	-0.119	0.308	0.067
780	-0.5	3.0	73.7	-0.060	0.358	0.125
812	-0.25	3.1	115.5	-0.0303	0.376	0.206
777	0	3.3	145.3	0	0.416	0.291
767 776	0.5	3.6 3.5	165.8 162.0	0.062 0.063	0.445 0.444	0.313 0.331
762 811	1.0	3.9 3.8	155.1 171.8	0.126 0.124	0.491 0.470	0.310 0.324
766 796	1.5	4.0 5.0	190.6 223.0	0.188 0.199	0.501 0.662	0.374 0.519
761 773 774 775 810	2.0	4.0 4.7 4.6 3.8 4.8	230.0 207.9 188.4 248.6 217.6	0.237 0.254 0.252 0.252 0.247	0.474 0.596 0.580 0.479 0.593	0.383 0.424 0.377 0.497 0.411
765 797 798 799	2.5	5.2 4.8 4.6 4.6	228.2 285.0 229.0 207.0	0.315 0.262 0.313 0.321	0.655 0.503 0.576 0.591	0.456 0.328 0.449 0.440
763 771	3.0 3.5	6.0 6.2	261.2 301.2	0.368 0.441	0.737 0.781	0.484 0.602
764	4.0	6.6	279.0	0.494	0.816	0.526
772	5.0	6.9	335.2	0.630	0.869	0.670

4.1.2 Crater Depth.

Figures 10 to 12 show the crater depth for the three different soil materials as function of depth-of-burst. At linear approximation, the relation between crater depth, d_k , and DOB is described in scaled dimensions by:

$$\text{(Eq. 2)} \quad \text{dry YTONG} \quad d_k = 0.328 + 1.226 * \text{DOB}$$

$$\text{(Eq. 3)} \quad \text{wet YTONG} \quad d_k = 0.347 + 1.137 * \text{DOB}$$

$$\text{(Eq. 4)} \quad \text{Clay/Loam} \quad d_k = 0.382 + 0.789 * \text{DOB}$$

where $[d_k] = \text{m/kg}^{1/3}$ and $[\text{DOB}] = \text{m/kg}^{1/3}$. In the Figures are also scales for $[d_k] = \text{cm}$ and $[\text{DOB}] = \text{cm}$, valid for 0.5-g NP charges.

Figure 13 indicates that the crater depth curves for dry YTONG and wet YTONG respectively, are nearly identical, whereas the curve for clay/loam differs and shows a flatter course.

4.1.3 Crater Volume.

The diagrams, Figure 14 to 16, depict the crater volume for the three different soil materials as function of DOB. A linear approximation seems to be adapted to describe the material behavior. In scaled dimensions we get the following linear functions:

$$\text{(Eq. 5)} \quad \text{dry YTONG} \quad V_k = 0.110 + 0.782 * \text{DOB}$$

$$\text{(Eq. 6)} \quad \text{wet YTONG} \quad V_k = 0.141 + 0.882 * \text{DOB}$$

$$\text{(Eq. 7)} \quad \text{Clay/Loam} \quad V_k = 0.227 + 0.738 * \text{DOB}$$

where $[V_k] = \text{m}^3/\text{kg}$ and $[\text{DOB}] = \text{m/kg}^{1/3}$. In addition also scales $[V_k] = \text{cm}^3$ and $[\text{DOB}] = \text{cm}$ for 0.5-g NP charges are given.

In Figure 17 the results are summarized for the three different soil materials. The slope of the curves for dry YTONG and clay/loam are quite similar whereas wet YTONG shows a steeper slope.

$V_k(\text{DOB})$ and $d_k(\text{DOB})$ are approximated by linear functions. Normally one would expect a proportion $V_k(\text{DOB}) \sim (d_k(\text{DOB}))^3$, but in view of change of crater form with DOB and in view of the data scatter of crater depth and crater volume it seems to be acceptable to describe the DOB dependence to be linear for both quantities. It would seem also reasonable that the amount of charge energy absorbed by the cratering process would be linearly related to the crater volume. But one has also to consider that possibly the confinement of the soil by the steel tube influences the amount of crater volume. Hence Figure 17 indicates that the amount of charge energy, available to drive the airblast wave decreases with DOB. This is certainly born out by pressure measurements.

4.1.4 Crater Ejecta.

A single shadow-picture has been made for each DOB-test. In these photographs, the shock front is usually visible and also the crater ejecta can be seen as a black cone. Some typical cases for the three soil materials under consideration are given in Figures 18 to 20. For large DOB (≤ 3 cm; $0.38 \text{ m/kg}^{1/3}$) it is noticeable that big lumps of soil material are thrown out of the crater and gas jets appear between the lumps. In these cases, no shock front is visible. This leads one to assume that the pressure propagates in form of randomly distributed compression waves.

To get a better idea of the crater ejecta kinematics and of the shock wave formation, some cinematographic pictures were taken with a Cordin framing camera (type 330). Compared with single-picture photographs (e.g., Figures 18 to 20), the quality of the individual frames of the film is worse. The spacial resolution power is substantially smaller and the exposure time is somewhat longer. Nevertheless the two picture series, Figures 21 and 22, give interesting information. Both tests were made at DOB = 2.5 cm ($= 0.315 \text{ m/kg}^{1/3}$), one in dry YTONG, the other in clay/loam. In these examples two shock fronts are clearly visible. For the dry aerated grout case (dry YTONG) the two shock fronts combine after a while (see pictures b to f of Figure 21), while for the clay/loam case the two wave fronts remain separated. To evaluate the speed of the crater ejecta, the height of the ejecta vs time was measured vertical above surface zero. Time zero was assumed to be the first analysed picture of the film. In Figure 23 the distance-time curve is shown for clay/loam. The approximation was made with a curve of second order. Differentiation gives the approximation function of the ejecta velocity. Although the speed is somewhat sensitive to the chosen approximation function for distance-time data, one nevertheless finds a maximum speed of 250 - 300 m/s. In the first 200 μs , the ejecta velocity increases; later the speed decays, because of decreasing of the pushing force. This is evident. The gas cloud of the HE-charge penetrates the crater ejecta and therefore their overpressure is reduced considerably. In the time interval shown in

Figure 23 the influence of gravity is negligible. In $500 \mu\text{s}$ a mass would reach a speed of about 5 mm/s. Therefore, the influence of gravity (due to the fact that the tests are made upside down) is negligible for the data reported here.

4.1.5 Comparison with Results of Real Soil Materials.

To investigate how the measured values fit in with the results for real soil, data were used from Reference [3]. Figure 24 shows a comparison of the crater depth in dry aerated grout with other soil materials. In [3] the crater depths are scaled with $W^{5/16}$, so that this scale was chosen for the conversion of our data. Of all the soil materials given in [3], sand or perhaps also alluvium have the closest resemblance to aerated grout although the density of both materials is higher.

Considering that the EMI experiments determine the true crater depth and not the apparent one, the deviation from the real sand curve is absolutely plausible. As expected, for the same DOB, dry YTONG has a larger crater depth. It is also apparent that the slope of the two curves are similar.

As shown in Figure 13, the crater depth data of wet YTONG do not differ significantly from dry YTONG. Therefore, also the comparison with real soil material, Figure 25, shows the same trend as mentioned for dry YTONG.

The slope of the crater depth curve vs DOB for wet clay/loam differs from the YTONG curves (see Figure 13) and runs as shown in Figure 26, more parallel to dry clay soil or playa, which are most similar to the material we used. As mentioned earlier, our clay/loam material was wet. So it makes sense that the experiments give a smaller crater depth than the data of Reference [3] for dry clay at the same scaled DOB. In Figure 27 the linear approximation curves of crater depth vs DOB for the three materials are combined and shown together with real soil curves. We cannot expect complete agreement between the presented values and the curves of Reference [3] because of the different definition of crater depth (true versus apparent crater respectively) and because of the different soil materials used. But even real soil of the same kind can differ noticeably from one location to another.

Comparison of true crater depth with apparent crater depth curves of different real soil materials from Reference [11] is made in Figure 28. The linear approximation functions are used. Also here the deviations are as discussed above.

