COMPUTATION OF BLAST PRESSURES FROM FOAM PROPELLANT FOR COMPACTION OF SOIL

K. B. AGARWAL & B. SIVA RAM

University of Roorkee, Roorkee

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The knowledge of blast pressure characteristics is a pre-requisite for a suitable application of foam propellant to emergency military construction such as compacting of the soil from an aircraft using the foam propellant. The foam propellant considered here is a combination of hydrazine and ammonium perchlorate. The blast pressure is found to be a function of the quantity of foam propellant used and the distance of the observation point. This paper attempts to compute the blast pressures versus time characteristics of a foam propellant strip.

Compaction of loose soil, for civilian or military constructions, is generally achieved by movement of heavy machines such as smooth rollers, sheep foot rollers etc. which are not generally recommended for use in forward areas. The feasibility and suitability of foam propellant for compaction of loose soil have been studied in this paper by computing the blast pressure characteristics of the foam propellant and its ability to compact.

The constructive use of explosives is of recent origin although the common man still associates explosives with demolition and destruction. Some fields in which the controlled use of explosives has been mainly utilised are : (i) compaction by blasting technique, (ii) rock blasting and quarrying, (iii) metal forming or shaping, (iv) propellants for rocket propulsion (by using a class of explosives which yield energy less spontaneously), and (v) study of geotechnical properties of earth crest by subsurface sounding, and many other uses yet under developmental stage e.g. soil compaction by foam propellant which requires scientific knowledge about the action of explosives. It is further felt that a basic knowledge of the explosives and their resultant blast action, is essential for understanding their detonation for reliability, accuracy and economy. This paper evaluates blast pressures in case of foamed propellant strip by using and developing the knowledge of explosive action. This study is primary to all the subsequent controlled use of a foamed propellant.

EXPLOSIVES AND THEIR YIELD

Explosion generally refers to any system capable of spontaneous thermodynamic release of energy. An explosive is a chemical substance which on disintegration, due to proper oxidation—reduction, is capable of explosion. Explosives of various classes are gun powder, wheat flour dust, TNT (Tinitro to luene) etc. The effectiveness of an explosive is mainly decided by the rate of energy release or decomposition. The explosives which have very high decomposition rate are termed as high explosives in contrast to low explosives. The explosives may be obtained in a vast range with varying effectiveness. Gun-powder decomposes at a slow rate so that the destructiveness is very limited and used only where the explosive action is required to be sustained. The burning rate or speed of travel of detonation in a low explosive is of the order of a few meters/sec compared to a high explosive in which case it is of the order of a few thousand meters/sec. This is why dynamite is effective in rock blasting.

The heat unit 'calorie' is used to measure total energy release in an explosion. This energy is measured by (i) Sand Crush Test or (ii) Ballistic Mortar test, where impulse effect is measured. Laboratory methods include measurement of elastic energy stored in the explosive container. These values, are however, informative rather than exact. They are good enough for the purpose of comparison of two types of explosives[1]. The strength of an explosive is generally stated in units of 'one ton' TNT. The standard unit of TNT is the amount of energy released on detonation of one gram of TNT which equals 1100 calories i.e. approximately one million kilocalories per ton of TNT. Thus an explosive releasing 2200 cal/gram shall be termed as having strength of 2 TNT. Table 1 gives strength factors[2—4] of some important explosives on the basis of measured values.

TABLE 1

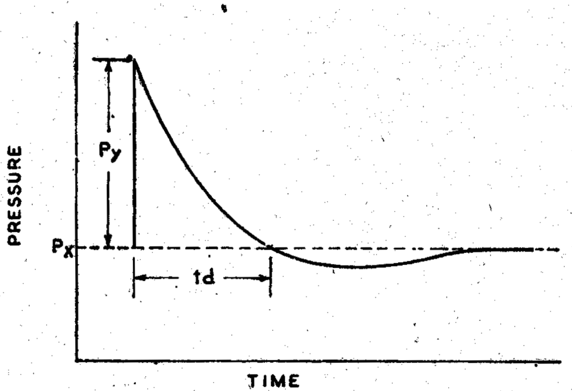
PROPERTIES OF SOME IMPORTANT EXPLOSIVE COMPOUNDS

