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THE UNIVERSITY OF MARYLAND

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Geotechnical Centrifuge Modeling of Explosion Induced Craters - A Check for Scaling Effects.

AFOSR 86--0095

Abstract: One hundred twenty-one model tests of explosion induced craters in dry sand were conducted using small charges of PETN detonated at accelerations between 1g and 101g; ninety-six were found to be useful in analysis. Extrapolation to prototype dimensions indicates that for half-buried charges, crater volume, V , is a function of explosive weight, $W^{0.84}$; crater radius and depth are functions of $W^{0.28}$. There were no detectable acceleration related scale effects from 31g to 101g. This confirms the value of the geotechnical centrifuge in modelling explosion induced craters at less than 100 g provided attention is paid to certain test conditions and scale effects. These include soil particle size, and angularity and soil strength which appear to strongly affect model crater volume and shape. Crater volume is also very sensitive to the unit weight of dry sand and to a lesser degree to charge location, geometry and orientation. Boundary effects arising from model dimensions and the centrifuge enclosure were examined.

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July 31, 1988

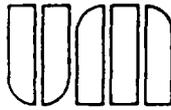
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Handwritten note: 101g 200g 100g

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July 31, 1988

Final Report:
 Geotechnical Centrifuge Modeling of Explosion Induced Craters -
 A Check for Scaling Effects -
 AFOSR-86-0095

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Final Report: Geotechnical Centrifuge Modeling of Explosion Induced Craters -
A Check for Scaling Effects
AFOSR-86-0095

I. Research Objectives:

The demand for the most effective use of large explosives in the two contexts of defense and peacetime application are matters of economics and national security. Full scale parametric studies to establish the important relationships between the characteristics of explosives, the circumstances of detonation, such as soil conditions, the height or the depth of burst, and the resulting shock loading and final crater, are not feasible. Existing field data are drawn from very diverse site and explosive conditions and show enormous scatter. Analytical models have been developed to predict real field events, but have been shown to be inadequate at present (Schmidt, 1985). This situation has led researchers to search for techniques of physical modeling to study real soil response which eliminate the imposition, to the greatest extent possible, of assumptions about soil response to explosions, which comply with requirements for similarity between model and field conditions as much as possible, and which also can be proven to be unaffected by unavoidable departures from complete similitude.

The conclusions of various researchers working to assess the effects of explosives, such as Crowley (1970) and Sedov (1959), was that similitude can only be satisfied in a 1g test if the model has the same scale as the prototype: the stumbling block which presents an obstacle to correct reduced scale modeling is the need to change gravitational acceleration. For large tests conducted at scales not much less than the prototype, the error in extrapolating from model to prototype may be acceptable but in much smaller tests at 1g that error may become too great for meaningful extrapolation. Here the application becomes clear of geotechnical centrifuge modelling in which small models can be tested under increased acceleration becomes clear.

Although it is known that Soviet researchers have investigated for some years large explosions using the centrifuge, as described by Pokrovsky and Fyodorov (1969), specific details of their work have remained largely unavailable to researchers in the West. Various

American researchers have been active, such as Nielsen (1983) and more recently, Felice et al. (1988), Townsend et al. (1988), and Kutter et al. (1988), but the field has been dominated by Schmidt and Holsapple (see Schmidt (1985) for a summary of publications). While Schmidt and Holsapple have completed many studies, which have properly included attention to establishing the validity of the technique, gaps remained in experimental confirmation of the absence of scaling effects in centrifuge models. In their studies of the relationship between the size of craters in sand and the explosive characteristics, they worked at accelerations predominantly over 300 g, although they also used data of Piekutowsky (1974) who worked at 1g. But 300 g is beyond the level of acceleration achievable on most geotechnical centrifuges available today in the United States. The focus of this research, then, was to determine in a systematic study if scale effects exist at those lower accelerations more typically achievable. If that is firmly established then similar research can be initiated on other aspects of soil response to explosives using lower acceleration centrifuges.

Certain questions of scaling were posed in the original proposal in response to this broad question; others arose as the research proceeded. The questions originally posed were:

1. What is the pattern of crater characteristics in progressively larger field tests? Is there a gradual change or a sudden change which makes the comparison of small explosions at 1g so different from large explosions that they cannot be compared? Or is there some threshold scale below which comparisons can be made with only small error, and above which small scale testing must be done on the centrifuge?
2. Are there any undesirable scale effects related to acceleration which develop in models of explosions in the range of scales typical of geotechnical centrifuges which should be considered in the selection of scale and the problem to be examined?
3. Are there particle size effects in that range of scales typical of geotechnical centrifuges which also should be considered in the selection of scale and the prototype soil which can be used in the model?

Additional questions treated during the study which were relevant to field conditions included:

4. How sensitive is crater volume to the unit weight of the sand?
5. How sensitive is crater volume to charge location?

and relevant to the models themselves:

6. What is the effect on crater dimensions of the depth and area of the soil bed on which detonation occurs?
7. What is the influence of the centrifuge enclosure itself on crater volume?

These questions were addressed at length in two civil engineering M.S. theses submitted to the University of Maryland: one by C.H. Serrano, "A Check for Scaling Effects on Explosion Induced Craters - Centrifuge Model Testing," and one by V.H. Ferrero "Further Checks for Scaling Effects on Explosion Induced Craters - Centrifuge Model Testing". A copy of the first thesis was sent to the Air Force Office of Scientific Research in the summer of 1987. A copy of the second will be arriving under separate cover. The material following is a summary of the work explained in detail in the theses.

A summary of the research described in C.H. Serrano's thesis is given in a paper presented at the International Conference on Geotechnical Centrifuge Modelling held in Paris, France from April 25 to April 27, 1988; a copy of that paper, entitled "Centrifuge Modelling of Explosion Induced Craters," was forwarded to the Air Force Office of Scientific Research earlier this year. An oral presentation of the same material was also made at the Soil Mechanics Seminar held for AFOSR grantees at the Massachusetts Institute of Technology in September, 1987. One or two formal papers on the subjects of this research will be submitted to technical journals and are now in the early stages of preparation; they will be sent to AFOSR when they are completed.

II. Experimental Method and Results

Research Question Number 1: What is the pattern of crater characteristics in progressively larger field tests? Is there a gradual change or a sudden change which makes the comparison of small explosions at 1g so different from large explosions that they cannot be compared? Or is there

some threshold scale below which comparisons can be made with only small error, and above which small scale testing must be done on the centrifuge?

a) Method:

The question of the pattern of crater characteristics in progressively larger field tests could be answered at 1g using explosives identical in all respects except for progressively increasing weight, detonated at sites also identical in every way. It can also be examined by conducting a series of tests in the centrifuge using a single explosive type and weight detonated in models of soil identical in all respects except for acceleration. This second method was followed in a series of tests of which thirty-three were suitable for analysis.

As many aspects of the tests as possible were intended to follow the techniques of Schmidt and Holsapple (1980). In keeping with this, the explosive selected was PETN (Pentaerythritol-tetranitrate). One gram charges were packed with an average density of 1.5 gm/cm^3 into a cylindrical form with diameter of 9.6 mm and height varying from 8.9 mm to 10.0 mm to give an aspect ratio as close as possible to 1.0. Lead azide was used as the initiator, and when combined with the PETN, the energy equivalent of the explosive was 1.005 gm of PETN, or 1.397 gm of TNT. The finished charge was pressed into a bed of sand bed to a half-buried position with the longitudinal axis of the cylinder placed horizontally.

The sand used for the soil beds in the models was a dry, uniformly graded ($C_u = 1.31$) Flintshot 2.8-Sawing-Trap quartz Ottawa sand with $D_{50} = 0.43 \text{ mm}$, again following Schmidt and Holsapple. The sand was rained from a height of 0.70 m into aluminum test containers 475 mm in diameter to achieve a unit weight of $16.72 \text{ kN/m}^3 \pm 0.03$ ($e=0.555 \pm 0.003$). In twenty-eight models the final depth of the sand was 254 mm; in five tests depth was varied from 305 mm to 178 mm without evidence of boundary effects.

The completed models were accelerated on a 200 g, 15 g-ton Genisco centrifuge to the desired acceleration at one of eight levels between 10 g and 100 g, modelling explosives of up to 1000 kg of PETN or 1390 kg of TNT extrapolating from N_g to 1g using π_w in equation 4 below.

The explosion was then detonated and when the dust had settled, the centrifuge was brought to a stop. The dimensions of the crater were recorded at 1 cm intervals in the horizontal plane using a simple profilometer to measure within 1 mm the profiles of eight radii at 45° intervals. These radii were averaged and the crater volume was calculated by means of cylindrical shells.

b) Results:

The data, listed in Table 1 and plotted in Figure 1 as model crater volume vs acceleration at detonation in multiples of earth's gravity were processed using dimensionless π groups reflecting crater volume, crater radius, and crater depth, which were examined as a function of a fourth π group which reflected explosive weight and test acceleration. A regression analysis was conducted on these data by Ferrero (1988) using the π groups shown below, originally defined by Schmidt and Holsapple (1980).

$$\pi_v = \frac{V\rho}{W} \quad (1)$$

$$\pi_R = R \left(\frac{\rho}{W} \right)^{\frac{1}{3}} \quad (2)$$

$$\pi_H = H \left(\frac{\rho}{W} \right)^{\frac{1}{3}} \quad (3)$$

$$\pi_W = \frac{g}{Q_e} \left(\frac{W}{\delta} \right)^{\frac{1}{3}} \quad (4)$$

V, R and H are apparent crater volume, radius and depth, g is acceleration in multiples of Earth's gravity, Q_e is specific energy of the explosive in ergs per gram which reduces to units of (length)²/(time)², δ is the density of the explosive, W is the mass and ρ is the soil density.