Extended DOB experiments (Stagecoach Project) with different charge weights for a single soil material are presented in Reference [12]. Charges of 216 lbs; 256 lbs; 2560 lbs; 3000 lbs; 40000 lbs; 2.4×10^6 lbs (nuclear) were used. Our charge of 0.5-g corresponds to 1.1×10^{-3} lbs. The soil is described as Nevada desert alluvium. Different scalings of crater dimensions are used in [12], namely $W^{1/4}$ and $W^{0.3}$. Moreover, we have added $W^{5/16}$ (as applied in [3]) and $W^{1/3}$ scaling (as used mostly in explosion modelling).

Of primary interest in the Stagecoach experiments was the critical examination of scaling laws for crater dimensions resulting from buried explosions. Examination of cratering phenomena by means of dimensional analysis and by model experiments produced the result that crater dimensions from explosions were proportional to the $1/3$ power of the explosion energy. Experiments with large chemical explosives and large nuclear explosions gave some indications that cube root scaling is not strictly valid over wide ranges of explosion energy. If lithostatic pressure is much greater than atmospheric pressure, forth root scaling prevails. For certain ranges of explosion energies W^m -scaling is expected, where $1/4 \leq m \leq 1/3$.

In Figures 29 to 34, a comparison is made with the data of Reference [12] and our data. Compared are crater depth and crater volume using the aforementioned four different scaling procedures. Concerning the slope, the dry aerated grout data for crater depth agree best with the desert alluvium values. Also water saturated aerated grout data show quite a good agreement with the slope of desert alluvium curves. As expected, the slope for clay/loam differs significantly.

The crater volume data may be influenced by the steel tube used to hold the soil material (see Figure 1). But one must also take into account that the data of our experiments are related to the true crater. It is not to be expected that the volumes of true and apparent craters are related proportionally. Then, the slope of the corresponding curves will be different.

We conclude that the small charge DOB test data of the true crater give the right order of magnitude, compared with real soil material. They show the same slope as actual soil materials used in tests with much larger charges. $W^{1/3}$ -scaling is adequate to compare the crater dimensions of different tests.

4.2 Airblast Environments.

The airblast was measured at 16 different places on the surface (see Figure 3). Figure 35 gives an example of a pressure-time record and demonstrates that not only the positive overpressure impulse, $I_+ = \int p dt$ is recorded, but also the time of arrival of the shock front. The positive phase duration of the blast can also be inferred from the records.

4.2.1 Pressures.

4.2.1.1 Wave Forms. Several pressure-time records of the three different soil materials are presented in Figures 36 to 41. Figures 36, 38, and 40 demonstrate the decay of peak overpressure as function of distance from ground zero (GZ) at three different depths of burst (DOB). The influence of DOB onto the blast overpressure is shown in Figures 37, 39, 41 respectively. Note that the scale of the different recording curves changes, because the peak overpressure varies strongly with distance and DOB.

For small DOB ($0 \leq \text{DOB [cm]} < 1.5$), the pressure-time curves are similar to an ideal Friedlander function and shows no disturbances. The shock front is steep. There are no signs of compression waves running ahead of the main wave.

With increasing DOB, the character of the curves changes. One notes two phases of the pressure increase. The first plateau is created by the upward motion of the soil that acts like a piston. This fast moving piston (see Figure 23) creates a bow wave. Also cracks are formed through which some compressed smoke can escape. Depending on DOB, lumps are formed and are partly perforated with cracks and are finally hurled out of the crater clearing the way for a propagation of the main compression wave. This wave steepens up in a short time to a shock (second phase of pressure rise). The resulting shock front shape can be described as "porched shock front". It is a question of time when the main shock reaches the porch front. It is said in the literature that the first phase of the pressure rise is created also due to ground shock waves. In our case this explanation is unrealistic. The soil specimen is embedded in a steel tube. This tube is shock isolated from the plate containing the pressure gauges. Also these gauges are shock isolated (see Figure 1). Under these circumstances, no significant ground shock signal can be measured by the pressure gauges.

At $\text{DOB} > 3 \text{ cm}$ ($= 0.378 \text{ m/kg}^{1/3}$) the lumps of the crater material keep increasingly prevent an uninterrupted propagation of the compressed smoke, so that no uniform shock front can be formed. An accumulation of compression waves propagates.

This explanation of the three typical wave-forms is not only based on the pressure-time records, but also on the crater ejecta pictures (e.g., Figures 18 to 20) and high-speed film analyses (Figures 21 to 23).

Figure 42 shows domains of the different wave forms. They differ from material to material. The borders between the different domains are not precisely defined. They depend to a certain degree on judgement.

4.2.1.2 Peak Overpressures. The dependence of the peak overpressure on DOB and ground range is shown in scaled form in Figures 43 to 45. The data of different tests at the same DOB are included in these diagrams. So one can make sure of the reproducibility of different tests under same conditions.

4.2.1.2.1 Fit Functions. For each data set, fit functions in form of:

$$\begin{aligned} \text{(Eq. 8)} \quad \log p &= a_0 + a_1 * \log(\text{GR}) + a_2 * (\log(\text{GR}))^2 \\ 1 &\leq \text{GR} [\text{m/kg}^{1/3}] \leq 10 \end{aligned}$$

have been determined from the measured values according to the least square method. The solid lines in Figures 43 to 45 correspond to these functions. While the agreement of different experiments at the same DOB ($\text{DOB} < 3 \text{ cm}$; $(0.378 \text{ m/kg}^{1/3})$) is excellent, there are major deviations at larger DOB's. We assign this to the formation of crater ejecta which has a strong influence on the pressure curve due to the numerous compression waves. In addition, it is very problematic to compare the well defined peak overpressure of a blast wave with the more random maximum pressure of a porched shock front or of the sum of compression waves (see e.g., Figures 36 to 41).

Another reason for deviations for the clay/loam experiments might be that the charge position cannot be controlled as precisely as at YTONG tests. But small variations in DOB strongly influence the peak overpressure values.

The coefficients of the approximation function (Eq. 8) as function of DOB are shown in Figures 46 to 48. This dependency can be described by the following fit functions where third order polynomials in most cases are sufficient for estimation purposes. They are valid within the limits:

$$-0.25 \leq \text{DOB} (\text{m/kg}^{1/3}) \leq 0.63$$

Aerated Grout (dry YTONG):

$$(Eq. 9) \quad a_0 = 0.9516 - 3.9002 * DOB - 5.7415 * DOB^2 + 10.060 * DOB^3$$

$$(Eq. 10) \quad a_1 = -2.3816 + 5.5376 * DOB + 6.4823 * DOB^2 - 18.950 * DOB^3$$

$$(Eq. 11) \quad a_2 = 0.5881 - 2.5779 * DOB - 3.2815 * DOB^2 + 8.3900 * DOB^3$$

Water saturated Grout (wet YTONG):

$$(Eq. 12) \quad a_0 = 0.8596 - 4.8773 * DOB - 6.4067 * DOB^2 + 13.000 * DOB^3$$

$$(Eq. 13) \quad a_1 = -2.1271 + 5.8440 * DOB + 3.4900 * DOB^2 - 14.700 * DOB^3$$

$$(Eq. 14) \quad a_2 = 0.4339 - 2.5637 * DOB - 1.6757 * DOB^2 + 6.8500 * DOB^3$$

Wet Clay/Loam:

$$(Eq. 15) \quad a_0 = 0.7386 - 5.1257 * DOB - 4.8570 * DOB^2 + 14.650 * DOB^3$$

$$(Eq. 16) \quad a_1 = -1.7355 + 6.0377 * DOB - 2.9671 * DOB^2 - 11.750 * DOB^3$$

$$(Eq. 17) \quad a_2 = 0.1833 - 2.7668 * DOB + 2.3120 * DOB^2 + 5.1300 * DOB^3$$

where DOB is given in scaled values; (m/kg^{1/3})

4.2.1.2.2 Overpressure-Range Curves. The equations (Eq. 8) to (Eq. 17) allow one to evaluate the overpressure-range curve for any DOB in the given range. But one has to taken into account that the character of the curves changes within the range. In Figures 49 to 51 overpressure-range curves are presented together with the transition lines of the different pressure domains.

Strictly speaking, only peak overpressures of the DOB-blastwave regime can be compared with HOB results. The range of such comparisons remains limited. One should therefore not be surprised, if in other domains overpressure-range curves of different DOB come close together (see e.g. Figure 51). The term peak overpressure has a different meaning in the other regimes (i.e., front porch regime and compression wave regime).