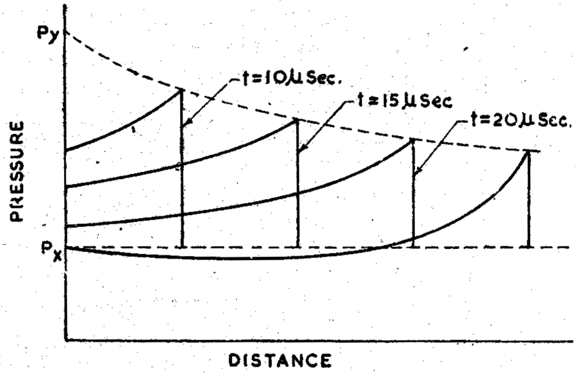
Explosive	Chemical formula	Molecular weight	Mp (°C)	Sp Gr	Explosive strength factor
Ammonium nitrate	$NH_4\text{-}ONO_2$	80	170	1·73	60
Ammonium perchlorate	$NH_4\text{-}ClO_4$	117	decompose	1·95	58
Hydrazine perchlorate	$N_2H_4\text{-}HClO_4$	132	—	—	122
Methyl nitrate	$CH_3\text{-}ONO_2$	77	—	1·22	180
Glycol dinitrate (GDN)	$C_2H_4\text{-}(ONO_2)_2$	152	20	1·48	160
Glycerin trinitrate (NG)	$C_3H_5\text{-}(ONO_2)_3$	227	2·2	1·59	186—128
Cyclotri-methylene (RPX)	$(\text{—}CH_2\text{-}NNO_2)_3$	222	204	1·82	160—130
Pentaery-thrital tetranitrate (PETN).	$C(CH_2\text{-}ONO_2)_4$	316	141	1·77	180—140
Dinitrotouluene (DNT)	$C_6H_3\,(NO_2)_3\,(CH_3)$	243	71	1·52	70
Trinitrotouluene (TNT)	$C_6H_3\,(NO_2)_3\,CH_3$	228	81	1·62	100

Blast Wave

An explosion generally produces blast wave when there is a huge release of energy. In an explosion the atmosphere around it is forcibly pushed back as there is a sudden release of voluminous gases many times more the explosive substance. This produces a uniform rising pressure pulse having different speed at different pressure level. The higher pressure value pulse overtakes the weaker, resulting in a saw tooth headed pressure pulse at a very short distance from source. This type of pressure wave with sharp initial peak is called shock wave.

In general, blast pressure at and any point first rises within a few micro-seconds and then decays exponentially at slower rate (see Fig. 1 & 2). The negative pressure portion of blast pressure is quite weak and therefore only the positive phase of blast wave is significant.





P_x — ATMOSPHERIC PRESSURE

P_y — PEAKOVER PRESSURE

td — DURATION OF +VE PHASE

Fig. 1—Blast wave.

Fig—2. Pressure distribution at different times (t).

FOAM PROPELLANT AND BLAST PRESSURES

The foamed propellant is an explosive mixture (liquid form for compaction purposes), suitably foamed up in order to generate a system useful for its engineering application. Physico-chemical studies regarding foams have been reviewed earlier[5]. The treatment henceforth pertains to a ribbon of foamed propellant that has been detonated at one of its ends. The explosion takes place throughout the system due to detonation wave whose velocity of travel will be explained subsequently. We shall henceforth be attempting to fiind the resulting blast pressure for this case. A model for the computation of blast pressures at various locations has been proposed. Fig. 3 shows model of a strip of foamed explosive in which the continuous propellant has been assumed to be made up of small explosive sources of definite weight to be concentrated on the nodes presumed distributed in the strip. Each of the source is supposed to act independent of the others. The blast pressures at any instant and at any location would be sum of all pressures contributed at that instant.

It may be noted that at any place and instant all of the nodes will not be contributing. One has to take into consideration the time lag caused by the detonation wave to travel a particular node, i. e. a node which is at a distance 'd' from the initiating end. The time lag that has to be considered for this node, will be $t_{lag} = d$ (Detonation vel.).