Table 1 - Crater Test Data

Centrifuge Model Data							Prototype Equivalent		
g Gravity	Shot Number	Sandbed Thickness (cm)	V Crater Volume (cc)	R Crater Radius (cm)	D Crater Depth (cm)	PETN Mass (lb)	Volume (ft ³)	Radius (ft)	Depth (ft)
1	11	30.48	1,136.0	13.49	4.3	2.21E-03	0.040	0.443	0.141
	12	25.40	1,392.0	14.24	5.5	2.21E-03	0.049	0.467	0.180
	31	25.40	1,038.6	14.02	4.9	2.21E-03	0.037	0.460	0.161
10	29	25.40	347.7	9.13	2.4	2.21E+00	12.279	2.995	0.787
	30	25.40	287.2	9.07	2.4	2.21E+00	10.142	2.976	0.787
20	10	25.40	307.7	8.86	2.6	1.77E+01	86.931	5.814	1.706
	23	25.40	275.8	8.90	2.3	1.77E+01	77.918	5.840	1.509
	38	25.40	273.8	8.90	2.3	1.77E+01	77.353	5.840	1.509
	39	25.40	253.8	8.13	2.3	1.77E+01	71.703	5.335	1.509
35	16	25.40	237.1	8.43	2.3	9.49E+01	358.997	9.680	2.641
	18	25.40	220.7	8.53	2.3	9.49E+01	334.165	9.795	2.641
	24	25.40	238.0	7.93	2.3	9.49E+01	360.360	9.106	2.641
	46	25.40	231.9	8.27	2.3	9.49E+01	351.124	9.496	2.641
	47	25.40	216.2	8.00	2.2	9.49E+01	327.352	9.186	2.526
50	17	25.40	208.3	7.87	2.2	2.77E+02	919.506	12.910	3.609
	19	25.40	187.0	7.83	1.9	2.77E+02	827.480	12.844	3.117
	25	25.40	169.4	7.63	1.8	2.77E+02	747.788	12.516	2.953
65	13	25.40	161.8	7.25	1.8	6.08E+02	1569.183	15.461	3.839
	15	25.40	138.7	7.44	1.8	6.08E+02	1345.153	15.866	3.839
	20	25.40	189.8	7.80	1.9	6.08E+02	1840.736	16.634	4.052
	26	25.40	186.0	7.74	2.0	6.08E+02	1803.882	16.506	4.265
	42	30.48	173.3	7.63	1.9	6.08E+02	1680.714	16.271	4.052
	43	30.48	143.7	7.94	1.7	6.08E+02	1393.644	16.932	3.625
80	44	17.78	187.6	7.81	1.8	6.08E+02	1819.399	16.655	3.839
	21	25.40	161.0	7.88	1.7	1.13E+03	2911.059	20.682	4.462
	27	25.40	158.7	7.56	1.7	1.13E+03	2869.472	19.843	4.462
	28	25.40	141.4	7.55	1.6	1.13E+03	2556.669	19.816	4.199
90	22	25.40	147.6	7.46	1.7	1.61E+03	3799.872	22.028	5.920
	32	25.40	137.1	7.38	1.7	1.61E+03	3529.556	21.791	5.020
	34	25.40	145.8	7.40	1.7	1.61E+03	3753.532	21.850	5.020
100	14	25.40	142.6	7.29	1.7	2.21E+03	5035.871	23.917	5.577
	35	25.40	144.0	7.16	1.6	2.21E+03	5085.311	23.491	5.249
	45	17.78	146.2	7.48	1.6	2.21E+03	5163.004	24.541	5.249

All charges were half-buried, cylindrical, 1.005 g/cm of PETN.

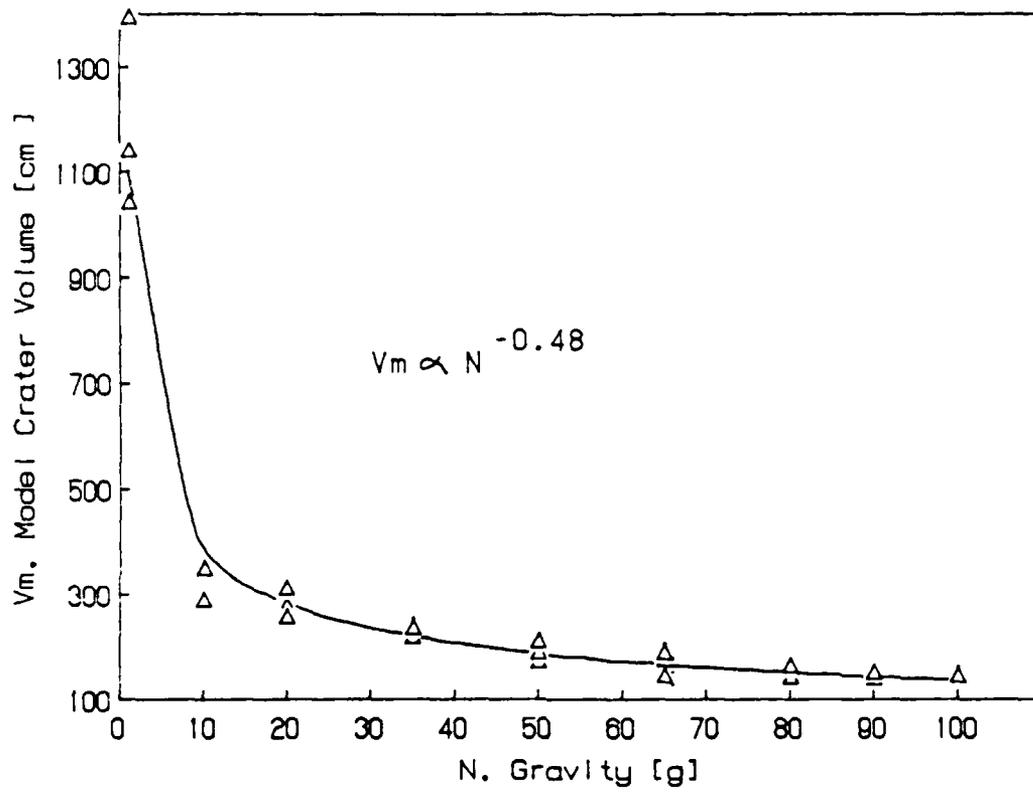


Figure 1 - Model Crater Volume vs Acceleration

The data fit the power model best which is consistent with the results of other researchers. The relationships derived are given in equations 5, 6 and 7, between model acceleration and crater dimensions,

$$V \propto N^{-0.48} \quad (5)$$

$$R \propto N^{-0.14} \quad (6)$$

$$H \propto N^{-0.17} \quad (7)$$

and in equations 8, 9 and 10 between prototype crater dimensions and mass of explosive depending for extrapolation on similarity of π_w :

$$V \propto W^{0.84} \quad (8)$$

$$R \propto W^{0.29} \quad (9)$$

$$H \propto W^{0.28} \quad (10)$$

These relationships depend on all soil and explosive conditions being held constant except for explosive weight. Attention has been paid to conducting this analysis in the natural scale rather than logarithmic which will give different exponents.

These values for the exponent of W for volume fall among values suggested in early theoretical work by Sachs (1944) and Lampson (1946), who predicted crater volume to be a linear function of explosive weight, and Haskell (1955) who predicted volume to be a function of $W^{0.75}$. Dillon (1972) attempted a statistical analysis of data of craters of two hundred field tests of explosives detonated under greatly varying soil and explosives conditions; he concluded that $V \propto W^{0.938}$. Schmidt and Holsapple (1980) conducted centrifuge model tests (after which these were modelled) on beds of somewhat denser (5% denser) deposits of the same Ottawa sand used in this work, varying both the acceleration and the weights of spherical charges of PETN and lead azide detonated half-buried; analysis of their data gave the relationships $V \propto W^{0.84}$, $R \propto W^{0.28}$ and $H \propto$

$W^{0.28}$, essentially the same as the values given above. This indicates that at least the phenomena occurring in their tests were the same occurring in these.

Figure 2 shows a plot of prototype crater volume (N^3 times larger than model crater volume according to manipulation of π_v defined in equation 1) vs prototype explosive weight (also N^3 times larger than the model explosive weight according to manipulation of π_w defined in equation 4) expressed in pounds of TNT. (TNT is the typical standard explosive to which all other explosives are compared). On that plot are drawn two lines: the upper one is derived from the data of this research, and the lower one is that derived from Schmidt and Holsapple (1980). The two lines appear parallel, which is to be expected given that the exponent from equation 8 is equal to that derived from Schmidt and Holsapple's data. But it is clear that Schmidt and Holsapple's data line is not coincident with the data line from this research, even when the same soil and explosive were used. It is speculated that this may be in large part the result of small differences in soil unit weight. Their values of γ_d were on average 5% greater than for this research. Research question number 4, posed as the research progressed, addressed that question and data are presented later in this report. It is sufficient to note here that the effect on crater size of differences in sand density is significant. Further contributing factors to the differences in crater volumes may arise from differences in charge density, configuration and detonation technique.