4.2.1.2.3 Estimation of Energy Absorption by Cratering Processes. In Reference [2], a free-air overpressure curve was given for the 0.5-g NP charges:

$$\begin{aligned} \text{(Eq. 18)} \quad \log p &= 1.047 - 2.289 * \log R && \text{for } 0.9 < R \leq 2.45 \\ &= 0.954 - 2.253 * \log R + 0.427 * (\log R)^2 && \text{for } 2.45 < R \leq 9.8 \end{aligned}$$

For an ideal surface burst the so-called 2W-assumption is made. This means, in a given distance, GR, from ground zero of an ideal surface burst, the same peak overpressure exists as in the same distance, R, of a free air explosion of the double charge weight (i.e., double the energy content). Or, related to the same charge weight: $GR = (2^{1/3}) R$. If the peak overpressure at the soil surface of a DOB test is compared with the result of a corresponding ideal surface experiment, the energy portion can be estimated, needed for the cratering processes and other energy absorbing mechanisms.

The Cranz- or Hopkinson-similarity law for explosions says:

"The ground range distances GR_1 and GR_2 with the same overpressure in a geometrical similar arrangement of two different explosions are proportional to the cube root of the corresponding charge weight".

$$\text{(Eq. 19)} \quad GR_1/W_1^{1/3} = GR_2/W_2^{1/3}$$

For a given distance R the peak overpressure p_1 for ideal surface condition is calculated, applying equation Eq. 18. Then, for a given DOB test, the distance GR_2 is determined by applying Eq. 8, where the same pressure $p_2 = p_1$ exists. The corresponding charge weight is evaluated by the similarity law, (Eq. 19). Under the assumption that the effective charge weight W_2 is reduced by energy absorbing processes such as cratering, we find:

$$\text{(Eq. 20)} \quad \frac{GR_1}{W_1^{1/3}} = \frac{2^{1/3} \cdot R}{W_1^{1/3}} = \frac{GR_2}{(W_1 - \Delta W)^{1/3}}$$

or

$$\text{(Eq. 21)} \quad \frac{\Delta W}{W} = 1 - 0.5 \left(\frac{GR_2}{R} \right)^3$$

For the three soil materials, the evaluated energy loss vs ground range is shown in Figures 52 to 54.

We conclude that the energy loss, based on the peak blast wave pressure is not constant; it varies with ground range. All the curves have a tendency to decrease with increasing ground range. This indicates that the peak pressure is not uniformly distributed in space. As demonstrated by photographs in section 4.1.4, the shock strength at DOB tests is favoured in vertical direction in the first phase of blast propagation. At later times an equalizing process takes place. As a consequence, the pressure near surface increases relatively with ground range, reducing the apparent energy loss.

At HOB tests ($DOB \leq 0$), the energy loss increases with ground range at short distances from GZ. Due to cratering processes energy is transmitted to the soil; rarefaction waves are created and follow the shock front. The peak overpressure is reduced and the evaluated energy loss is increased.

Differences for dry and wet YTONG in the HOB-region are caused by the porosity. The pores of wet YTONG are water-filled and can only absorb a small amount of compressed gas of the blast wave. This may explain the fact that energy losses for dry YTONG are higher than in wet YTONG. Differences in the DOB-region of this two materials may be also be influenced by the higher density or by the weight of the overburden layer. The same tendency can be noticed for wet clay/loam.

For different ground range positions, the percentage of energy losses is given in Figures 55 to 57 as function of DOB. The curves are relatively close together and indicate that for these soil materials the energy loss at $DOB = 0$ [$m/kg^{1/3}$] is about 50 %. Also note that for small heights of burst (e.g., $HOB = 1 D$), a significant amount of the charge energy (20 - 30 per cent) is lost from the blast wave and absorbed in the soil material. The ideal-surface assumption is not a good approximation in this regime.

4.2.1.2.4 Isobaric DOB-Curves. Figure 58 shows isobaric height-of-burst curves for a hydrodynamically smooth surface, completed with DOB-curves for dry aerated grout in the intermediate-pressure regime (taken from Reference [2], Figure 27). With increasing DOB, the extremely strong attenuation of the blast wave is clearly visible. In Figure 58 an area is also marked ($0.3 \leq HOB (m/kg^{1/3}) \leq -0.2$; $0 \leq GR (m/kg^{1/3}) \leq 5$) indicating the range where the isobaric DOB data in the intermediate-pressure regime are presented in the following diagrams.

The isobaric DOB diagrams are given in Figures 59 to 61 in the intermediate-pressure regime, whereas Figures 62 to 64 show these curves in the low-pressure regime. In the diagrams the scales for HOB and GR are not the same. The correlated data points are linked with fit curves.

In Figures 65 to 68 the isobaric DOB curves of the three soil materials are compared. In addition, in Figures 65 and 66 also the isobaric HOB curves for a hydrodynamically smooth surface are shown. All isobaric curves for the three soil materials deviate from the smooth surface results below $\text{HOB} \leq 0.25 \text{ (m/kg}^{1/3}\text{)}$. This value is also about the limit where crater formation in the soil material is observed. The most significant deviation is found in the range $0 < \text{HOB (m/kg}^{1/3}\text{)} < 0.1$. Here the isobaric curves - especially of dry aerated grout - show a bulge, compared to the other materials. We believe that the porosity of the material is the reason. Gas is pressed into the pores, reducing the remaining energy to drive the shock wave. Also at the estimation of the energy losses (section 4.2.1.2.3), the tendency of highest energy losses at aerated grout in this region was noticed.

In the diagrams of Figures 65 to 68 also the transition lines are indicated between regions of different wave forms. Strictly speaking, the isobaric DOB curves can only be compared in the blast wave regime.

4.2.2 Overpressure Impulses.

4.2.2.1 Impulse-Range Curves. As demonstrated in Figure 35, not only the pressure time history was recorded, but also the overpressure impulse and the positive phase duration was measured. In Figure 69 to 71 diagrams of impulse vs. ground range for several DOB are shown. In general, the scatter of the data increase with DOB. This is not surprising if one recalls the complicated interactions between cratering processes and formation of the different wave systems in air. One should also remember that the pressure at the soil surface is used to determine the impulse of the positive overpressure phase.

4.2.2.2 Fit Functions. For each set of impulse-ground range data, fit functions of the form:

$$\begin{aligned} \text{(Eq. 22)} \quad \log I+ &= b_0 + b_1 * \log \text{GR} + b_2 * (\log \text{GR})^2 \\ &1 \leq \text{GR [m/kg}^{1/3}\text{]} \leq 10 \end{aligned}$$

have been determined, according to the least square method. The coefficients of the fit functions depend on DOB. Using a third order polynomial approximation, they can be depicted by the following functions, where

$$-0.25 \leq \text{DOB} [\text{m/kg}^{1/3}] \leq 0.63$$

Dry Aerated Grout (dry YTONG)

$$(\text{Eq. 23}) \quad b_0 = 0.1765 - 1.9620 * \text{DOB} - 1.7172 * \text{DOB}^2 + 4.9040 * \text{DOB}^3$$

$$(\text{Eq. 24}) \quad b_1 = -0.5949 + 2.0708 * \text{DOB} - 1.6700 * \text{DOB}^2 - 6.4450 * \text{DOB}^3$$

$$(\text{Eq. 25}) \quad b_2 = -0.2009 - 1.2159 * \text{DOB} + 1.0193 * \text{DOB}^2 + 2.4320 * \text{DOB}^3$$

Water Saturated Grout (wet YTONG)

$$(\text{Eq. 26}) \quad b_0 = 0.0951 - 2.3065 * \text{DOB} - 0.7824 * \text{DOB}^2 + 3.0855 * \text{DOB}^3$$

$$(\text{Eq. 27}) \quad b_1 = -0.4737 + 1.8461 * \text{DOB} - 3.6947 * \text{DOB}^2 + 0.5210 * \text{DOB}^3$$

$$(\text{Eq. 28}) \quad b_2 = -0.2726 - 1.0104 * \text{DOB} + 1.5717 * \text{DOB}^2 + 1.3135 * \text{DOB}^3$$

Wet Clay/Loam

$$(\text{Eq. 29}) \quad b_0 = 0.0974 - 2.2366 * \text{DOB} - 1.0388 * \text{DOB}^2 + 4.0740 * \text{DOB}^3$$

$$(\text{Eq. 30}) \quad b_1 = -0.3835 + 1.9128 * \text{DOB} - 4.1936 * \text{DOB}^2 + 2.3850 * \text{DOB}^3$$

$$(\text{Eq. 31}) \quad b_2 = -0.3514 - 0.9747 * \text{DOB} + 3.3949 * \text{DOB}^2 - 4.1055 * \text{DOB}^3$$

DOB is given in scaled values; $[\text{m/kg}^{1/3}]$

Logarithmic plots of impulse-range curves for different DOB are presented in Figures 72 to 74.