It is evident that for a node to start contributing pressure at a location (at distance '*d*' from the node) at least a time period of $t_{lag} + t_{reach}$ should pass, where t_{reach} is the time required for blast pressure to reach the location of the distance '*d*'. Finally the node will stop contributing the pressure as soon as the total time exceeds a period of $t_{lag} + t_{reach} + t_{dur}$' where t_{dur}, is the time duration of the blast wave.

Peak Overpressure

Brode[6] has numerically worked out peak overpressure generated in a nominal standard atmosphere in the following two cases : (i) a point source of one TNT strength; (ii) a finite size spherical source of one TNT strength. The action of the finite size of explosive is to allow the expansion of exploding gases thus allowing the reduction of overall pressure. The tables produced by Brode[6] have been sufficiently supported by the experimental results. These Tables give a correspondence between distance from the source and the per cent peak overpressure. A plot (for finite size TNT) for the peak overpressure ratio versus distance has been shown in Fig. 4 and equations have been proposed. These can be approximated to sufficient accuracy by expontential relations in four distance ranges (for finite size one pound TNT). The proposed relations for peak overpressure ratio $\frac{P}{P_x}$ are :

For $R < 10$ ft use $P/P_x = 1{\cdot}7 \times 10^3 R^{-4/3}$

For $10 \text{ ft} \leqslant R < 47$ ft use $P/P_x = 9 \times 10^3 R^{-2}$

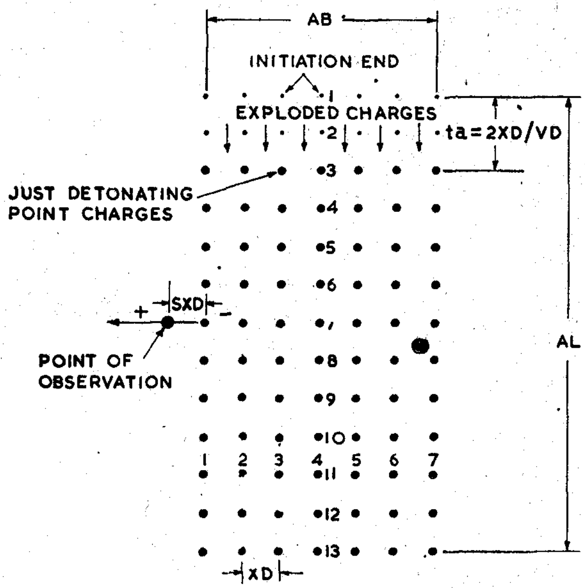


Fig. 3—Mathematical model for a strip of foam propellant.

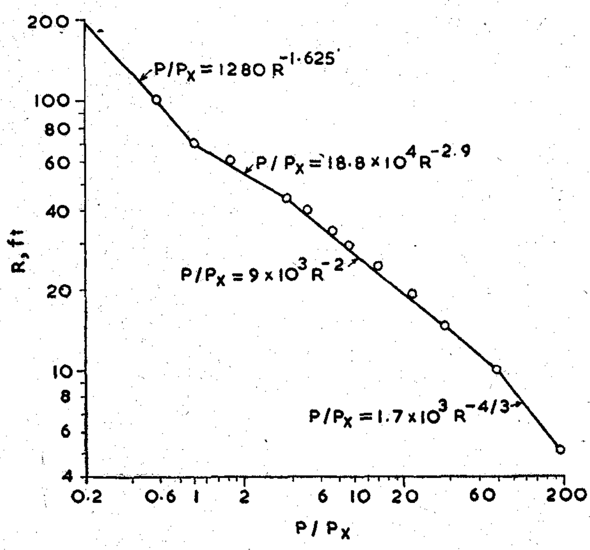


Fig. 4—Distance 'R' *vs* peak overpressure ratio (P/P)x) for finite size TNT.

For $47 \text{ ft} \leqslant R < 70 \text{ ft}$ use $P/P_x = 18{\cdot}8 \times 10^4 \times R^{-2.9}$

For $R \geqslant 70 \text{ ft}$ use $P/P_x = 1280 \times R^{-1{\cdot}625}$

Similar curves were obtained for point source by plotting them on double log graph. The intermediate curves for other charge sizes of same strength can be drawn by interpolating their values between the point source and the finite TNT. For this purpose, the charge size factor is defined as equal tc

$$\left(\frac{V,\quad \rho}{V_o,\ \rho_o}\right)^{\frac{1}{3}} = \left(\frac{V}{V_o} \times f_d\right)^{\frac{1}{3}}$$

where V is the volume of the actual explosive charge; V_o is the volume of TNT required to give the same yield; ρ and ρ_o are the densities at actual and nominal standard atmosphere respectively and f_d is the density factor.