Also shown on the plot are data of four full scale craters produced by half-buried charges detonated in a somewhat moist sand with otherwise unidentified properties and selected because they were in the range of equivalent weights of TNT modelled by this research. They were chosen from a compendium of field tests assembled by Rooke et al. (1974) and are taken from a single field test series involving three different explosive types intended to investigate the influence of bedrock on crater dimensions. Table 2 provides details of the events.

Note that no tests were conducted using PETN, and ESRIC-5 and ESRIC-9, the only two identical to each other, as far as is discernible from the data provided, had craters different in volume by 29%. This leads one to recall criticism by both Chabai (1965) and Dillon (1972) of the

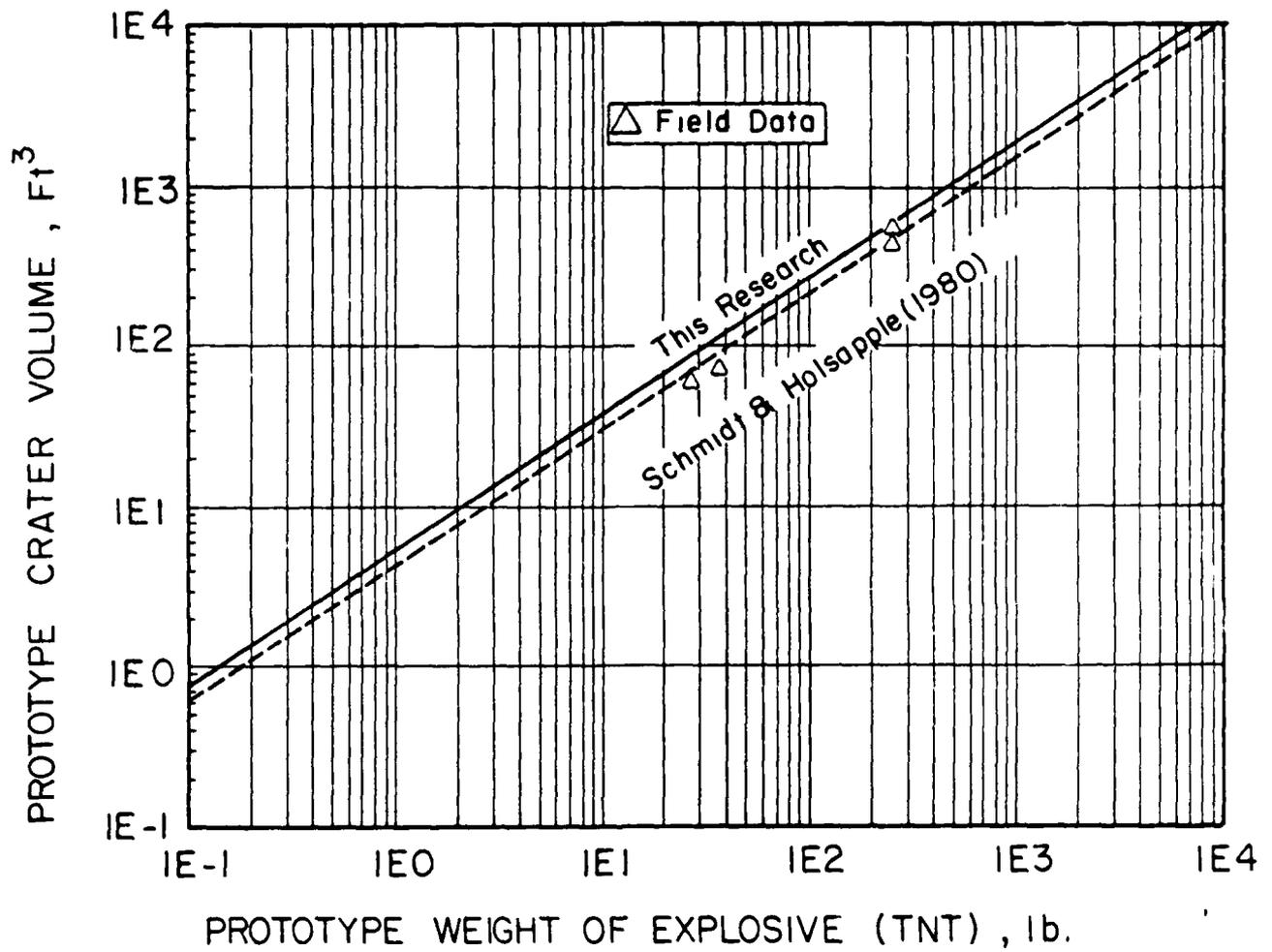


FIGURE 2 - Full Scale Prototype Volume vs Full scale Prototype Weight of Explosive in Equivalent Weight of TNT

Table 2 - Field Test Data from Rooke et al. (1974)

Event	Explosive Type	Equivalent W in lbs of TNT	Crater Volume (ft ³)	Crater Radius (ft)	Crater Depth (ft)
ESRIC-10	C-3	27.0 lb	61	4.5	2.3
ESRIC-13	Dynamite	36.8 lb	73	4.9	2.4
ESRIC- 5	TNT	256.0 lb	419	8.5	3.4
ESRIC- 9	TNT	256.0 lb	419	9.2	4.4

reliability of field data and the care in field technique. Further, the sand was moist and the location of the bedrock is unknown. Nonetheless, this was the best set of comparable data found. It is apparent, first, that the data line of this research consistently overestimates crater size, as does Schmidt and Holsapple's data line in three out of four cases, although theirs does so to a lesser degree, and second, in comparing the ratio of crater depth to crater radius that these prototype craters have shapes which differ from those of the model craters: these full size craters have smaller radii and greater depths. Failure of the centrifuge models to predict more closely the sizes of the prototype craters is attributed in large part to a combination of unquantified differences in the explosives used, unidentified differences in the soils, and other unexplained reasons responsible for the field scatter both within these tests and in data of field tests in general, some of which are considered below. But in the absence of more care in field control and documentation to narrow the scatter of full scale data, the closeness of the research data lines to the field data points in Figure 2 is considered to be a general confirmation of the modelling technique. There remains, however, a clear need for better documentation of full scale site conditions and explosive control.

c) Conclusions:

The relationship between prototype weights of explosives and prototype crater volumes for half-buried charges in dry sand developed by Schmidt and Holsapple from centrifuge tests at accelerations predominantly greater than 300 g was confirmed by thirty-three models tested at less than 100g for this research; the relationships fell in the midst of those developed both empirically from field data of widely varying explosive and field conditions, and theoretically. The discrepancy between actual crater sizes predicted by Schmidt and Holsapple from very similar tests compared to those of this research is attributed to effects arising from small differences in sand unit weight and charge characteristics which are likely to be important influences also on field results. Comparison of model predictions to data of crater sizes from a small set of field tests selected from Rooke et al.'s compendium because field conditions and sizes of explosives were the closest found to those modelled, showed that this research overpredicted the volumes of these field craters and predicted different shapes; Schmidt and Holsapple's tended also to overpredict volume, although to a lesser degree. This is attributed to unquantified differences in field and explosive conditions. The closeness of the points to the research data lines is interpreted as a general confirmation of the validity of the technique but the need for good field data is clear.

The answers, then, to the parts of research question 1 are as follow. When soil and explosive conditions are unchanged except for explosive weight, W , crater volume for a half-buried charges in dry sand can be expected to be a function of $W^{0.84}$, crater radius of $W^{0.28}$ or $W^{0.29}$, and crater depth of $W^{0.28}$, and there is no evidence of a "regime effect" indicating a radical change in the nature of the phenomenon at some threshold value of W . This is true for models tested from 1g to 463g. This means that dimensions of small test craters can be extrapolated to these of large test craters once relationships between explosive weight and crater dimensions are developed for a given soil and explosive configuration. The enormity of that task alone supports the continued usefulness of the centrifuge, although the refining of numerical models using centrifuge models as well defined prototypes for calibration is a logical parallel task.

Research Question Number 2: Are there any undesirable scale effects related to acceleration which develop in models of explosions in the range of scales typical of geotechnical centrifuges which should be considered in the selection of scale and the problem to be examined?

a) Method

Acceleration associated scale effects on centrifuge models of explosion induced craters can be assessed in some respects by examining the change in crater dimensions occurring in a series of tests in which all parameters are the same except for acceleration, N . In the series of tests described under research question number 1, Ferrero (1988) found crater volume measured by Serrano (1987) to be proportional to $N^{-0.48}$ in tests at less than 100 g, and proportional to $N^{-0.50}$ in tests by Schmidt and Holsapple (1980) working mostly over 300 g. The closeness of these two exponents suggests that there are no acceleration level related scale effects. There is, however, a second way to address the question using the technique of modelling of models.

Since all models are extrapolated using π groups to predict full scale events, it should also be possible, in the absence of scale effects, to select a single hypothetical full scale event and model the same event at several scales. For identical soil conditions and explosive types the two variables which can be varied are acceleration, N (also equal to scale), and explosive weight, W . From equation 4, π_w predicts that if δ and Q_e are constant, as they will be for a single type of explosive, then similarity depends on a constant product WN^3 .