4.2.2.3 Iso-Impulse DOB Curves. By means of fit functions for the impulse of the positive overpressure phase, the distances to a given impulse value can be determined. Some scaled iso-impulse DOB curves are arranged in Figures 75 to 77 for the three soil materials.

4.2.3 Arrival Times.

4.2.3.1 Arrival-Time - Range Curves. Zero time is defined as time of charge ignition. In the pressure records (see Figure 35) the arrival of the shock front can easily be detected in the blast wave regime. More uncertainty exists in the compression wave regime.

Arrival-time-range curves are shown in Figures 78 to 80. It is evident that the curves start with a delay, depending on DOB. This time delay is mainly caused by the clearing time needed before the cloud of the detonated charge can escape and expand and drive the blast wave.

4.2.3.2 Fit Functions. For each set of time of arrival data, fit functions of the form:

$$(Eq. 32) \quad t_a = c_1 * \log GR + c_2/GR + GR/c_0 + c_3$$

$$1 \leq GR [m/kg^{1/3}] \leq 10$$

have been determined, according to the least square method, where c_0 means sound speed in air and t_a and GR are given in cube-root scaled values. The coefficients depend on DOB. Using a third order polynomial approximation, they can be represented by the following functions in the interval, where

$$-0.25 \leq DOB [m/kg^{1/3}] \leq 0.63$$

Dry Aerated Grout (dry YTONG)

$$(Eq. 33) \quad c_1 = -3.807E-3 + 6.132E-3 * DOB + 3.462E-3 * DOB^2 + 1.891E-2 * DOB^3$$

$$(Eq. 34) \quad c_2 = 1.242E-3 - 6.820E-3 * DOB - 1.457E-2 * DOB^2 + 6.289E-2 * DOB^3$$

$$(Eq. 35) \quad c_3 = -3.360E-3 + 1.018E-2 * DOB + 2.461E-2 * DOB^2 - 5.461E-2 * DOB^3$$

Water Saturated Grout (wet YTONG)

$$(Eq. 36) \quad c_1 = -4.204E-3 + 1.166E-2 * DOB + 2.190E-2 * DOB^2 - 5.648E-2 * DOB^3$$

$$(Eq. 37) \quad c_2 = 7.017E-4 - 2.751E-3 * DOB + 6.626E-3 * DOB^2 - 1.503E-2 * DOB^3$$

$$(Eq. 38) \quad c_3 = -2.677E-3 + 8.172E-3 * DOB + 1.478E-3 * DOB^2 - 9.124E-2 * DOB^3$$

Wet Clay/Loam

$$(Eq. 39) \quad c_1 = -4.333E-3 + 9.811E-3 * DOB + 1.475E-2 * DOB^2 - 3.127E-2 * DOB^3$$

$$(Eq. 40) \quad c_2 = 6.023E-4 - 4.668E-3 * DOB - 3.999E-4 * DOB^2 + 1.211E-2 * DOB^3$$

$$(Eq. 41) \quad c_3 = -8.024E-4 + 6.186E-3 * DOB - 2.409E-2 * DOB^2 + 2.300E-2 * DOB^3$$

where DOB is given in scaled values; $[m/kg^{1/3}]$

Logarithmic plots of arrival time - range curves are presented in Figures 81 to 83.

4.2.3.3 Iso-Arrival Time DOB Curves. By means of fit functions for time of arrival curves, the ground range for a constant arrival time can be determined. Constant arrival time DOB curves are shown in Figures 84 to 86 for the three soil materials.

4.2.3.4 Independent Evaluation of Peak Overpressure. Arrival time data can be used to evaluate, independently from pressure measurements, peak overpressure range curves. The propagation speed of the shock front is obtained by time differentiation of the function $GR = GR(ta)$. This speed is directly related to the peak overpressure of the shock front. It is evident that this method works properly only in the blast wave regime.

As approximation function is used:

$$(Eq. 42) \quad GR = d_1 * \log ta + d_2/ta + c_0 * ta + d_3$$

where c_0 = sound speed and ta and GR are given in cube-root scaled values. The propagation speed of the shock front is then:

$$\text{Eq. 43)} \quad dGR/dt_a = c_0 + d_1/(t_a * \ln 10) - d_2/t_a^2$$

If ideal gas conditions are assumed, the shock Mach number is

$$\text{(Eq. 44)} \quad M_s = W/c_0 \quad (W = \text{shock front speed})$$

and the shock strength

$$\text{(Eq. 45)} \quad P_{10} = (7 * M_s^2 - 1)/6 = (p + p_0)/p_0$$

(p = overpressure; p₀ = ambient pressure)

Or the peak overpressure

$$\text{(Eq. 46)} \quad p = p_0 * (M_s^2 - 1) * 7/6$$

This procedure was applied to the arrival time data. Some results are presented in the diagrams of Figures 87 to 89. The upper diagrams show the measured t_a values at different ground ranges, approximated by the function (Eq. 42). From this specific function, the velocity of the shock front is determined, applying (Eq. 43). In the lower diagrams, the calculated overpressure-range function (Eq. 44 to Eq. 46) is plotted. The peak overpressures are also given, measured by pressure gauges.

We conclude that the calculated pressure-range curves, based on the arrival time data, approximate very well the measured peak overpressures in the blast wave region. Both independent methods give the same values and prove that our gauges are able to accurately measure these blastwave pressures.

4.2.4 Positive Phase Durations.

4.2.4.1 Duration-Range Curves. The duration of the positive overpressure phase of a blast wave is a quantity that cannot be measured very precisely. The intersection of overpressure curve and zero pressure line (abscissa of pressure time record) is often very flat. Small shifts of the zero line have a great influence on the intersection point and therefore on the time duration. Also the crater ejecta formation with the different compression and rarefaction waves influence strongly the measured duration values.

Measured time duration-range results are presented in Figures 90 to 92. As expected, the scatter of the data larger than for other quantities of the blast wave. Especially at large DOB, the measured values vary considerably. But on the other side, the interval of the time data is comparably limited. At $DOB \geq 3 \text{ cm}$ ($0.378 \text{ m/kg}^{1/3}$) the duration of the positive overpressure phase is practically constant.

4.2.4.2 Fit Functions. For each set of time duration-range data, fit functions of the type:

$$\begin{aligned} \text{(Eq. 47)} \quad \log t+ &= e_0 + e_1 * \log GR + e_2 * (\log GR)^2 \\ &1 \leq GR [\text{m/kg}^{1/3}] \leq 10 \end{aligned}$$

have been determined, according to the least square method. Using a third order polynomial as fit function for the coefficient of equation (Eq. 47), the following functions were obtained in the interval:

$$-0.25 \leq DOB [\text{m/kg}^{1/3}] \leq 0.63$$

Dry Aerated Grout (dry YTONG)

$$\text{(Eq. 48)} \quad e_0 = -3.030 + 0.8294 * DOB + 1.9510 * DOB^2 - 1.6230 * DOB^3$$

$$\text{(Eq. 49)} \quad e_1 = 0.9863 - 0.3838 * DOB - 7.5028 * DOB^2 + 10.295 * DOB^3$$

$$\text{(Eq. 50)} \quad e_2 = -0.3326 - 0.59361 * DOB + 4.7449 * DOB^2 - 6.7200 * DOB^3$$

Saturated Aerated Grout (wet YTONG)

$$\text{(Eq. 51)} \quad e_0 = -3.1492 + 1.2350 * DOB + 4.9975 * DOB^2 - 5.4100 * DOB^3$$

$$\text{(Eq. 52)} \quad e_1 = 1.2532 - 1.8612 * DOB - 7.8808 * DOB^2 + 12.890 * DOB^3$$

$$\text{(Eq. 53)} \quad e_2 = -0.5343 + 0.2599 * DOB + 4.1609 * DOB^2 - 5.2500 * DOB^3$$

Wet Clay/Loam

$$(Eq. 54) \quad e_0 = -3.0175 + 1.4429 * DOB + 3.5410 * DOB^2 - 5.3650 * DOB^3$$

$$(Eq. 55) \quad e_1 = 0.9166 - 1.4064 * DOB - 3.2040 * DOB^2 + 6.5600 * DOB^3$$

$$(Eq. 56) \quad e_2 = -0.2958 + 0.0122 * DOB + 0.8082 * DOB^2 - 1.5151 * DOB^3$$

where DOB, GR, t+ resp. are given in scaled values.