A charge size factor of zero corresponds to a point source explosion and a value of unity corresponds to finite size TNT of nominal standard charge. Hoffman & mills[7] However nothing is available in literature regarding the charge size factor greater than unity. It can be further shown that charge size factor may be related to respective densities by following formula:

Charge size factor $= \left(\frac{\text{density of standard TNT. charge}}{\text{density of reqd. explosive} \times \text{strength factor}}\right)^{\frac{1}{3}}$. Values of strength factor are listed in Table 1 for some important explosives.

Charge size Factor of Foamed Propellant

The density of hydrazine and ammonium perchlorate mixture may be assumed to be about 1·65 gm/cc as it is a mixture of two phases namely ammonium perchalorate (constituting nearly 55% of the total mixture) with density not less than 1·95 gm/cc hydrazine with a density of nearly 1 gm/cc. On foaming, the density may reduce to half i.e. ·825 gm/cc and the charge size factor will be $(1{\cdot}62/{\cdot}825\times1{\cdot}22)^{1/3} = 1{\cdot}15$

Since no standard data appears to be available for such a case the charge size factor may be asssume to be euqual to one. The use of charge size factor of (=1) can further be justified because subsequently we idealize the foamed propellant as charges concentrated at points and the charge size factor will then be $(1{\cdot}62/1{\cdot}65\times1{\cdot}22)^{1/3} = {\cdot}94$. Therefore an average charge size factor of '1' may hold good.

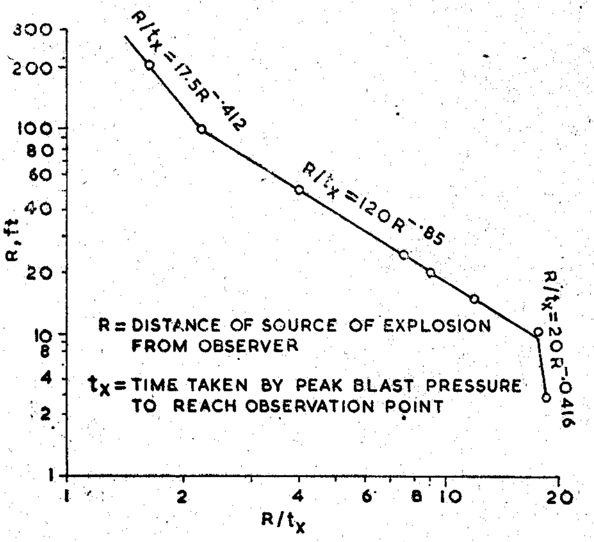


Fig. 5—Graph for Log R *vs* Log R/*tx*.

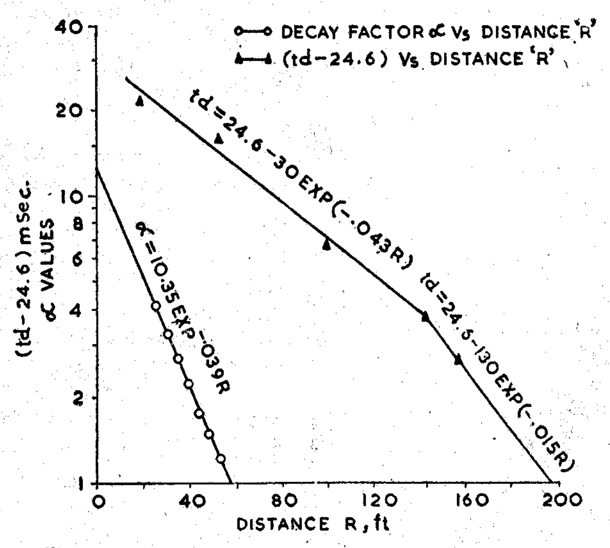


Fig. 6—Variation of factor α and time duration with distanc from source.