Three hypothetical full scale explosive weights were selected. The equivalent of 1.005 gm of PETN at 35 g modelled a hypothetical prototype at 1g of $(1.005 \text{ gm})(35)^3$ which equals 43.1 kg PETN or 59.9 kg TNT; this hypothetical prototype was also to be modelled with 0.5 gm of PETN at 44.1 g and with 1.5 gm of PETN at 30.6 g. The prototype equivalent of 1.005 gm of PETN at 50 g is 125.6 kg of PETN or 174.6 kg of TNT; this hypothetical prototype was also to be modelled with 0.5 gm of PETN at 63.0 g and with 1.5 gm of PETN at 43.7 g. And finally, the prototype equivalent of 1.005 gm of PETN at 80 g is 514.6 kg of PETN or 715.2 kg of TNT; this was to be modelled with 0.5 gm of PETN at 100.8 g, with 1.5 gm of PETN at 69.9 g, and with

2.0 gm at 63.5 g. Twenty-six models were tested. If different scales predict within a group the same prototype crater volume, then modelling of models has been achieved and there is said to be no scaling effects within those ranges of scale and acceleration.

All model preparation and testing were identical to those models discussed under research question number 1, except that the diameters of the explosives were changed when the weights of PETN were changed, to maintain a height to diameter ratio as close to one as possible, and sand density changed slightly due to a change in graduate student..

b) Results:

The data of the twenty-six tests conducted are listed in Table 3 and plotted in Figure 3 in logarithmic space relating the logarithm of gravities to the logarithm of prototype volume. Four models were discarded in further analysis being identified as outliers using Dixon's (1953) method. The reasons for eliminating these four points was based on statistical concepts and no physical explanations are suggested; certainly there is no pattern to the outliers which suggests a different trend in the data.

The results plotted in Figure 3 show that within each group a single hypothetical full scale crater has been modelled, with variation of no more than $\pm 6\%$ when outliers are eliminated. The results further show that when data points of explosives of the same weight are connected for 0.5 gm, 1.0 gm and 1.5 gm charges, the result is three lines very close to being parallel. This means that the same relationship between explosive weight and crater volume exists for model explosives both larger and smaller than 1 gm of PETN, and there is no hidden explosive size effect. This also means that the same family of data could also have been collected by working at one acceleration, N , and increasing the weight of the explosive, although the latitude for the size of prototype explosive weights that could be modelled in this way is less: since π_w is a function of WN^3 much greater variation in the prototype modelled can be achieved by varying N .

Two other points are relevant to the question of scale effects using consistency of crater shape as a measure. First, the values of the ratio of crater depth to crater radius vary from 0.20 to

Table 3 - Test Results for Modeling of Models - Ottawa Sand

Shot #	MODEL DATA			PROTOTYPE EQUIVALENT	
	Explosive Wt. (gm)	Acceleration (gravities)	Crater Volume (cm ³)	Equiv. Weight (kg of TNT)	Crater Volume (m ³)
78	0.5	44.1	62.9	59.9	5.397
89	0.5	44.1	62.7		5.380
77	0.5	44.1	58.4		4.975
92	1.0	35.0	124.2		5.325
93	1.0	35.0	136.6		5.856
79*	1.0	35.0	164.3		7.043
80*	1.0	35.0	157.9		6.772
81	1.5	30.6	198.2		5.678
82	1.5	30.6	199.8		5.728
73	0.5	63.0	52.5		174.6
74	0.5	63.0	55.4	13.861	
64	1.0	50.0	110.1	13.767	
75	1.5	43.7	161.8	13.487	
91	1.5	43.7	161.1	13.427	
76*	1.5	43.7	189.2	15.760	
83	0.5	100.8	46.2	715.2	47.295
95	0.5	100.8	43.5		44.702
84	0.5	100.8	40.1		41.058
90	0.5	100.8	49.9		51.087
85*	1.0	80.0	76.8		39.314
88	1.0	80.0	89.5		45.815
94	1.0	80.0	95.0		48.616
86	1.5	69.9	134.6		45.966
87	1.5	69.9	137.2		46.870
96	2.0	63.5	191.1		48.941
97	2.0	63.5	172.9		44.270

* Result not included in the analysis as being outliers according to Dixon's method.

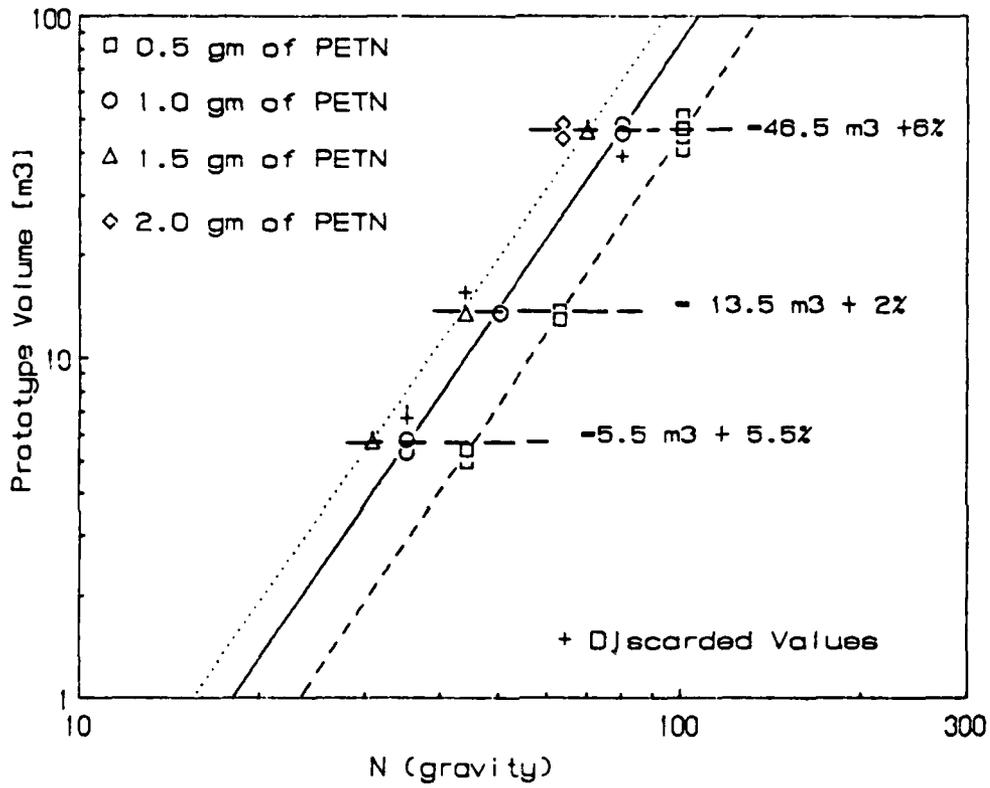


Figure 3 Prototype Volume vs. Gravity - Log-Log Scale

0.29 without a discernible pattern through all test accelerations and for all sizes of charge. And second, a model crater of a given model volume, regardless of either the acceleration or the weight of the half-buried PETN explosive used to produce the crater, has approximately uniform depth and radius (compare, for example, test data of models 81, 82 and 96, or 93, 86 and 87). This is not surprising. The calculation of crater volume is a function of R^2 and H^1 , and the sum of twice the exponent governing crater radius and once the exponent for depth as a function of explosive weight at 1g is equal to the exponent governing crater volume: $2(0.28) + (0.28) = 0.84$. The shapes of craters then, are approximately uniform and are not related to scale in this range under these test conditions.

c) Conclusions:

The results of the technique of modelling of models indicate that there are no undesirable acceleration related scale effects for the configurations tested at scales varying between $N=31$ and $N=101$ provided all soil and explosive conditions are the same in all models and the product WN^3 is a constant. The pattern of the results confirms the relationships between explosive weight and crater size developed in the discussion of research question 1. Further the shapes of all craters are approximately the same and are not related to scale.

Research Question Number 3: Are there particle size effects in that range of scales typical of geotechnical centrifuges which also should be considered in the selection of scale and prototype soil which can be used in the model?

a) Method:

Under ideal circumstances, soil from the field would be used directly in a centrifuge model to ensure identical stress and strain in model and prototype. A question arises, however, as to possible differences due to the effects of unscaled particle size in a small model where particles are,

proportionally speaking, much larger than in the full scale prototype. This question was addressed in two ways.

First, four sands were selected being as close as possible to each other with respect to mineralogy and angularity, with parallel grain size distribution curves but differing significantly in particle diameter. Ottawa sand, used in all models for research questions 1 and 2, did not exist in sufficiently different grain sizes for this research question. Instead, sand from a different soil deposit in Mystic Connecticut was chosen. The grain size distributions for the four sands, MWSS 85, MWSS 45 (the sand most similar in particle size to the Ottawa sand), MWSS 18 and MWSS 10, is shown in Figure 4. These quartz sands were significantly more angular than the quartz Ottawa sands. They were all deposited to achieve a unit weight as close to each other as possible, in this case, 15 kN/m^3 . Eleven models were accelerated to 65g, half-buried 1gm charges of PETN were detonated, and the resulting craters measured. The sizes of the craters were compared to examine the presence or absence of particle size effects.