Logarithmic plots of duration-range curves are presented in Figures 93 to 95.

4.2.4.3 Iso-Duration DOB Curves. By means of fit functions for the duration curves, the ground range for a constant value of positive phase were determined. Scaled constant duration DOB curves are shown in Figures 96 to 98 for the three soil materials.

4.2.5 Comparison with Results of Free Field Tests.

To investigate how the laboratory data agree with free field measurements, some comparisons were made with results presented in Reference [12]. Extensive test results are very well presented there. The soil material was desert alluvium. Therefore it cannot be expected that complete agreement exists between the model tests with different soil materials and the free field experiments. In Reference [12] charges between 256 lbs (116 kg) and 40000 lbs (18400 kg) were used; also some nuclear explosion data are included, whereas in our experiments only 0.5-g charges were applied. What can be demonstrated by this comparison, we believe, is the consistency of the data sets and at least the agreement of the individual values in the right order of magnitude. A good indication for correct results of the model tests is the same tendency or the slope of the different curves.

4.2.5.1 Wave Forms. In Figure 99 results of two institutions, namely Ballistic Research Lab. Aberdeen Proving Ground (BRL), and Naval Ordnance Lab., Silver Spring, (NOL) are compared with our registration curves for two different DOB and ground ranges, resp. $W^{1/3}$ scaling was applied. Figure 99 demonstrates that also in laboratory small scale tests, depending on DOB, different wave forms exist. Not in detail, but in general the character of the wave shape is quite similar. At DOB = 3 cm ($= 0.38 \text{ m/kg}^{1/3}$) front porch blast waves exist but not at DOB = 1.5 cm ($= 0.19 \text{ m/kg}^{1/3}$). The same result is discovered at the free field tests. More examples for different wave forms are given in Figures 36 to 41.

Transition from one wave form to another is compared in Figure 100 for desert alluvium (Reference [12]) and dry aerated grout. The curves differ of course but the small scale values deviate in the whole range less than a factor of two. They show beyond it the same trend of dependency on ground range.

4.2.5.2 Peak Overpressures. For free field tests at two different DOB in desert alluvium, a diagram of peak overpressure vs ground range is shown in Figure 101, taken from [12]. Included are scaled curves for tests in aerated grout, water saturated grout and clay/loam, resp. Altogether, the conformity is acceptable, considering the different test conditions. Water saturated grout shows the closest agreement with desert alluvium. Also clay/loam differs not too much. This behavior can be noticed just so in Figure 102, where the overpressure suppression vs DOB of the different soil materials is shown. At aerated grout the weight of the overburden has the smallest value. So it is reasonable that the overpressure suppression is smaller compared with the other materials.

4.2.5.3 Impulses of Positive Overpressure Phase. A comparison of scaled overpressure impulse vs scaled ground range is made in Figure 103. The data of the free field tests are taken from Reference [12]. At and near the surface the curves for aerated grout and especially for water saturated grout are in a good agreement with the desert alluvium values. This is not so surprising because the influence of the soil for near-surface bursts is not so strongly pronounced. But even at $DOB = 1 \text{ [ft/lbs}^{1/3}]$ the wet YTONG data are within the scatter of the desert alluvium values. It is noteworthy that the slopes of the impulse curves for the different soil materials are nearly identical. Also the suppression of the blast impulse as function of DOB agrees very well, as shown in Figure 104 for water saturated grout (wet YTONG).

4.2.5.4 Arrival Times. Arrival time curves vs ground range are expected to be parallel at great distances because the shock strength of the blast is small and the propagation velocity approaches the sound speed. The influence of the soil material and of DOB are noticeable only near ground zero. In Figures 105 and 106 arrival time vs ground range curves for dry YTONG and wet, resp. are compared with 40000 lbs results at $DOB = 17 \text{ ft}$ and 34 ft for desert alluvium. The curves behave as expected. Due to the test conditions for YTONG experiments, direct ground-shock induced air shocks are not present.

4.2.5.5 Positive Phase Durations. As discussed earlier, the evaluation of the positive phase duration is not very accurate, especially in the region of porched shocks and compression waves. Nevertheless the comparison with desert alluvium results demonstrates that even for this quantity the results are quite similar as shown in Figures 107 and 108. Typically, the positive phase duration of dry aerated grout is smaller than for water saturated grout and clay/loam. The reason might be the smaller overburden mass at the same DOB. The clearing time of the crater is therefore shorter. The model tests show that at large DOB the positive phase duration is practically constant, which is in full agreement with the observations at free field experiments.

SECTION 5

CONCLUSIONS

- 1.) The tests have demonstrated the feasibility of performing airblast DOB experiments at laboratory scale.
- 2.) The data sets of airblast environments from buried HE charges for the three applied different materials are self consistent.
- 3.) The transition effects from HOB to DOB are documented for peak overpressure, overpressure impulse, arrival time and positive phase duration. Corresponding fit functions are given.
- 4.) Different mechanisms for airblast creation at DOB tests were demonstrated photographically. At small DOB the crater ejecta do not significantly influence the expansion of the explosion smoke. As a consequence, a blast wave is formed with a shape of a Friedlander function. At intermediate DOB the ejecta material acts like a moving piston. A bow wave is created before the detonation products can expand in free air. Then, a porched waveform is observed. At large DOB numerous randomly distributed compression waves are observed. These different regions are also found in free field tests.
- 5.) An estimate of the energy absorption due to cratering processes and specific material behavior is given. The energy losses, based on overpressure measurements, depend on DOB and ground range. At $DOB = 0$ about 50 % of the total energy are lost as driver for the blast wave.
- 6.) The comparison with numerous tests in desert alluvium shows that the data sets are self consistent. The deviations due to different soil materials and different charge weights are plausible and are self consistent.
- 7.) The laboratory-scale test method for DOB investigations is especially useful for parameter studies.

SECTION 6

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Figure 1 Installation of the 0.5-g charge into aerated grout and shock-isolated mounting of the set-up into the explosion chamber.

Figure 2 General view showing the construction of the soil material holder.

Figure 3 Position of the shock-isolated pressure gauges MK 1 to MK 16.

CHARGE GEOMETRYRADIUS DEPTH

HALF BURIED SPHERE

1.0

1.0

SURFACE TANGENT SPHERE

0.74

0.61

HEMISPHERE

0.97

1.08

Figure 4 Apparent crater dimensions of different charge geometries and definition of apparent and true crater depth, resp., [3]

Figure 6 Examples of craters in water saturated grout (wet YTONG) at different depths of burst.

Figure 7 True crater contours in aerated grout (dry YTONG).

Figure 7 Continued.

Figure 8 True crater contours in water saturated grout (wet YTONG).

Figure 8 Continued.

Figure 9 True crater contours in wet clay/loam.

Figure 9 Continued.

DOB = 4cm

DOB = 5cm

DOB = 2.5cm

DOB = 3.5cm

DOB = 1.5cm

DOB = 2cm

Figure 10 True crater depth in aerated grout (dry YTONG) vs depth of burst.

Figure 11 True crater depth in water saturated grout (wet YTONG) vs depth of burst.

Figure 12 True crater depth in wet clay/loam vs depth of burst.

Figure 14 True crater volume in aerated grout (dry YTONG) vs depth of burst.

Figure 15 True crater volume in water saturated grout (wet YTONG)

Figure 16 True crater volume in wet clay/loam vs depth of burst.

Figure 17 Comparison of the crater volume approximation curves

Figure 18 Examples of crater ejecta at different depths of burst in dry aerated grout (dry YTONG)
 (Δt = time difference between ignition and exposure)
 a) HOB = 2.0 cm ($-0.252 \text{ m/kg}^{1/3}$); $\Delta t = 500 \mu\text{s}$; Test 814
 b) HOB = 1.0 cm ($-0.126 \text{ m/kg}^{1/3}$); $\Delta t = 500 \mu\text{s}$; Test 815
 c) HOB = 0.5 cm ($-0.063 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 802

Figure 18 Continued.