Arrival Time and Duration of Blast Pressure

The velocity of shock wave is uniquely related to peak overpressure. Thus arrival time for a given shock can be obtained in this manner, based on the data quoted by Kinney[8] as shown in Fig. 5.

$$\text{For } R < 10 \text{ ft}, \quad t = (1/44\cdot1).\ R^{1\cdot416}$$

$$\text{For } 10 \text{ ft} \leqslant R < 100 \text{ ft}, \ t = (1/120).\ R^{1\cdot85}$$

$$\text{For } R \geqslant 100 \text{ ft}, \quad t = (1/17\cdot5).\ R^{1\cdot412}$$

Fig. 6 shows the duration of blast pressure plotted against R (distance of source of explosion from observer) for a finite size 1 ton. TNT (Kinney[8]).

The equations assigned for various ranges are :

$$R < 15 \text{ ft}, \quad t_d = (3\cdot5 - \cdot2\ R)$$

$$15 \text{ ft} \leqslant R < 144 \text{ ft}, \quad t_d = \{ 24\cdot6 - 30 \text{ Exp } (-\cdot043\ R) \}$$

$$R \geqslant 144 \text{ ft}, \quad t_d = \{ 24\cdot6 - 130 \text{ Exp } (-\cdot015\ R) \}$$

Residual Shock Pressure

The shock pressure after passing a peak, exponentially decays. The intermediate pressure Pi can be evaluated by the formulae.

$$P_i = P_o \left(1 - \frac{t}{t_d}\right) \text{Exp} \left(- \alpha \frac{t}{t_d} \right)$$

where P_o is the initial blast pressure

t is time past after arrival of peak pressure of a shock wave

t_d is duration of the shock wave

α is decay parameter which can be obtained from the relation.

$$R < 60 \text{ ft} \quad \alpha = 10\cdot35 \text{ Exp } (-\cdot039\ R)$$

$$R \geqslant 60 \text{ ft} \quad \alpha = 1 = \text{constant}$$

Detonation Velocity

For the condensed explosives with density ρ_o between 1 to 1·6g/cc, the detonation velocity as quoted by Rinehart[9] may be taken directly proportional to the initial density as follows :

$$D = A\rho_o$$

where A is a constant and is equal to $4\cdot5 \times 10^5$ cm^4/g. sec for TNT.

In the present work, no attempt has been made to find new relation for the foam propellant and the same relation has also been used for ρ_o 1 g/cc. However the better relationship can be established experimentally.

SCALING LAWS

Scaling laws have been used in the present work to find the blast pressure for various cases.

Scaled Distances

Distances were scaled according to the energy equivalence relation.

$$\text{Scaled distance} = \frac{(\rho/\rho_0)^{\frac{1}{3}}}{(w/w_0)^{\frac{1}{3}}} \times (\text{Actual distance}) = \frac{f_d}{\lambda} (\text{Actual distance})$$

where f_d is density factor and is equal to $(\rho/\rho_0)^{\frac{1}{3}}$ and 'λ' is the yield factor given by $(w/w_0)^{\frac{1}{3}}$. Here w is weight of explosive detonated and w_0 is that for a nominal standard test.

Scaled Time

$$\text{Actual time} = (\text{Scaled time}).\ \lambda/f_d \times f_a$$

GR.	FOAM No. OF PROP.	CASE	DET. VEL. COEF.	XD (cm)	FOAM PROP. IN gm / SPREAD OVER cm^2	S	No. OF NODES LONGITUDINALLY (M)	No. OF NODES LATERALLY (K)
A	3	1	0.4	6	1	+1	13	7
	3	4	0.4	6	1	-2·5	13	7
	3	5	0.4	6	1	-1·5	13	7
B	3	4	0.4	6	1	-2.5	13	7
	4	2	0.4	6	1	-2.5	13	7
C	3	3	0.4	6	1.25	CENTRE OF STRIP	13	4
	3	6	0.4	3.6	1·25		13	6