The second approach was to take one sand with grain size different from the Ottawa sand used in the previous tests, and to detonate a series of six half-buried 1gm charges of PETN at different accelerations. The relationships between acceleration of the model and the crater dimensions could then be compared to those developed for Ottawa sand with a different grain size, again a measure of grain size effects.

b) Results

Table 4 gives data of all the tests conducted in these two series. Figure 5 shows a plot of grain size vs crater volume for the results for the first approach to the question; 5a is uncorrected for differences in unit weight and 5b is "corrected" using the relationship between γ and model crater volume developed for Ottawa sand in research question number 4 in the absence of separate tests for the MWSS soils. If grain size had no effect on crater volume, then all craters in all four sands would have had the same dimensions and would plot on that figure as a horizontal line. It is clear that this is not the case here. In figure 5a, there is a significant increase in crater size with

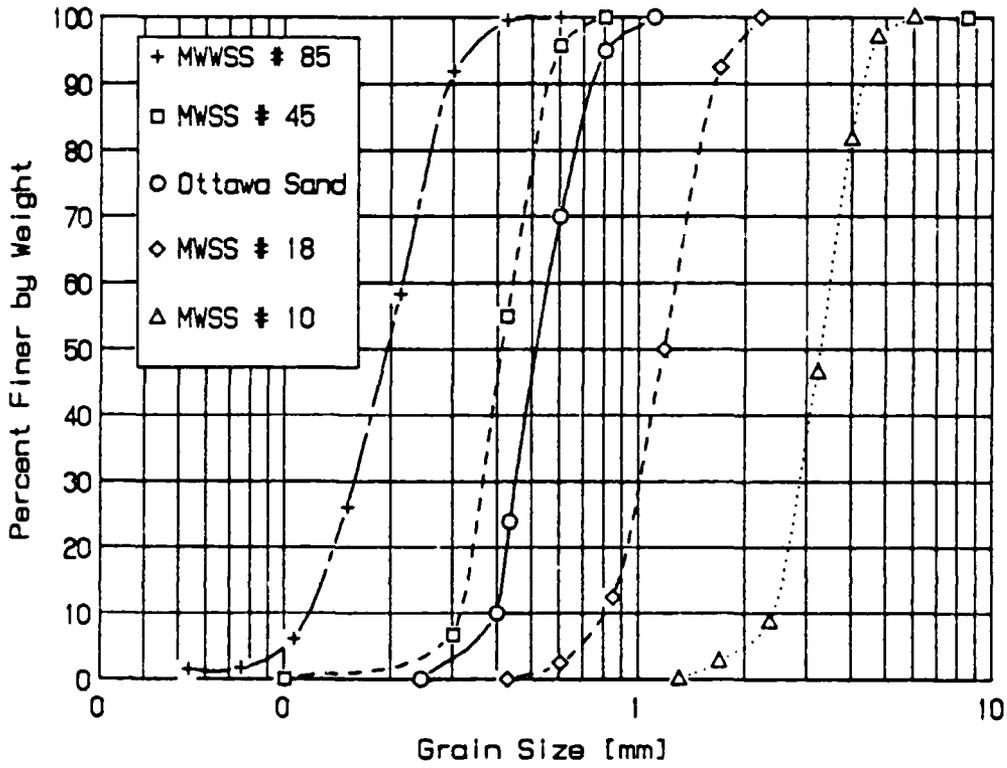
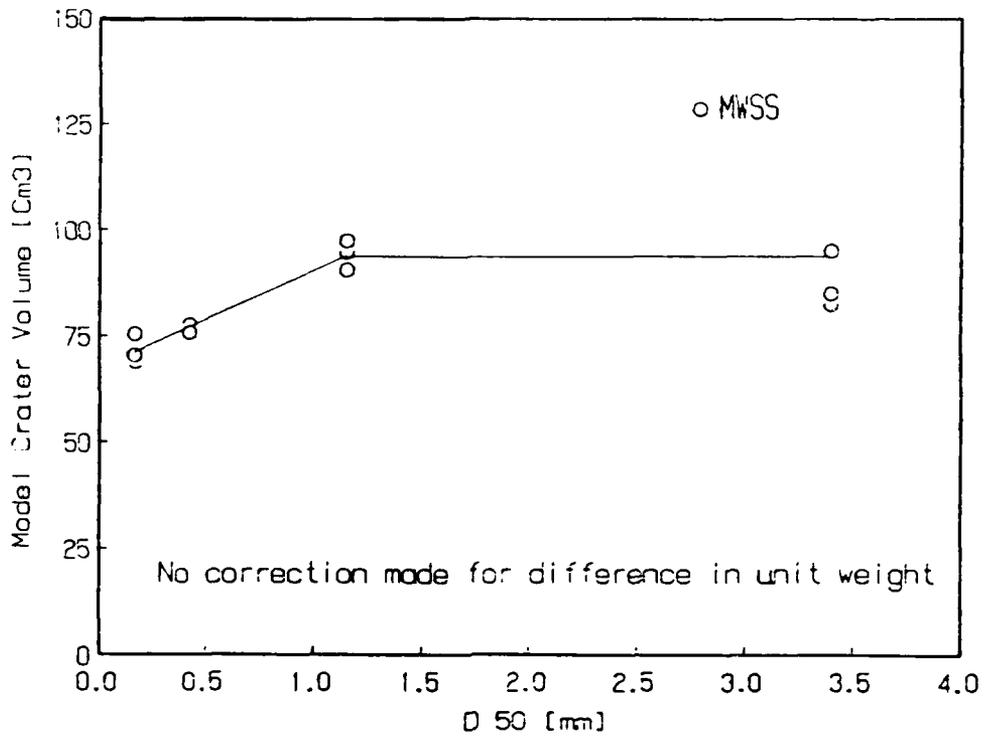


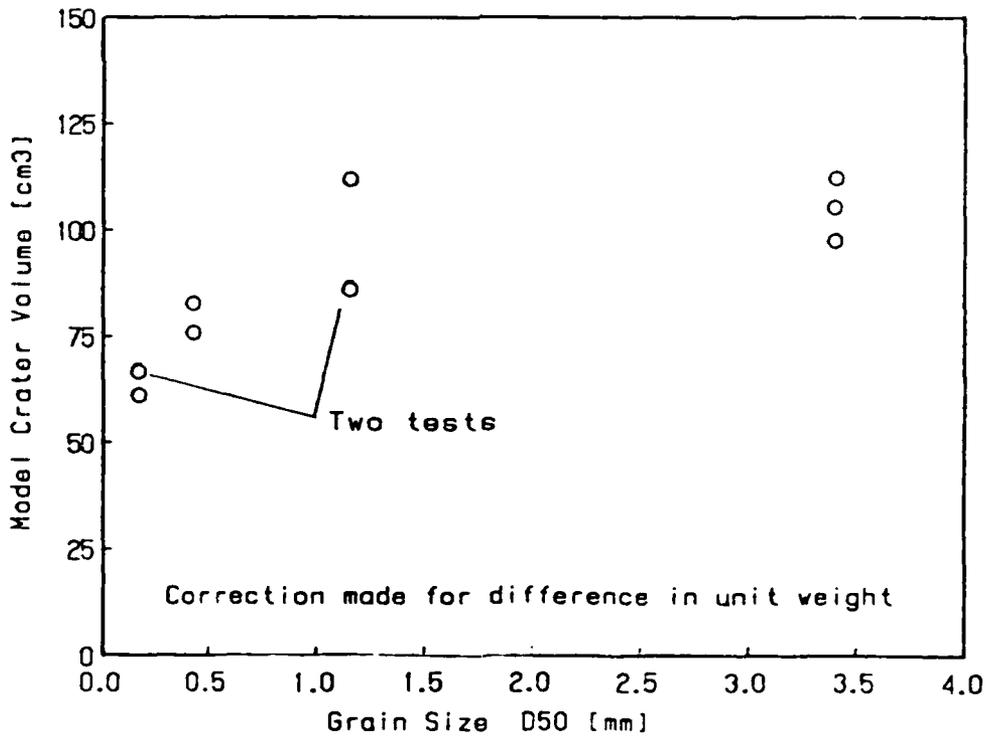
Figure 4 Granulometric Curves for the Five Sands Used in this Research

TABLE 4 Test Data in Mystic White Silica Sand

Test #	Accel-eration (g)	Charge Parameters					Box Parameters				
		W Charge Mass (gm)	R Charge Radius (cm)	L Charge Length (cm)	D Charge Density (gm/cm ³)	D.O.B. Charge Location	I.R.I.N. Charge Preparat.	Sec- tion of Sand	Depth (cm)	Type of Sand	Sand Density (100/m ³)
105	65	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#10	15.40
106	65	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#10	15.30
107	65	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	14.91
108	65	1.005	0.48	0.89	1.560	H.B	I.N	C2	25.41	MWSS#18	14.81
109	65	1.005	0.48	0.92	1.509	H.B	I.N	C1	25.41	MWSS#45	15.00
110	65	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#45	15.11
111	65	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#85	14.91
112	65	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#85	14.81
113	65	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#85	14.81
114	65	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	15.30
115	65	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#10	15.30
116	35	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	14.81
117	35	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	15.21
118	35	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#18	14.81
119	80	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	14.81
120	80	1.005	0.48	0.94	1.477	H.B	I.N	C2	25.41	MWSS#18	15.00
121	80	1.005	0.48	0.94	1.477	H.B	I.N	C1	25.41	MWSS#18	14.81