- d) HOB = 0.25 cm ($-0.032 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 804
 e) DOB = 0 cm ($0 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 803
 f) DOB = 0.5 cm ($0.063 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 809

Figure 18 Concluded.

- g) DOB = 2.0 cm ($0.252 \text{ m/kg}^{1/3}$); $\Delta t = 1000 \mu\text{s}$; Test 713
- h) DOB = 4.0 cm ($0.504 \text{ m/kg}^{1/3}$); $\Delta t = 700 \mu\text{s}$; Test 721
- i) DOB = 5.0 cm ($0.630 \text{ m/kg}^{1/3}$); $\Delta t = 2000 \mu\text{s}$; Test 725

Figure 19 Examples of crater ejecta at different depths of burst in water saturated grout (wet YTONG)
 (Δt = time difference between ignition and exposure)
 a) HOB = 2.0 cm ($-0.252 \text{ m/kg}^{1/3}$); $\Delta t = 500 \mu\text{s}$; Test 783
 b) HOB = 0.5 cm ($-0.063 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 801
 c) HOB = 0.25 cm ($-0.032 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 807

Figure 19 Continued.

- d) $DOB = 0 \text{ cm}$ ($0 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 805
- e) $DOB = 0.5 \text{ cm}$ ($0.063 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 806
- f) $DOB = 1.0 \text{ cm}$ ($0.126 \text{ m/kg}^{1/3}$); $\Delta t = 550 \mu\text{s}$; Test 758

g)

h)

i)

Figure 19 Concluded.

- g) DOB = 2.0 cm ($0.252 \text{ m/kg}^{1/3}$); $\Delta t = 800 \mu\text{s}$; Test 788
- h) DOB = 3.0 cm ($0.378 \text{ m/kg}^{1/3}$); $\Delta t = 1500 \mu\text{s}$; Test 793
- i) DOB = 4.0 cm ($0.504 \text{ m/kg}^{1/3}$); $\Delta t = 1700 \mu\text{s}$; Test 795

Figure 20 Examples of crater ejecta at different depths of burst in clay/loam (Δt = time difference between ignition and exposure).

- a) HOB = 2.0 cm ($-0.240 \text{ m/kg}^{1/3}$); $\Delta t = 500 \mu\text{s}$; Test 813
- b) HOB = 0.5 cm ($-0.060 \text{ m/kg}^{1/3}$); $\Delta t = 300 \mu\text{s}$; Test 780
- c) HOB = 0.25 cm ($-0.030 \text{ m/kg}^{1/3}$); $\Delta t = 600 \mu\text{s}$; Test 812

Figure 20 Continued.

- d) DOB = 0 cm ($0 \text{ m/kg}^{1/3}$); $\Delta t = 300 \mu\text{s}$; Test 777
 e) DOB = 0.5 cm ($0.063 \text{ m/kg}^{1/3}$); $\Delta t = 650 \mu\text{s}$; Test 776
 f) DOB = 1.0 cm ($0.126 \text{ m/kg}^{1/3}$); $\Delta t = 550 \mu\text{s}$; Test 762

Figure 20 Concluded.

- g) DOB = 2.0 cm ($0.247 \text{ m/kg}^{1/3}$); $\Delta t = 800 \mu\text{s}$; Test 810
- h) DOB = 3.0 cm ($0.368 \text{ m/kg}^{1/3}$); $\Delta t = 1000 \mu\text{s}$; Test 763
- i) DOB = 4.0 cm ($0.494 \text{ m/kg}^{1/3}$); $\Delta t = 1200 \mu\text{s}$; Test 764

a)

b)

c)

d)

Figure 21 Picture sequence of a high-speed film showing the movement of the crater ejecta and the shock wave formation. Test 816
 Soil material: dry aerated grout (dry YTONG); DOB = 2.5 cm ($0.315 \text{ m/kg}^{1/3}$)
 a) $t = 0 \mu\text{s}$; b) $t = 30 \mu\text{s}$; c) $t = 60 \mu\text{s}$; d) $t = 90 \mu\text{s}$

Figure 21

Continued.

e) $t = 120 \mu s$; f) $t = 150 \mu s$; g) $t = 180 \mu s$; h) $t = 210 \mu s$

Figure 22 Picture series of a high-speed film showing the movement of the crater ejecta and the shock wave formation. Test: 799
 Soil material: wet clay/loam; DOB = 2.5 cm ($0.315 \text{ m/kg}^{1/3}$)
 a) $t = 0 \mu\text{s}$; b) $t = 30 \mu\text{s}$; c) $t = 60 \mu\text{s}$; d) $t = 120 \mu\text{s}$

Figure 22 Continued.
e) $t = 180 \mu s$; f) $t = 240 \mu s$; g) $t = 300 \mu s$; h) $t = 360 \mu s$

Figure 23 Position and velocity of crater ejecta
 Soil material: wet clay/loam
 DOB = 2.5 cm ($0.315 \text{ m/kg}^{1/3}$). Test 799

Figure 24 True crater depth vs DOB for dry aerated grout (dry YTONG) compared with apparent crater depth of real soil materials [3].

Figure 25 True crater depth vs DOB for water-saturated grout (wet YTONG) compared with apparent crater depth of real soil materials [3].

Figure 26 True crater depth vs DOB at wet clay/loam compared with apparent crater depth of real soil materials [3].

Figure 27 Comparison of linear approximation curves for true crater depth with apparent crater depth of real soil material [3].

Figure 28 Comparison of measured true crater depth with apparent crater depth of different soil material [Ref. 11].

Figure 29 True crater depth vs DOB for dry YTONG compared with apparent crater depth of desert alluvium [12].
 left diagram: $W^{1/4}$ scaling
 right diagram: $W^{0.3}$ scaling

Figure 29

Continued.
left diagram:
right diagram:

$W^{5/16}$ scaling
 $W^{1/3}$ scaling

Figure 30 True crater depth vs DOB at wet YTONG compared with apparent crater depth at desert alluvium [12].
left diagram: $W^{1/4}$ scaling
right diagram: $W^{0.3}$ scaling

Figure 30

Continued
 left diagram:
 right diagram:

W^{5/16} scaling
 W^{1/3} scaling

Figure 31 Continued.
left diagram:
right diagram:

$W^{5/16}$ scaling
 $W^{1/3}$ scaling

Figure 32 True crater volume vs DOB for dry YTONG compared with apparent crater volume of desert alluvium [12]
left diagram: $W^{1/4}$ -scaling
right diagram: $W^{0.3}$ -scaling

Figure 32 Continued.
left diagram:
right diagram:

$W^{5/16}$ scaling
 $W^{1/3}$ scaling

Figure 33

True crater volume vs DOB for wet YTONG compared with
apparent crater volume of desert alluvium [12]

left diagram:

$W^{1/4}$ -scaling

right diagram:

$W^{0.3}$ -scaling

Figure 33 Continued.
left diagram:
right diagram:

$W^{5/16}$ scaling
 $W^{1/3}$ scaling

Figure 34

True crater volume for DOB at clay/loam compared with
apparent crater volume of desert alluvium [12]

left diagram: $W^{1/4}$ -scaling
right diagram: $W^{0.3}$ -scaling

Figure 34 Continued.
left diagram:
right diagram:

$W^{5/16}$ scaling
 $W^{1/3}$ scaling

071704.kMM/G9/NV Mk 4 1bar/V an LVer

I+ = +26.594 mbar*ms
 t+ = +214.500 μs
 t0 = +1000.000 μs (+1000.0 Vmax - Pstart 199.1)
 pmax = 1346.60 mbar

Figure 35

Example of a pressure-time record.

DOB = 1.0 cm Distance from GZ: 27 cm

Soil material: dry aerated grout (dry YTONG)

Test No.: 717/4

Peak overpressure, time of arrival, positive phase duration and positive impulse resp. are recorded.

