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Exploratory Depth-of-Burst Experiments

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December 1991

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Interim Report

EXPLORATORY DEPTH-OF-BURST EXPERIMENTS

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12 December 1991

Interim Report

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SUMMARY

This reports describes the first small-scale explosion experiments with aerated grout (i.e., YTONG). Apart from data referring to crater depth and volume versus depth of burst (DOB), isobaric DOB curves in the range of $1.5 \text{ psi} \leq p \leq 15 \text{ psi}$ were established. The comparison with previous HOB values shows that the ground range to a given overpressure is considerably reduced with increasing depth of burst.

We plan to continue the airblast investigations with different types of soil materials.

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SECTION 1

INTRODUCTION

While much airblast data are available for height-of-burst (HOB) effects (e.g., References 1 - 4), systematic airblast data for depth-of-burst (DOB) effects is much more limited (References 5 - 11). 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. The main interest was to be to investigate blast wave data in order to be able to complete the isobaric HOB curves for DOB cases. The data recording concerning crater depth and crater volume are of secondary importance. As is known, not all physical data (e.g., gravity) can, on a model scale, be chosen in accordance with the requirements of the similarity laws for crater formation.

Therefore, the significance of DOB model tests is mainly to determine the influence of different parameters (e.g., soil material, overburden) on the airblast environment. Small-scale tests seem to be highly suitable for such parametric studies, for example:

- (a) They are inexpensive, therefore parametric studies are feasible.
- (b) They can be performed in a relatively short time.
- (c) The properties of the simulated soil material can easily be controlled.
- (d) Tests can be repeated under identical conditions.
- (e) Laboratory measuring techniques can be applied, including high-speed photographic visualization.
- (f) The present test equipment can be used, with only slight alterations.

In the present report the test set up will be described and first DOB results will be presented. It will thus be proved that small-scale tests can be used to solve some of the current physical DOB problems.

SECTION 2

EXPERIMENT DESIGN

The first objective was simply to check the feasibility of DOB experiments. Therefore only minor alterations were made to the existing explosion chamber (see Ref. 1). For instance, the measuring system installed in the roof plate of the chamber remained basically the same. The result of this was that the DOB experiments were carried out - as it is the case with our HOB tests - upside down.

2.1 SOIL MATERIAL.

Because of the geometrical arrangement, the simulated soil had to be cohesive. The material chosen for the initial DOB tests was an aerated grout (i.e., foam concrete with a German trade name YTONG). This material, which is used in house construction and has a good heat insulation, is easy to treat mechanically. The material properties of YTONG are listed in Table 1.

Table 1. Material Properties of YTONG.

specific weight:	0.4 g/cm ³	(25 pound/ft ³)
Young's modulus:	1300 N/mm ²	(1.885 · 10 ⁵ psi)
compressive strength:	2.5 N/mm ²	(363 psi)
heat conductivity:	0.12 W/mK	
grain size	0.02 - 0.2 mm	

Microscopic photographs showing the fracture surfaces of the aerated grout (YTONG) are presented in Figure 1. The grain size of about 0.1 mm can be estimated from the inserted scale. The material is extremely porous. The specific weight is therefore only 0.4 g/cm³.

YTONG is usually supplied in blocks of 59.9 cm x 25.0 cm x 24.9 cm. With the help of a core drill, cylinders were bored and finished on the lathe. Thus the foam concrete, 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, only those foam

concrete cylinders have been used for the experiments that were stored and dried in the laboratory for several days. They were only used when there were no further changes in the daily weight checks.

2.2 INSTALLATION OF THE CHARGE.

The installation of the 0.5-g charge is sketched in Fig. 2. A hole with a diameter of about 10.4 mm is drilled concentrically into the YTONG cylinder. The bore depth is chosen in such a way that the required overburden remains constant. 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 (diameter 1 cm) 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 a steel tube with an inner diameter of 100.5 mm so that the plane face ends flush with the rim of the tube.

The designations used in this report are explained in Fig. 3.

2.3 INSTALLATION INTO THE EXPLOSION CHAMBER.

Figure 2 schematically shows the installation of an YTONG cylinder set into a steel tube. To reduce the transmission of acceleration impulses created by the detonation of the charge, the steel tube has been installed shock-isolated into the explosion chamber. The mounting of the pressure gauges, which proved so worthwhile with the HOB tests, was retained.

Figure 4 gives a general view showing not only the construction of the steel cylinder but also 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 gauge in relation to ground zero is depicted in Fig. 5. Gauge MK1 is 90 mm away from GZ. The distance between gauges MK1 to MK13 is 60 mm each. Gauges MK14, MK15 and MK16 are arranged in a distance of 85 mm, 99.4 mm and 150 mm, respectively. They are not on the same radius as gauges MK1 to MK13.