(a)



(b)

Figure 5 Model Crater Volumes for Differentes MWSS Sands at 65g:(a) Not Corrected, (b) Corrected

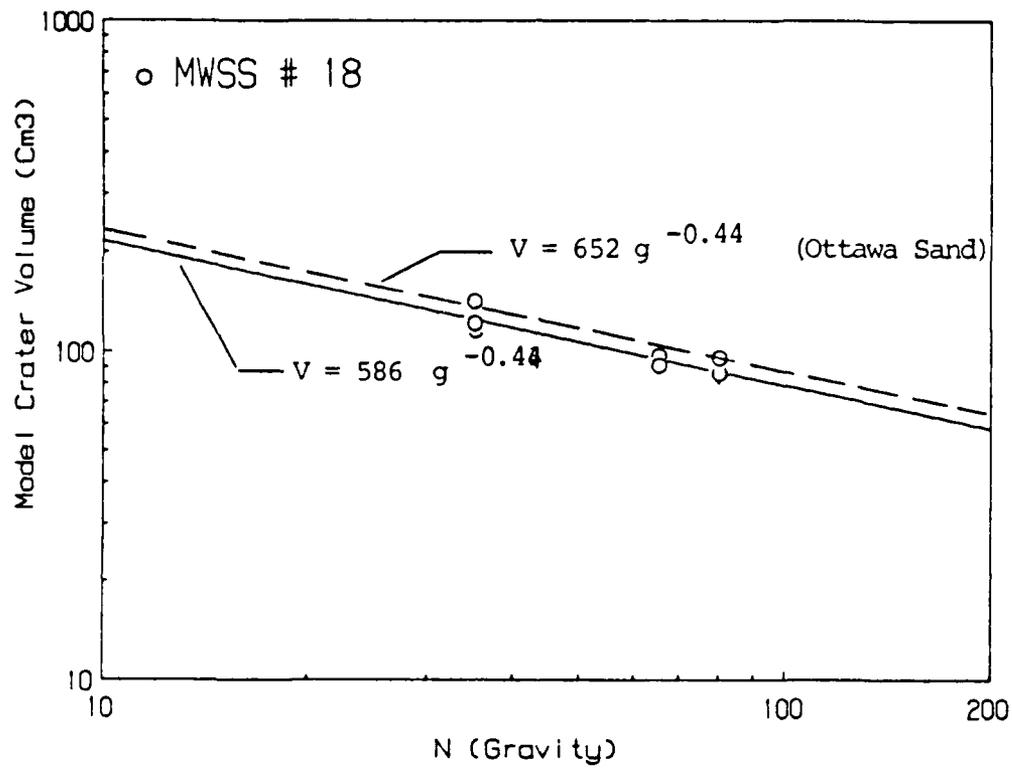


Figure 6 MWSS 18 - Model Crater Volume vs. Gravity

increasing grain size from $D_{50} = 0.16$ mm through $D_{50} = 0.42$ mm up to $D_{50} = 1.15$ mm: the difference in crater size is 32%. In the "corrected" figure 5b, the difference is greater. It may also be noteworthy that the values of ϕ for MWSS 18 and MWSS 45 from static low stress shear tests are 48° and 42° , respectively, which by itself would be expected to cause a reduction rather than an increase in volume with increasing grain size if those difference were relevant under these loadings. In the sand with grain size larger than that of MWSS 18, however, there is little effect of grain size. It is possible to speculate that this trend is due to the fact that large grains usually have more flaws than small grains, which will lead to more particle breakage during the explosion and larger craters, or that a large number of small voids in fine soils acts to reduce the efficiency of transmission of stresses causing cratering. The degree of particle breakage in a soil is likely to be an unscaled function of the actual size of explosive used, although within the range of tests conducted with Ottawa sand with explosive weights varying between 2.0gm and 0.5gm there was no apparent influence of particle breakage. In a model the energy released will be much less than in a prototype so that particle breakage may also be much less, but the relative effect of the breakage on the resulting model crater dimensions and the extrapolated prototype crater size may be much more. This question is not answered by these tests. Nonetheless, the trend of these results is consistent with the conclusions of Piekutowski (1975). It is in contradiction, however, to the conclusions of Schmidt and Holsapple (1978) who maintained that there are no particle scale effects at high accelerations, but they did not consider effects of soil unit weights, a very important variable influencing on crater size.

The second series of tests to examine grain size effects was carried out using one sand, MWSS 18. Data of these tests is given in Table 4 and plotted in Figure 6. The variation of model crater volume as a function of acceleration follows a trend very close to that found for Ottawa sand in spite of differences in grain size, density and angularity. The slope of the logarithmic relationship between N and model crater volume was calculated by a linear regression analysis to be -0.438 which is very close to that obtained for Ottawa sand tests conducted in this work, -0.443, although the intercept is different.

It is also of significance to note that although the MWSS45 and the Ottawa Sand were most similar in grain size and both quartz, the craters in the Ottawa Sand are larger at 65g notwithstanding the fact the unit weight of Ottawa sand was greater, which Piekutowski (1974), Dillon (1972) and work in this research mentioned later under research question number 4 have shown leads to smaller craters in a given sand. It is possible that this may be affected by differences in shear strength: static direct shear tests showed that the peak angle of friction for MWSS 45 was 42° and for Ottawa sand was 39° , and if these strength values are relevant then the weaker soil is expected to develop a larger crater. The difference may also be a function of cratering efficiency as well as angularity, which may influence the frequency of particle contact breakage.

One further point is relevant regarding grain size. The Ottawa sand craters showed a ratio of crater depth to crater radius varying without apparent pattern between 0.20 and 0.29, and this same range was also observed for models of MWSS 85 and MWSS 45 at 65g. This was not observed for MWSS 10 and MWSS 18: the average value of that same ratio measured in twelve models tested at 35g, 65g and 80g was 0.34 ± 0.04 . This was because crater depths tended to increase in those models with larger grains although radii stayed approximately the same. This may be a further indication that particle breakage, logically greatest directly under the explosive where confinement is greatest, may be an important factor in this trend.

The magnitude of these effects remains unquantified at this point with this limited data but it highlights the point that replication of grain size alone is not a sufficient standard for choosing a model soil. Questions therefore remain regarding the effects on crater dimensions of both grain size and angularity. Only data of real prototypes conducted in different sand and compared both to each other and to models can answer these questions.

c) Conclusions

Grain size has clear effects on model crater size and may be a function of model explosive size but not of acceleration. Soils with larger grains developed larger craters, possibly due to

particle breakage. The effect of grain size on field explosions is unknown until further parametric tests are conducted. Angularity of grains and relatively small differences in soil strength may also be important to model crater size.

Research Question Number 4: How sensitive is crater volume to the unit weight of the sand?

Piekutowsky (1974) found marked effects on crater volume of relatively small differences in soil unit weight. Although Schmidt and Holsapple's (1980) and Serrano's (1987) techniques were intentionally very similar, Schmidt and Holsapple reported craters with volumes smaller than those of Serrano and the unit weight of soils used in their tests was consistently greater than Serrano's. It therefore seemed likely that γ was an important variable in crater size.

In order to examine the importance of overall sand density on crater formation in this research, two tests were performed using Ottawa sand deposited at unit weights intentionally less than those in all other models of Ottawa sand: model 66 was tested at 50g with Ottawa sand at 15.60 kN/m^3 ($D_r = 29\%$) and model 67 was also tested at 50g but with $\gamma = 15.89 \text{ kN/m}^3$ ($D_r = 44\%$). The results of these tests and two others conducted at 50g with $\gamma = 16.78 \text{ kN/m}^3$ ($D_r = 89\%$) and $\gamma = 16.87 \text{ kN/m}^3$ ($D_r = 93\%$) are shown in Table 5. These results are plotted in Figure 7: here the best fit to the data predicts an 8% decrease in unit weight or a 36% decrease in D_r results in a 72% increase in crater volume. Piekutowski (1974) performed three tests at 1g in the same sand with 16.09 kN/m^3 and 17.67 kN/m^3 in which the apparent crater volume obtained was 71% larger for the test conducted in sand at 9% lower density.

It is apparent, then, that small differences in the unit weight of a sand lead to large differences in crater volume. This is a parameter relevant to field explosions and in examining data of field tests, does not appear to be emphasized in site investigations before tests.