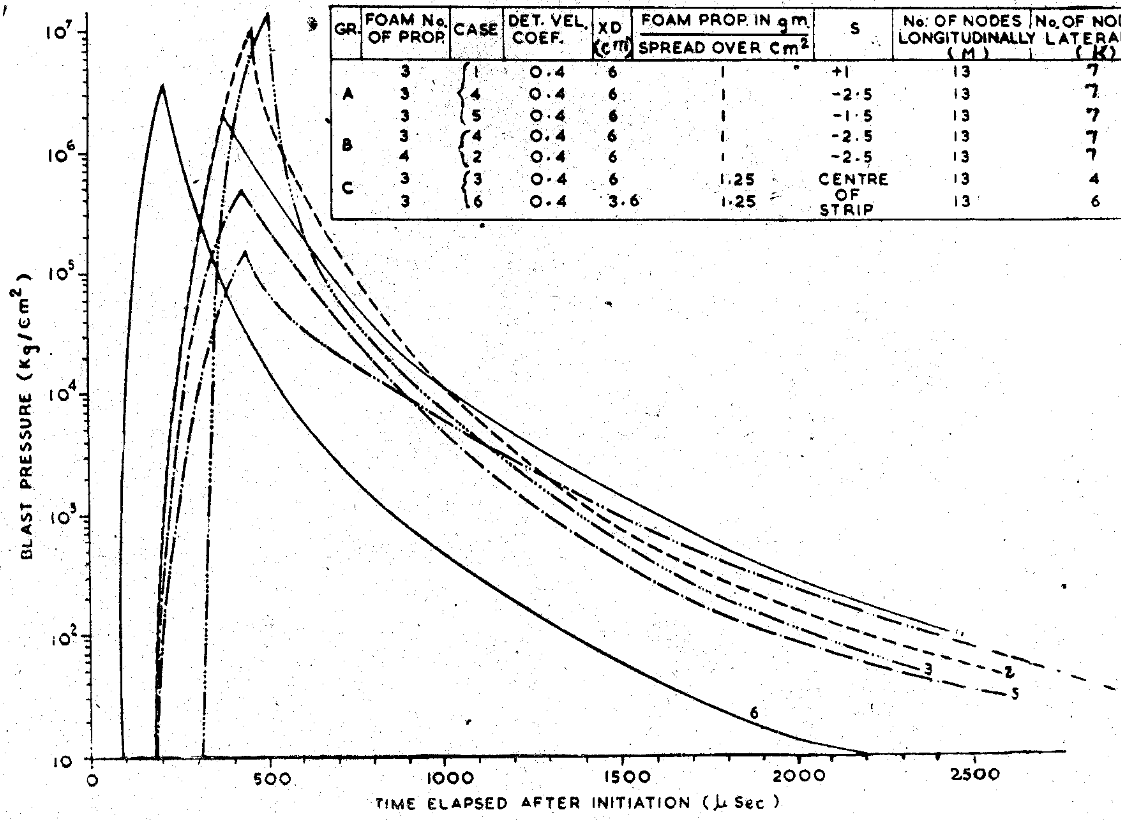


Fig. 7—Time elapsed after initiation (μ Sec.)

Where f_y is the transmission factor. It is the ratio of velocity in required media to that in the normal standard media.

RESULTS AND DISCUSSION

Extensive computer programme was devised to exactly represent the model shown in Fig. 3. The computations were based on the scheme as discussed earlier assuming the charge size factor and transmission factor as unity. The following physical parameters were varied :

F=The foam material in grams which has been spread over one square centimetre area.

FN_0=Foam number of foam propellant. It is the ratio of volume of foamed substance to the volume of parent liquid.

XD=The unit distance between node points in centimetres as shown in Fig. 3.

$(M\text{-}1)\ XD$=The length of foam strip considered for computation with 'M' nodes longitudinally.

$(K\text{-}1)\ XD$=The width of foam strip in centimetres and has been uniformly chosen=30cm except in group 3 where width is chosen as 18 cm. 'K' no. of nodes laterally considered.

$S.XD$=The distance of observation from the arbitrary origin as shown in Fig. 3.

The point of observation is orbitrarily choosen situated along the middle row of the propellaut strip and is generally the next extreme node of this row. S. XD is the distance fom the point of observation on the middle row considering postive to the left and negative to the right.

Results of the present study are given in Fig. 7 and 8.