No alterations were made to the recording equipment and the optical arrangement for the shadow and schlieren photographs (single photographs). They are described in Ref. 1.

SECTION 3

TEST MATRIX

The test matrix is presented in Table 2. We found that experiments with $DOB > 5$ cm did not create significant pressure pulses. Note that the DOB is counted positive from the surface to the installation point, so that $DOB = -0.5$ cm indicates a charge tangent above the surface. As before, the diameter of the 0.5-g explosive sphere is 1 cm.

Table 2. Test Matrix.

DOB [cm]	-0.5 (tangent)	0	0.25	0.35	0.5	1.0
Test No.	723 726	722	735	736	737 738	717

DOB [cm]	1.5	2.0	2.5	3.0	4.0	5.0
Test No.	740	712 713 719	741 742	718 720	721	724 725

To get a better idea about how the measuring data fit in with previous full-scale experiments, Table 3 presents some DOB tests, for which airblast data were also 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 3, the scaling was $W^{1/3}$. As shown in the table, the additional objective of our tests is to determine the transition of the airblast data from HOB to DOB.

Table 3. HE Events with Airblast Data.

SDOB [ft/kt ^{1/3}]	HE Event	Yield	Soil	EMI Experiments	
				SDOB [ft/kt ^{1/3}]	Depth [Charge Dia]
				-14	-0.5-D
				0	0-D
				7	0.25-D
				9.8	0.35-D
				14	0.5-D
				28	1-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-D
				70	2.5-D
74.4	Essex-I-6MU	10-T	LMD		
73.3	Essex-I-6MWS	10-T	LMD		
81	Buckboard-11	20-T	Basalt		
81.5	Essex-I-6MU	8-T	LMD		
				84	3-D
108	Stagecoach-3	20-T	Alluvium		
				112	4-D
135	Buckboard-12	20-T	Basalt		
				140	5-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, resp., is given in Fig. 7. The crater volume, V_k , was determined by the difference in weight, ΔG , of the aerated grout before and after the experiment. Since the specific weight γ_{cyl} was determined for each YTONG cylinder before the bore hole, we have

$$V_k = \Delta G / \gamma_{cyl} .$$

Table 4 gives the results obtained so far, while Fig. 6 shows the crater of an YTONG sample that is still to be found in the steel cylinder. Some photographs of craters at different DOB have been compiled in Fig. 8. Figure 9 depicts some typical crater cross-sections measured 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 there is an edge that is more or less distinct for all DOB tests. It also has to be pointed out that the experiments at the same DOB show very little scatter in the crater dimensions.

Figure 10 shows the crater depth as a function of the DOB. Figure 11 shows that the crater volume increased linearly with the depth of burst:

$$V_k = 50.70 \text{ DOB} + 53.45 \quad (\text{for DOB} \leq 5 \text{ cm})$$

where $[V_k] = \text{cm}^3$ and $[\text{DOB}] = \text{cm}$ for 0.5-g charge. It would seem reasonable that the amount of charge energy absorbed by the cratering process would be linearly related to the crater volume. Hence Fig. 11 indicates that the amount of charge energy available to drive the airblast wave decreases with depth of burst. This is certainly born out by the pressure measurements.

A single picture has been made for each DOB test. In these photographs, the shock front is visible and the crater ejecta can usually be seen as a black cone. Some typical cases are given in Fig. 12.¹ For high DOB (≥ 4 cm) it is noticeable that big lumps of aerated grout are apparently hurled out of the crater and gas jets appear in between. In these cases, no shock front is visible. This leads one to assume that the pressure distribution takes place in the form of compression waves.

To investigate how the measuring values for YTONG fit in with the results for real soil materials, data were used from [4]. Figure 13 shows this comparison. In [4], 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 [4], sand has the closest resemblance to aerated grout (YTONG), although the density of sand is higher.

Considering that the EMI experiments determine the true crater depth and not the apparent crater depth, the deviation of the YTONG curve from the sand curve is absolutely plausible. As expected, it has the same DOB for higher crater depths. It is also noticeable that the slope of the two curves show a good agreement.

We may conclude, with caution, that the model tests allow qualitative statements and that parametric studies are suitable for a better understanding of the influences of different soil parameters on the crater formation.

¹ On some partial pictures the silhouette of a tank can be seen. These photographs were made when dealing with a different problem that will be presented in a separate technical note.

Table 4. Crater Depth and Crater Volume.