TABLE 5 Tests at 50g in Ottawa Sand at Different Unit Weights

Test #	Unit Weight of sand KN/m ³	Crater Parameters			Lip Parameters		
		Radius cm	Depth cm	Volume cm ³	Radius cm	Height cm	Volume cm ³
65	16.87	6.73	1.9	123.6	9.0	0.32	73.6
72	16.78	6.45	2.4	119.6	8.0	0.30	45.9
66	15.60	6.90	3.2	180.4	8.0	0.21	15.9
67	15.89	8.11	2.7	195.9	9.0	0.18	22.5

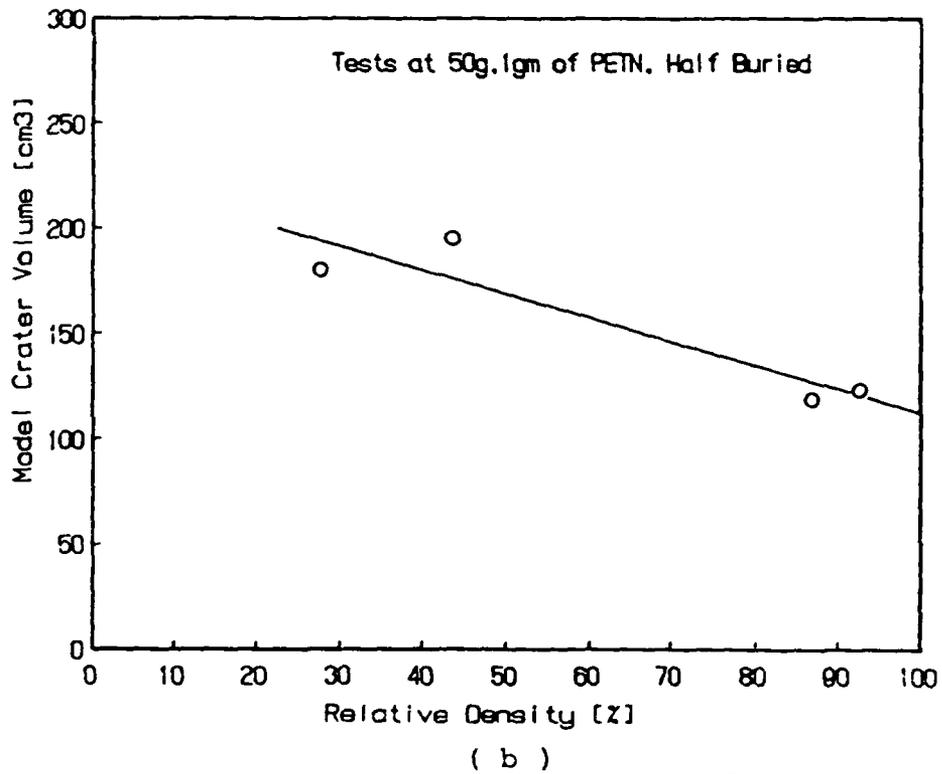
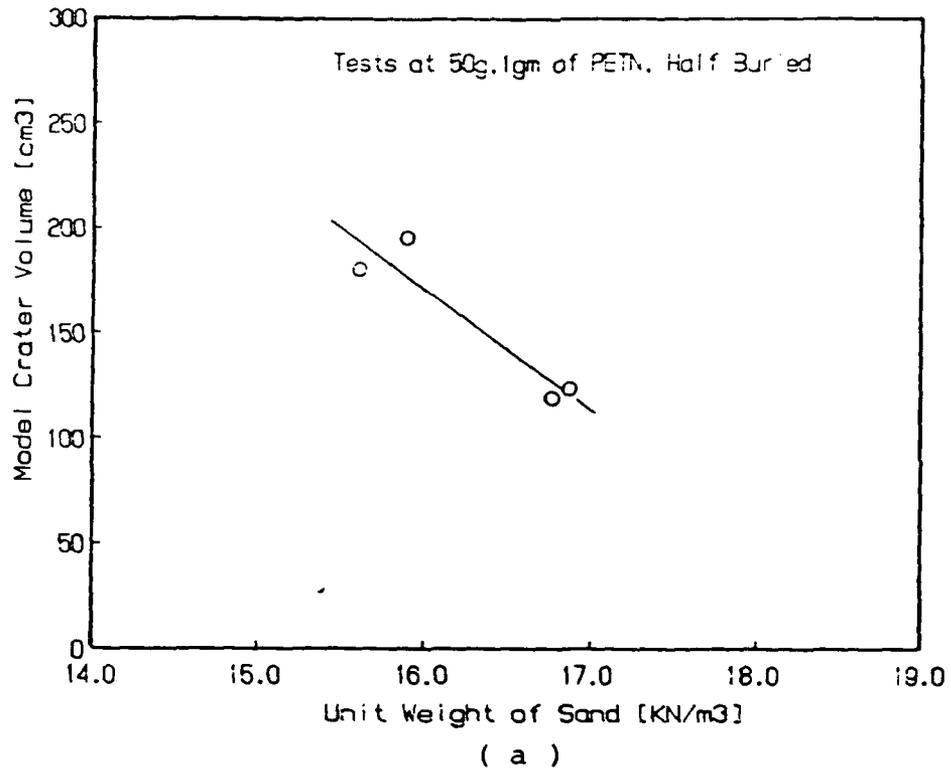


Figure 7 Variation of Model Crater Volume as a Function of: (a) Unit Weight, (b) Relative Density

Research Question Number 5: How sensitive is crater volume to charge location?

a) Method

In order to clarify the importance of charge location, a series of six tests was carried out at 65g using 1gm charges of PETN; two were half-buried (102 and 103), two were surface tangent (98 and 99) and two were fully buried just below the soil surface (100 and 101). Three other tests were also conducted at 65g using 2gm charges of PETN, half-buried, but two were laid with their longitudinal axes horizontal, one half-buried and one surface tangent (lying on the soil surface), and the third was half-buried but with its longitudinal axis vertical; the purpose of this was to investigate the effect of subtle differences in charge orientation.

b) Results:

The results of the first six tests are shown in Table 6. The trend observed in this series of tests is shown in Figure 8 where the crater volume is plotted against the charge location. Within this range of depths of burial, crater volume increases with depth of burial as less energy is dissipated to the air and more is transmitted to the soil. In comparing differences in crater volume when depth or height of burial is changed with respect to the crater volume obtained for the half buried charge, when the charge lies on the soil surface (HOB = 1.0) volume decreases according to the least squares fit to the data by 54.5%, and when it is buried just below the surface (DOB = 1.0) volume increases by 54.5%. This is similar, again, to results of Piekutowski (1974) who worked at 1g with 1.7gm charges of lead azide in beds of Ottawa sand with $\gamma = 17.65 \text{ kN/m}^3$: he found that crater volume was 30% greater for DOB = 1.0 and 30% smaller for HOB = 1.0.

Tests 68, 69 and 70 were 2gm charges with ratios of length to diameter equal to 1.7, unlike all other charges in which every effort was made to come as close as possible to one. This was expected to exaggerate effects of charge orientation. Models 68 and 70 were tested with their longitudinal axes oriented horizontally. The difference in crater volume between the half-buried charge and the charge with HOB=1.0 was a decrease of 43%, close to the difference found using

TABLE 6 Effect of Charge Location in Crater Formation

Tests	Charge Location	Unit Weight	Crater Parameter		
		of sand KN/m ³	Radius cm	Depth cm	Volume cm ³
98	Surface tang. above (HOB = 1.0)	17.05	4.95	0.70	45.57
99	Surface tang. above (HOB = 1.0)	17.15	5.21	0.80	49.55
100	Surface tang. below (DOB = 1.0)	17.15	7.35	2.00	160.48
101	Surface tang. below (DOB = 1.0)	17.14	7.17	1.80	154.04
102	Half buried (DOB = 0.0)	17.11	6.79	1.20	104.43
103	Half buried (DOB = 0.0)	17.21	6.32	1.20	93.54