General

The complete study of blast pressure and the influence of various physical parameters has been done in four groups. These groups have been listed on top of Fig. 7 and 8 which show variation of blast pressure with time. Group A consists of cases 1, 4, 5, where the influence of varying the point of observation from the centre of strip (case 4) to a point outside the strip has been studied and shown in Fig. 7. For this group, the value of foam quantity (F), Foam No. Nodal distance (XD) and number of total nodes ($M \times K$) were kept constant. It can be seen that the peak blast pressure is maximum at the centre and that the same gradually decreases as the point moves away from centre. In this case it can be noticed that significant blast pressure is experienced even at a point just outside the strip. The rise time to peak gradually increases for observation points which are away from the centre. The decay of the pressure from peak is relatively faster for points closer to the centre of the strip.

In group B (cases 4 and 2), the influence of varying the foam number on blast pressure has been studied by keeping the other parameters constant. It can be observed from Fig. 7, that for a given quantity of propellant, the foaming has a definite influence on the blast pressure. Greater the foam number, greater seems to be the peak blast pressure. After the peak, the pressure of bigger foam number drops rapidly.

Group C, study has been carried out to find the influence of varying the total area of propellant strip keeping the width constant. It is found from cases 3 and 6, the increased length of propellant strip has increased the arrival time to the centre of strip and has caused the increased pressure. However the rise time and decay time follow similar trend.

In group D, study has been carried out for the influence of variable quantity of foam propellant per unit area on blast pressure in cases 4, 7, 8 and 9. It is shown graphically in Fig. 8. It can be clearly observed from the Figure that the foam quantity plays an important part in governing the value of the peak blast pressure. The greater is the foam quantity per unit area greater is the peak blast pressure and the total time duration, but smaller is the rise time. The graph between foam quantity (gm/cm²) and the resultant peak blast pressure was plotted on log-log scale as shown in Fig. 9. The equation for the straight line relation fitted in the above plot is peak blast pressure $P/p_x = 8 \times 10^6 F^{2.556}$, where F is the quantity of foamp ropellant per square centimetre.

Depth of Compaction

The depth of compaction due to blast pressures can be studied by using the approximate formulae[10]. The depth to which the pressure wave penetrates one-dimensionally into a soil medium is given by :

$$XR = \frac{C_0^2}{g} \left\{ \left(\text{Exp} \left(\frac{\sigma}{\sigma - 1} \right) \frac{1}{\epsilon^*} \cdot \frac{g \triangle t}{C_0} \right) - 1 \right\}$$

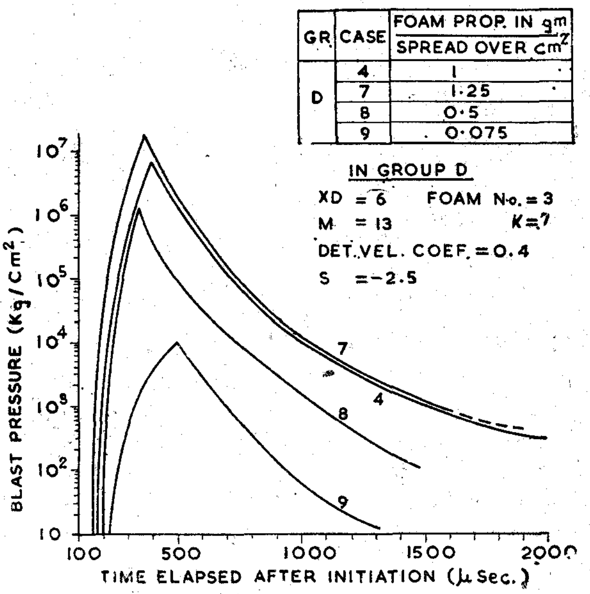


Fig. 8—Time elapsed after initiation (μ Sec.).

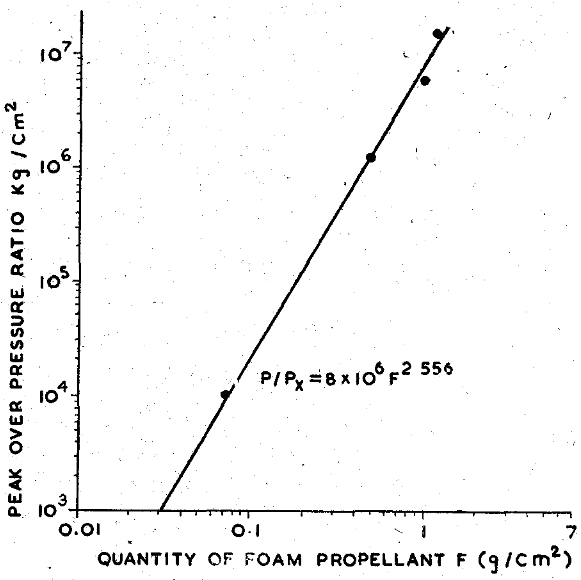


Fig. 9—Quantity of foam propellant F (g/cm²)