DOB [cm]	Test No. -	Depth [cm]	Volume [cm ³]	Scaled DOB [m/kg ^{1/3}]	Scaled Depth [m/kg ^{1/3}]	Scaled Volume [m ³ /kg]
-0.5	723 726	1.8 1.8	14.3 16.3	-0.0630	0.227 0.227	0.0286 0.0326
0	722	2.7	32.2	0	0.340	0.0644
0.35	735	2.7	83.7	0.0315	0.340	0.167
0.35	736	2.9	70.9	0.0441	0.365	0.142
0.5	737 738	3.1 3.0	76.7 85.7	0.0630	0.391 0.378	0.153 0.171
1.0	717	4.0	-	0.126	0.504	-
1.5	740	5.0	163.1	0.189	0.630	0.326
2.0	712 713 719	5.3 5.3 5.0	- - 177.1	0.252	0.668 0.668 0.630	- - 0.354
2.5	741 742	5.9 6.0	179.1 194.9	0.315	0.743 0.756	0.358 0.390
3.0	718 720	6.4 6.2	197.1 193.0	0.378	0.806 0.781	0.394 0.386
4.0	721	7.2	223.2	0.504	0.907	0.446
5.0	724 725	8.5 9.0	307.4 315.8	0.630	1.071 1.134	0.615 0.632

4.2 PRESSURE MEASUREMENTS.

Figures 14, 15, 16, and 17 show examples of pressure recordings at DOB = -0.5, 0, 0.5, 1, 2, 3, 4, and 5 cm, respectively. The positions of the measuring channels can be taken from Fig. 4.

Note that the scale for the different recording curves (Figs. 14 - 21) is not the same, because the peak overpressure varies strongly with distance and DOB. To emphasize the strong fall of the peak overpressure along with the increasing distance from ground zero, the same scale was used for test 717, DOB = 1 cm, Fig. 22. In addition to the pressure curve in this Figure, the positive phase impulse curve is also given.

At low DOB (Figs. 14 - 17), the pressure curve is similar to an ideal Friedlander function and shows no disturbances. The shock front is sharp. There are no signs of compression waves running ahead of the main wave. The situation varies with increasing DOB (Figs. 19 - 21). In this case, there is no steep shock front, but one notes two phases of the pressure increase. Both seem to be caused by compression waves. The reason for the first might be the fact that, after the detonation of the charge, the overburden is initially moved like a piston. This may lead to the formation of cracks through which a part of the compressed smoke escapes. Lumps are perforated with cracks and are finally hurled out of the crater clearing the way for a propagation of the main compression wave. However, they keep preventing an uninterrupted propagation so that no uniform shock front can be formed. This may be responsible for the slow pressure increase of the second phase. At lower DOB, the overburden flies off at high velocity and is reduced to very small particles. This is also suggested by the photographs of the crater ejecta. The compressed gas smoke, although delayed with increasing DOB, is therefore suddenly released and can produce a steep shock front.

The dependence of the peak overpressure on DOB and ground range (GR) is shown in a scaled form in Fig. 23. The legends gives the assignment of the symbols to the depth of burst. The test numbers can also be taken from it. For each test, fit functions with the form

$$\log p = a_0 + a_1 \log GR + a_2 (\log GR)^2$$

have been determined from the measuring values according to the least square method. The curves shown in Fig. 23 correspond to these functions. While the agreement of different experiments at the same DOB for $DOB \leq 3$ cm is excellent (cf. DOB = -0.5 cm, 2.0 cm, 3.0 cm), there are major deviations at DOB = 5 cm. We assign this to the formation of crater ejecta which has a strong influence on the pressure curve in the compression waves. In addition, it is very problematic to compare the well defined peak overpressure of a blast wave to the more random maximum pressure of compression waves (see, e.g., Figs. 17 and 21).

The same considerations apply to the dependence of the positive impulse of the DOB given in Fig. 24. The measuring data, given in a scaled form, are consistent for $DOB \leq 3$ cm.

By means of the fit functions for the peak overpressure, the distances to a given pressure value can be determined in the usual way. In Fig. 25, some isobaric DOB curves are arranged in scaled coordinates. The values for $HOB = 0.063 \text{ m/kg}^{1/3}$ correspond to charges tangent above the surface. A boundary line at $GR = 1.07 \text{ m/kg}^{1/3}$ is drawn in the diagram. It indicates the position of the measuring gauge closest to ground zero. No measuring data are available for smaller values of GR.

To compare with isobaric HOB curves, the DOB data have been plotted on our previously published diagrams. Figure 26 shows peak pressure height-of-burst curves for a hydrodynamically-smooth surface in the low-pressure regime (taken from Ref. 2, Fig. 7). This diagram has been completed by DOB curves from Fig. 25 that were derived for aerated grout (YTONG). The DOB curves are difficult to distinguish because of the small ordinate scale. With increasing depth of burst, however, the extremely strong attenuation of the blast wave is clearly visible. As a result, the ground ranges in which the given peak overpressures appear are considerably reduced, because the cratering process absorbs energy.