Figure 36 Comparison of pressure-time records at various distances
 Charge weight: 0.5 g
 Distance from GZ 15 cm ($1.89 \text{ m/kg}^{1/3}$); 27 cm ($3.40 \text{ m/kg}^{1/3}$)
 39 cm ($4.91 \text{ m/kg}^{1/3}$); 57 cm ($7.18 \text{ m/kg}^{1/3}$)
 Soil material: dry aerated grout (dry YTONG)
 DOB: 1 cm ($0.126 \text{ m/kg}^{1/3}$)
 Test No.: 717/2; 717/4; 717/6; 717/9

Figure 36 Continued:
 DOB: 2 cm ($0.252 \text{ m/kg}^{1/3}$)
 Test No.: 719/2; 719/4; 719/6; 719/9

Figure 36

Concluded:

DOB: 3 cm ($0.378 \text{ m/kg}^{1/3}$)

Test No.: 720/2; 720/4; 720/6; 720/9

DOB = 1cm

2cm

3cm

Figure 37

Comparison of pressure-time records at different DOB
 Soil material: dry aerated grout (dry YTONG)
 Distance from GZ 15 cm ($1.89 \text{ m/kg}^{1/3}$)
 Test No.: 717/2; 719/2; 720/2

DOB = 1cm

2cm

3cm

Figure 37

Continued:

Distance from GZ 27 cm ($3.40 \text{ m/kg}^{1/3}$)

Test No.: 717/4; 719/4; 720/4

DOB = 1cm

2cm

3cm

Figure 37

Continued:
 Distance from GZ 39 cm ($4.91 \text{ m/kg}^{1/3}$)
 Test No.: 717/6; 719/6; 720/6

DOB = 1cm

2cm

3cm

Figure 37

Concluded:

Distance from GZ 57 cm ($7.18 \text{ m/kg}^{1/3}$)

Test No.: 717/9; 719/9; 720/9

Figure 38

Comparison of pressure-time records at various distances

Charge weight: 0.5 g

Distance from GZ

15 cm (1.89 m/kg^{1/3}); 27 cm (3.40 m/kg^{1/3})39 cm (4.91 m/kg^{1/3}); 63 cm (7.94 m/kg^{1/3})

Soil material: water-saturated grout (wet YTONG)

DOB: 1.0 cm (0.125 m/kg^{1/3})

Test No.: 758/2; 758/4; 758/6; 758/10

Figure 38 Continued: -
 DOB: 2.0 cm ($0.252 \text{ m/kg}^{1/3}$)
 Test No.: 789/2; 789/4; 789/6; 789/10

Figure 38

Concluded:
 DOB: 3.0 cm ($0.378 \text{ m/kg}^{1/3}$)
 Test No.: 792/2; 792/4; 792/6; 792/10

DOB = 1cm

2cm

3cm

Figure 39 Comparison of pressure-time records at different DOB
 Soil material: water saturated grout (wet YTONG)
 Distance from GZ: 15 cm ($1.89 \text{ m/kg}^{1/3}$)
 Test No. 758/2; 789/2; 792/2

DOB = 1cm

2cm

3cm

Figure 39

Continued:

Distance from GZ: 27 cm ($3.40 \text{ m/kg}^{1/3}$)

Test No. 758/4; 789/4; 792/4

DOB = 1cm

2cm

3cm

Figure 39

Continued:
 Distance from GZ: 39 cm ($4.91 \text{ m/kg}^{1/3}$)
 Test No. 758/6; 789/6; 792/6

DOB = 1cm

2cm

3cm

Figure 39

Concluded:

Distance from GZ: 63 cm ($7.94 \text{ m/kg}^{1/3}$)

Test No. 758/10; 789/10; 792/10

Figure 40 Comparison of pressure-time records at various distances
 Charge weight: 0.53 g
 Distance from GZ: 15 cm ($1.85 \text{ m/kg}^{1/3}$); 27 cm ($3.33 \text{ m/kg}^{1/3}$)
 39 cm ($4.81 \text{ m/kg}^{1/3}$); 63 cm ($7.77 \text{ m/kg}^{1/3}$)
 Soil material: wet clay/loam
 DOB: 1.0 cm
 Test No.: 811/2; 811/4; 811/6; 811/10

Figure 40

Continued:

Charge weight: 0.53 g

DOB: 2.0 cm

Test No.: 810/2; 810/4; 810/6; 810/10

Figure 40

Concluded:

Charge weight: 0.54 g

DOB: 3.0 cm

Test No.: 763/2; 763/4; 763/6; 763/10

DOB = 1 cm

DOB = 2 cm

DOB = 3 cm

Figure 41

Comparison of pressure-time records at different DOB

Soil material: wet clay/loam

Distance from GZ: 15 cm ($1.85 \text{ m/kg}^{1/3}$)

Test No. 811/2; 810/2; 763/2

DOB = 1 cm

DOB = 2 cm

DOB = 3 cm

Figure 41

Continued:

Distance from GZ: 27 cm ($3.33 \text{ m/kg}^{1/3}$)

Test No. 811/4; 810/4; 763/4

DOB = 1 cm

DOB = 2 cm

DOB = 3 cm

Figure 41

Continued:
Distance from GZ: 39 cm ($4.81 \text{ m/kg}^{1/3}$)
Test No. 811/6; 810/6; 763/6

DOB = 1 cm

DOB = 2 cm

DOB = 3 cm

Figure 41

Concluded:

Distance from GZ: 63 cm ($7.77 \text{ m/kg}^{1/3}$)

Test No. 811/10; 810/10; 763/10

Figure 42 Domains of different wave forms for DOB in dry aerated grout (dry YTONG), water saturated grout (wet YTONG) and wet clay/loam.

Figure 43

Peak overpressure vs ground range at different DOB
Soil material: dry aerated grout (dry YTONG)

DOB = -1.0 cm DOB = 0.0 cm DOB = 1.0 cm
DOB = 2.0 cm DOB = 3.0 cm DOB = 4.0 cm

Figure 44

Peak overpressure vs ground range at different DOB

Soil material: water saturated grout (wet YTONG)

DOB = -1.0 cm

DOB = 0.0 cm

DOB = 1.0 cm

DOB = 2.0 cm

DOB = 3.0 cm

DOB = 4.0 cm

Figure 45

Peak overpressure vs ground range at different DOB
Soil material: clay/loam.

DOB = -1.0 cm DOB = 0.0 cm DOB = 1.0 cm
DOB = 2.0 cm DOB = 3.0 cm DOB = 4.0 cm

Figure 46 Coefficients a_i vs DOB of the approximation function
 $\log p = \sum_{i=0}^2 a_i (\log GR)^i$ for dry YTONG.

Figure 47 Coefficients a_i vs DOB of the approximation function
 $\log p = \sum_0^2 a_i (\log GR)^i$ for wet YTONG.

Figure 48 Coefficients a_i vs DOB of the approximation function
 $\log p = \sum_0^2 a_i (\log GR)^i$ for clay/loam.

Figure 49 Peak Overpressure vs Ground Range (Logarithmic plot with domains of different wave forms).
Soil material: dry aerated grout (dry YTONG)

Figure 50 Peak Overpressure vs Ground Range (Logarithmic plot with domains of different wave forms).
Soil material: water saturated grout (wet YTONG)

Figure 51 Peak Overpressure vs Ground Range (Logarithmic plot with domains of different wave forms).
Soil material: wet clay/loam

Figure 52 Percentage of Energy Losses vs Ground Range
Soil material: dry aerated grout (dry YTONG)

Figure 53 Percentage of Energy Losses vs Ground Range
Soil material: water saturated grout (wet YTONG)

Figure 54 Percentage of Energy Losses vs Ground Range
Soil material: clay/loam

Figure 55 Percentage of Energy Losses vs DOB at $GR = 2 \text{ [m/kg}^{1/3}]$

Figure 56 Percentage of Energy Losses vs DOB at $GR = 6 \text{ [m/kg}^{1/3}]$

Figure 57 Percentage of Energy Losses vs DOB at $GR = 10 [m/kg^{1/3}]$

Figure 58 Isobaric HOB-curves for a hydrodynamically-smooth surface completed with DOB-curves for dry aerated grout [Ref. 2]. Specially marked is the region in which the isobaric DOB data are presented in the following figures.