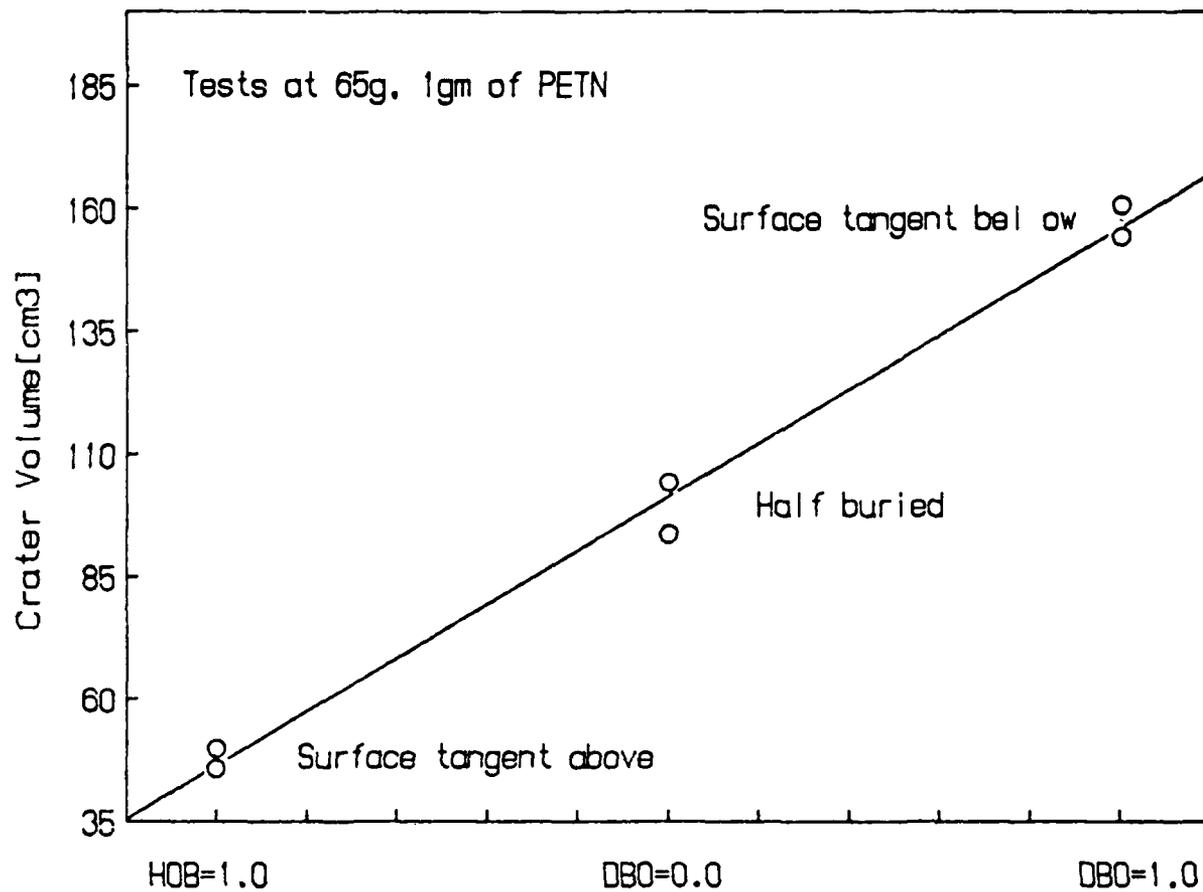


Figure 8 Model Crater Volume vs. Charge Location in Flintshot Ottawa Sand

1 gm charges. The effect of the reorientation of the charge when it was positioned vertically but still half-buried, was to increase crater volume by 18%. This highlights that explosive geometry, including both the shape of the explosive and the orientation, or distribution of the charge material, can be important to crater development.

c) Conclusions:

Relatively small differences in charge location can result in significant differences in crater volume. Charge geometry and orientation can also affect volume. These are factors important for consideration in field tests.

Research Question Number 6: What is the effect on crater dimensions of the depth and area of the soil bed on which detonation occurs?

a) Method

Boundary effects may arise from many sources in a model which attempts to simulate in a relatively small volume that which occurs in the field in a large deposit of sand with distant boundaries. The depth of the sand deposit in the model is one possible model boundary effect which required investigation. At 1g, where crater volume is largest, the effects of the depth of the sand deposit will also be greatest. Ten tests were conducted at 1g with different depths of Ottawa sand, varying from 19 cm to 41 cm.

Boundary materials and the area of the model deposit are other possible sources of boundary effects and these were also examined. Tests were done again at 1g where craters are largest and the boundary effects therefore the greatest. Some tests were conducted in square boxes with bigger sections and volumes than the cylindrical aluminum boxes used on the centrifuge in this research.

b) Results:

Figure 9 shows a plot of tests conducted on sand beds. There is no clear evidence of boundary effects arising from the depth of sand bed in this range. Certainly crater depth in no tests conducted was greater than 5.2 cm (and $R=11.6$ cm) at 1g and in centrifuge tests 3.2 cm (and $R=6.9$ cm). Rooke et al. (1974) concluded from field data that the presence of bedrock beneath a soil deposit affected crater formation only when the depth to the overburden depth was less than the crater radius, clearly never the case in any of these models. Surface area of the models had some effect: a three and a half fold increase in sample surface area led to a difference at 1g of a 10% increase in crater volume; effects on radius are negligible; effects on crater depth are greater, 35%, suggesting a change also in the shape of crater. More tests are necessary in this area, but there were also no discernible differences in prototype equivalent dimensions between craters created at 10g and those at higher accelerations, attributable to container size effects.

Crater lip dimensions were found to be more heavily influenced by model soil boundaries, especially soil depth, even when crater volume was not. Part of this may be due to the fall back of crater ejecta which bounces off the vertical sides of the box: Schmidt and Holsapple used model containers filled to the brim to eliminate that effect. But most field and other laboratory data neglect to include crater lip dimensions. It is therefore concluded that it is not an important measurement from a practical point of view, although it is important to understanding the overall mechanisms at work in cratering.

c) Conclusions:

Model soil depths between 19 cm and 41 cm showed no effect on crater volumes with depths of up to 5.2 cm. The proximity of model vertical boundaries did show an influence but no greater than 10% at 1g on crater volume for a three and a half fold difference in area. Crater lip dimensions were affected, possibly by the fall back of ejecta which would have otherwise been thrown from the area.

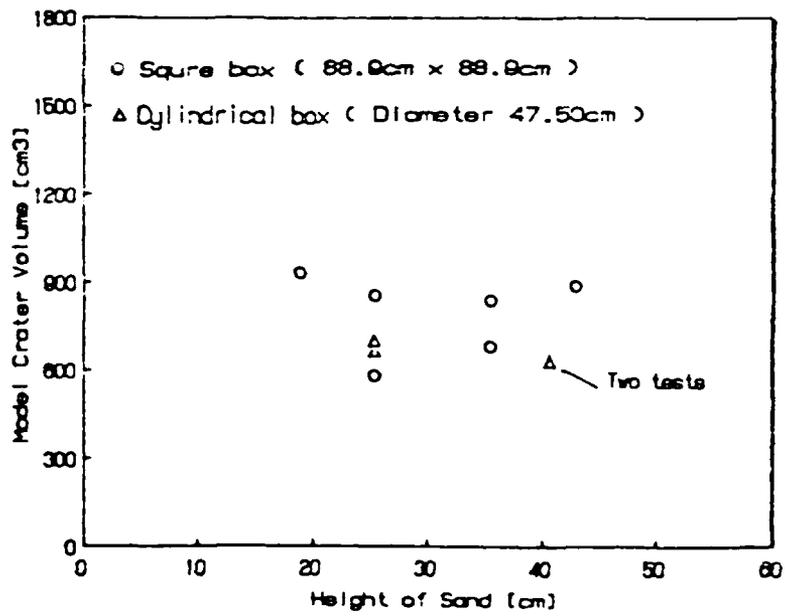


Figure 9 - Crater Volume vs Height of Sand
(1g, 1 gram PETN, half-buried)

Research Question Number 7: What is the influence of the centrifuge container itself on crater volume?

Schmidt et al. (1986) executed a series of four tests at 1g to measure the influence of the confinement of the centrifuge protective shell on crater volume. They found that as the test environment was more open the crater volume was significantly greater. Their data showed that the effect of confinement on crater size at 1g for charges located surface tangent may be such that craters produced outside the centrifuge are greater than craters produced inside the enclosed centrifuge by as much as 30%. Three tests were conducted in this work using half-buried, 1 gm charges of PETN. The trend of the results was the same as Schmidt et al.'s but the magnitude of the effect was less, 12%. Test acceleration, charge location, weight, size and possibly other boundary effects may all contribute to the difference in the magnitudes of the effect. Or, in the absence of a full battery of tests, this difference may only be scatter. No conclusions can be raised about implications with regard to prototype extrapolation, but the possible effect is troubling.

III. Overall Conclusions:

1. Explosion induced craters (from half-buried high explosives) are modelled on the centrifuge on beds of dry sand and governed by similar relationships from 1g to 463g. Extrapolation of centrifuge model data to prototype dimensions indicates that crater volume is a function of explosive weight as $W^{0.84}$, and radius and depth are functions of $W^{0.28}$. Careful full scale prototype confirmation of these points is still required. No "regime" effects were observed. This implies that small field tests may be conducted and extrapolated to larger field tests provided site conditions are uniform once similar relationships are developed for those conditions.
2. There are no detectable scale effects arising from model acceleration between scales of 31 g and 101 g.
3. Soil particle size and angularity appear to affect strongly both crater volume and shape. This may be influenced by the size of the model explosive used, but apparently not by acceleration.
4. Crater volume is extremely sensitive to the unit weight of dry sand.
5. Crater volume is sensitive to charge location, geometry and orientation.
6. There was no evidence of an effect from model soil depth from tests with soil depth greater than 19 cm for models with a maximum crater depth of 5.2 cm and crater radius of 11.6 cm. There was evidence of an effect on crater volume from model surface area, although it was relatively minor; the effect on crater radius was negligible, but on crater depth was greater. Crater lip volume was more strongly effected by model dimensions.
7. The centrifuge enclosure itself may be affecting model crater volume.

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V. Publications

1. M.S. Theses
 - i) C.H. Serrano (1987) "A Check for Scaling Effects on Explosion Induced Craters - Centrifuge Model Testing."
 - ii) V.H. Ferrero (1988) "Further Checks for Scaling Effects on Explosion Induced Craters - Centrifuge Model Testing"

2. Conference Proceedings
 - i) C.H. Serrano, R.D. Dick, D.J. Goodings and W.L. Fournery (1988) "Centrifuge Modelling of Explosion Induced Craters," International Conference on Geotechnical Centrifuge Modelling, April 25-27, 1988, Paris, France.
 - ii) D.J. Goodings and W.L. Fournery (1987) "Geotechnical Centrifuge Modeling of Explosion Induced Craters," Soil Mechanics Seminar, Sept. 14-15, 1987, M.I.T., Cambridge MA.

3. Journal Papers - one or two forthcoming.

VI. Professional Personnel:

1. Faculty Researchers

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2. Graduate Student Researchers

C.H. Serrano degree awarded: M.S. (1987) in Civil Engineering
V.H. Ferrero degree awarded: M.S. (1988) in Civil Engineering