Figure 27 gives a corresponding representation for the intermediate-pressure regime. The HOB curves are taken from Ref. 2, Fig. 8. One can clearly see in Fig. 27 that for $HOB = 0.0603$ (charge tangent to the surface) the ground ranges for YTONG have smaller values than for a hydrodynamically-smooth surface. This points out to the fact that more energy is absorbed in the aerated grout than in a hard material such as Makrolon.

SECTION 5

CONCLUSIONS

These exploratory tests have demonstrated the feasibility of performing airblast depth-of-burst experiments at laboratory scale. This method should be used to investigate how the material properties effect the DOB curves. To validate the scalability of the results, laboratory simulations of selected large-scale HE events (Table 3) should be performed. Hence, experiments with materials that simulate the following soils will be considered:

- Alluvium (silted lake-bed material)
- Basalt (granite rock)
- Layered Marine Deposits
- water-saturated YTONG
- wet clay

SECTION 6

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Figure 1. Microscopic photographs showing the fracture surface of aerated grout (YTONG).
Graduation mark distance: 5/100 mm.

Figure 2. Installation of the 0.5-g charge into aerated grout and shock-isolated mounting of the set-up into the explosion chamber.

Figure 3. Definition of depth of burst, DOB, and overburden, H.

Figure 4. General view showing the construction of the YTONG holder.

Figure 5. Position of the shock-isolated pressure gauges, MK1 - MK16.

Figure 6. Aerated-grout specimen after test (still embedded in steel tube).

<u>CHARGE GEOMETRY</u>	<u>RADIUS</u>	<u>DEPTH</u>
HALF BURIED SPHERE	1.0	1.0
SURFACE TANGENT SPHERE	0.74	0.61
HEMISPHERE	0.97	1.08

Figure 7. Apparent crater dimensions of different charge geometries and definition of apparent and true crater depths, resp.

DOB
= - 0.5 cm

DOB
= 3 cm

= 0 cm

= 4 cm

= 2 cm

= 5 cm

Figure 8. Examples of craters at different depths of burst

Figure 9. True crater contours.

Crater-Depth vs DOB

Aerated Grout (YTONG)

Figure 10. True crater depth vs depth of burst.

Crater-Volume vs DOB

Aerated Grout (YTONG)

Figure 11. True crater volume vs depth of burst.

Figure 12. Examples of crater ejecta at different depths of burst.

TNT Spheres

Apparent Crater Depth vs Depth of Burst

(from DASIAC - TN - 86 - 15)

Figure 13. Comparison of YTONG crater depth with other soil material [3].

Figure 14. Pressure-time records at different ground ranges (test 723), MK1, MK3, MK5, MK7, MK9, MK11; DOB = -0.5 cm; YTONG; W = 0.5 g.

Figure 15. Pressure-time records at different ground ranges (test 722), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 0 cm; YTONG; W = 0.5 g.

Figure 16. Pressure-time records at different ground ranges (test 737), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 0.5 cm; YTONG; W = 0.5 g.

Figure 17. Pressure-time records at different ground ranges (test 717), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 1.0 cm; YTONG; W = 0.5 g.

Figure 18. Pressure-time records at different ground ranges (test 719), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 2.0 cm; YONG; W = 0.5 g.

Figure 19. Pressure-time records at different ground ranges (test 720), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 3.0 cm; YTONG; W = 0.5 g.

Figure 20. Pressure-time records at different ground ranges (test 721), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 4.0 cm; YTONG; W = 0.5 g.

Figure 21. Pressure-time records at different ground ranges (test 725), MK1, MK2, MK3, MK4, MK6, MK8; DOB = 5.0 cm; YTONG; W = 0.5 g.

Figure 22. Pressure-time and impulse-time records at different ground ranges (test 717), MK1, MK3, MK5, MK7, MK9, MK11; DOB = 1.0 cm; YTONG; W = 0.5 g.

Overpressure versus Ground Distance

$$\text{Fit: } \log P_r = A_0 + A_1 \log Gr + A_2 (\log Gr)^2$$

Figure 23. Peak overpressure vs ground range at different depths of burst; YTONG.

Pos. Impulse versus Ground Distance

Fit: $\log I+ = \text{SUM} (A_i (\log BR)^{b_i})$

Figure 24. Positive impulse vs ground range at different depths of burst; YTONG.

Isobaric DOB (HOB) - Curves

YTONG

Figure 25. Isobaric depth-of-burst curves.

Figure 26: Comparison of DOB results with peak-overpressure HOB curves for hydrodynamically-smooth surface (Makrolon). - Low-pressure regime.

Figure 27. Comparison of DOB results with peak-overpressure HOB curves for hydrodynamically-smooth surface (Makrolon). - Intermediate-pressure regime.

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