where

C_o is the wave velocity in 1D at zero pressure

g is acceleration due to gravity

$\sigma = (1 - k)^{-1/2}$ where k is the plasticity ratio i.e. unrecovered deformation to the applied loading deformation.

$\triangle t$ is time duration of blast in seconds pressure in seconds.

ϵ^* maximum strain at 1 D. at which further packing is impossible without crushing

The practically value may be guessed as :

$k=0\cdot75$, $\sigma=2$, $\epsilon^*=\cdot01$, and $C_o = 25$ metre/sec. (for very loose sand)'

$$XR = \frac{625}{9\cdot 80}\left\{\text{Exp}\ \frac{2\times 9\cdot 80}{.01\times 25}\triangle t - 1\right\} = 64.\ \left\{\text{Exp}\ (\ .0785\ )\ \triangle t - 1\right\}$$

Hence a pulse of 10 mili-seconds will penetrate one-dimensional to a depth of 100 metres and a pulse lasting for 5 mili-second to a depth of 32 metres.

The limitation of the above equation should not be overlooked as it assumes purely one-dimensional loading with no crushing of the particles. It also does not take into consideration the change in properties of soil due to dynamic loading. Assuming that the blast wave will last for 5 milli-seconds, it would at least penetrate up to a depth of about 3 to 4 metres, which seems to be more than satisfactory for surface compaction purposes. From the above discussion, it is felt that the quantity of $0\cdot075$ gm/cm^2 of foam propellant will be suitable for the emergency surface compaction of soil by this method.

CONCLUSION

The surface compaction of the soil can be achieved by using foamed propellant where the conventional methods cannot be adopted. Feasibility and suitability of compaction of soil by foam propellant by the help of theoretical consideration has been presented on the basis of current knowledge on the subject.

The computational method of finding blast pressure from a strip of foamed propellant, has been proposed here. The analysis reveals that a quantity of $0\cdot075$ gm/cm^2 of foam propellant will be satisfactory for compaction of loose soil up to a depth of about 3 to 4 metres.

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REFERENCES

1. ROBINS, C. S. (1944) "Explosions, their Anatomy and Distrectiveness", (McGraw Hill Book Co. N. Y.).

2. ROBINSON, C.S., (1944) "The Thermodynamics of Fire-arms", (McGraw Hill Book Co., Inc. N.Y.).

3. Lothrope and Handrick, (1949) "The Relationship Between Performance and Constitution of Pure Organic Explosives", Chem. Rew. Vol. 44, 419.

4. TOMILSON, W.R., "Properties of Explosives of the Military Interest", Picatinny Arsenal Technical Report 1940, Rev. 1, 1958.

5. AGARWAL, K. B. & SIVARAM, B. (1973) "Foams and their Application in Military operations and constructions" Golden Jublee Seminar On Plant Design and opration (New Structural Matterial and Substitute) held in H. B. I. T. Kanpur Jan 73.

6. HARELD, L. BRODE, "Numerical solution of Blast Waves", JR. of Appl. Phys. 26; 766 (1955) "A calculation of Blast wave from a spherical charge of T.N.T." Santa Monica. The Rand Corporation (1957).

7. HOFFMAN & MILLS (1956) "Air Blast Measurement About Explosive Charge at Side-on and Normal Insidence" Ballistic Research Lab. Report 988.

8. KINNEY, G.F. (1962), "Explosive Shocks in Air", (The McMillan Company, N.Y.).

9. RINEHART, J.S. and John Pearson, (1963) "Explosive Working of Metals", (Pergamon Press, Oxford).

10. GINSBERG, L., "Propagation of Elastic Shock Waves in the Ground", Journal of Structures Division, Proc. ASCE, Feb. 1964 page 125.