Figure 59 Isobaric DOB-curves for dry aerated grout (dry YTONG)
Intermediate-pressure regime

Figure 60 Isobaric DOB-curves for water saturated grout (wet YTONG)
Intermediate-pressure regime

Figure 61 Isobaric DOB-curves for clay/loam
Intermediate-pressure regime

Figure 62 Isobaric DOB-curves for dry aerated grout (dry YTONG)
Low-pressure regime

Figure 63 Isobaric DOB-curves for water saturated grout (wet YTONG)
Low-pressure regime

Figure 64 Isobaric DOB-curves for clay/loam
Low-pressure regime

Figure 65 Comparison of isobaric DOB-curves for the three soil materials in the low-pressure regime. Black curves are valid for "hydrodynamically smooth surface". Pressure parameter: 1 psi; 3 psi; 6 psi; 10 psi; 15 psi

Figure 66 Comparison of isobaric DOB-curves for the three soil materials in the low-pressure regime. Black curves are valid for "hydrodynamically smooth surface". Pressure parameter: 2 psi; 4 psi; 8 psi; 15 psi

Figure 67 Comparison of isobaric DOB-curves for the three soil materials in the intermediate-pressure regime. Black curves are valid for "hydrodynamically smooth surface". Pressure parameter: 8 psi; 15 psi; 30 psi; 70 psi; 150 psi

Figure 68 Comparison of isobaric DOB-curves for the three soil materials in the intermediate-pressure regime. Black curves are valid for "hydrodynamically smooth surface". Pressure parameter: 10 psi; 20 psi; 50 psi; 100 psi; 200 psi

Figure 69

Positive phase impulse vs ground range at different DOB. Soil material: dry aerated grout (dry YTONG)

DOB = -1.0 cm;

DOB = 0 cm;

DOB = 1.0 cm

DOB = 2.0 cm;

DOB = 3.0 cm;

DOB = 4.0 cm

Figure 70 Positive phase impulse vs ground range at different DOB. Soil material: water saturated grout (wet YTONG)
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm
 DOB = 2.0 cm; DOB = 3.0 cm; DOB = 4.0 cm

Figure 71 Positive phase impulse vs ground range at different DOB. Soil material: clay/loam
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm
 DOB = 2.0 cm; DOB = 3.0 cm; DOB = 4.0 cm

Figure 72 Logarithmic plot for impulse-range curves.
Soil material: aerated grout (dry YTONG)

Figure 73 Logarithmic plots for impulse-range curves
Soil material: water saturated grout (wet YTONG)

Figure 74 Logarithmic plots for impulse-range curves
Soil material: clay/loam

Figure 75 Iso-impulse DOB curves for aerated grout (dry YTONG)

Figure 76 Iso-impulse DOB curves for water saturated grout (wet YTONG)

Figure 77 Iso-impulse DOB-curves for clay/loam.

Figure 78 Time of arrival vs ground range at different DOB. Soil material: dry aerated grout (dry YTONG)
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm
 DOB = 2.0 cm; DOB = 3.0 cm; DOB = 4.0 cm

Figure 79

Time of arrival vs ground range at different DOB. Soil material: water saturated grout (wet YTONG)

DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm; DOB = 2.0 cm; DOB = 3.0 cm; DOB = 4.0 cm

Figure 80 Time of arrival vs ground range at different DOB. Soil material: clay/loam
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm
 DOB = 2.0 cm; DOB = 3.0 cm; DOB = 4.0 cm

Figure 81 Logarithmic plots of arrival-time range curves.
Soil material: aerated grout (dry YTONG)

Figure 82 Logarithmic plots of arrival-time range curves.
Soil material: water saturated grout (wet YTONG)

Figure 83 Logarithmic plots of arrival-time range curves.
Soil material: clay/loam

Figure 84 Constant arrival time DOB-curves for dry aerated grout (dry YTONG).

Figure 85 Constant arrival time DOB-curves for water saturated grout (wet YTONG).

Figure 86 Constant arrival time DOB-curves for clay/loam.

Figure 87 Determination of peak overpressure by using time-of-arrival data
 upper diagrams: ground range vs arrival time with approximation curve and deduced shock front velocity
 lower diagrams: calculated pressure-range curve compared with measured peak pressure values
 soil material: dry aerated grout (dry YTONG)
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm

Determination of peak overpressure by using time-of-arrival data
upper diagrams:
ground range vs arrival time with approximation curve and deduced shock front velocity
lower diagrams:
calculated pressure-range curve compared with measured peak pressure values
soil material:
water saturated grout (wet YTONG)
DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm

Figure 89

Determination of peak overpressure by using time-of-arrival data
 upper diagrams: ground range vs arrival time with approximation curve and deduced shock front velocity
 lower diagrams: calculated pressure-range curve compared with measured peak pressure values
 soil material: clay/loam
 DOB = -1.0 cm; DOB = 0 cm; DOB = 1.0 cm

Figure 90

Time duration of positive overpressure phase vs ground range at different DOB
soil material: dry aerated grout

DOB = -1.0 cm DOB = 0 cm DOB = 1.0 cm
DOB = 2.0 cm DOB = 3.0 cm DOB = 4.0 cm

Figure 91 Time duration of positive overpressure phase vs ground range at different DOB
 soil material: water saturated grout (wet YTONG)
 DOB = -1.0 cm DOB = 0 cm DOB = 1.0 cm
 DOB = 2.0 cm DOB = 3.0 cm DOB = 4.0 cm

Figure 92 Time duration of positive overpressure phase vs ground range at different DOB
soil material: clay/loam
DOB = -1.0 cm DOB = 0 cm DOB = 1.0 cm
DOB = 2.0 cm DOB = 3.0 cm DOB = 4.0 cm

Figure 93 Logarithmic plots of positive phase duration range curves.
Soil material: aerated grout (dry YTONG)

Figure 94 Logarithmic plots of positive phase duration range curves.
Soil material: water saturated grout (wet YTONG)

Figure 95 Logarithmic plots of positive phase duration range curves.
Soil material: clay/loam

Figure 96 Constant duration DOB-curves for dry aerated grout (dry YTONG).

Figure 97 Constant duration DOB-curves for water saturated grout (wet YTONG).

Figure 98 Constant duration DOB-curves for clay/loam.

Figure 99 Comparison with wave forms from Ref. [12].

- a) BRL { DOB = 17 ft; GR = 160 ft
b) NOL { $\approx 0.20 \text{ m/kg}^{1/3}$; $\approx 1.86 \text{ m/kg}^{1/3}$
- c) BRL { DOB = 17 ft; GR = 430 ft
d) NOL { $\approx 0.20 \text{ m/kg}^{1/3}$; $\approx 5.0 \text{ m/kg}^{1/3}$

- e) EMI DOB = 1.5 cm; GR = 15 cm
 $\approx 0.19 \text{ m/kg}^{1/3}$; $\approx 1.89 \text{ m/kg}^{1/3}$
- f) EMI DOB 1.5 cm; GR = 39 cm
 $\approx 0.19 \text{ m/kg}^{1/3}$; $\approx 4.9 \text{ m/kg}^{1/3}$

Figure 100 Comparison of wave form transitions for desert alluvium [from Ref. 12] and dry aerated grout (dry YTONG).

Figure 101 Peak overpressure vs ground range for desert alluvium [Ref. 12] compared with results for aerated grout, water saturated grout and clay/loam.

Figure 102

Peak overpressure suppression as function of DOB for desert alluvium [Ref. 12] compared with results for aerated grout, water saturated grout and clay/loam.

Figure 103

Impulse vs ground range for all charges fired in NTS desert alluvium [Ref. 12] compared with results for aerated grout and water saturated grout.

Figure 103 Continued

Figure 104

Suppression of blast impulse as function of DOB for desert alluvium [Ref. 12] compared with results for water saturated grout.

Figure 105 Arrival time vs ground range for desert alluvium [Ref. 12] compared with results for aerated grout and water saturated grout, resp.

Figure 106 Arrival time vs ground range for $\text{DOB} = 0.5 \text{ [ft/lbs}^{1/3}]$ ($= 17 \text{ ft}$) and $\text{DOB} = 1.0 \text{ [ft/lbs}^{1/3}]$ ($= 34 \text{ ft}$) [Ref. 12] compared with results for aerated grout and water saturated grout, resp.

Figure 107

Effect of charge burial in desert alluvium on positive phase duration [Ref. 12] compared with results for aerated grout and water saturated grout, resp.

Figure 108

Positive phase duration vs ground range for all charges fired in desert alluvium [Ref. 12] compared with results for aerated grout and water saturated grout, resp.

Figure 108 Continued.

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