CHAPTER 26

Underwater blasting

26.1 INTRODUCTION

Underwater or submarine blastings are used for various types of labor such as the deepening of harbors and channels, the excavation of trenches for the installation of oil and gas pipelines and communication cables, water conducts for hydroelectric plants and factories, demolition of pillars and sunken ships, excavation for foundations in civil engineering, exploitation of consolidated deposits, etc.

All these operations call for a higher degree of specialization and experience than needed for surface work. Some factors which must be taken into consideration for successful results of these blastings are:

– The drilling and charging of the blastholes is usually done from the surface with special equipment.

– Powder factors are from 3 to 6 times higher than those in bench or surface blasts.

– The results of each round must be satisfactory because secondary fragmentation is difficult and costly.

– The explosives and initiation sequences have to have good underwater properties and be resistant to the hydrostatic pressure.

– The disturbing environmental effects are more noticeable because the land vibrations are usually accompanied by low frequency components whereas the hydraulic shock wave has a large radius of action.

26.2 METHODS OF EXECUTION

Underwater rock fragmentation can be performed with or without blastholes. In the first instance, the main inconveniences are:

– Little information of the rock mass and lack of topographical precision.

– Difficulty in maintaining the holes open for a length of time.

– Difficult control of collaring and blasthole deviation.

– Complicated planning and control of the operations.

– Risk of flash-over between holes.

– Secondary blasting and toe excavation are costly.

Within this group, the principal operation methods are:

a) Drilling and blasting through rockfill.

b) Surface drilling and blasting from floating pontoons or rafts and self-elevating platforms.

c) Drilling and blasting with divers.

d) When the water is not too deep, under 4 meters, it is usually advantageous to fill in the area to be excavated with rock material and drill and charge the holes through the filling.

e) Surface drilling is done from two types of structures: floating pontoons or rafts and self-elevating, spudded platforms.

There is no standard design, because many of these structures are built for specific labors and are taken apart afterwards. The choice of one or another depends upon the environmental conditions, tides, waves, etc., and of the magnitude of the operation. Drilling from a self-elevating platform eliminates many of the interruptions caused by exterior agents, but a higher initial investment is called for because of the necessary special equipment to put the spudded platform on its feet.

The work area, which is similar to a workshop, is in function with the excavation volume which, at the same time, conditions the amount of main and auxilliary equipment needed. The first are the drilling rigs, the compressors and the boilers, and the second are the generators, the anchor wires, the winches, the explosives store, the warehouse, the control cabins and offices, etc. In Fig. 26.2 two types of rafts are shown, with drilling from the side (a), through a central well of the raft (b) and a self-elevating platform (c).

The objective persued with these structures is to carry out the maximum number of blastholes and operations from them, apart from the existing conditions. Also, the rigs are usually set up on high towers or masts which lessen drill steel lengthening and tubing operations, Fig. 26.3.

At the same time, the drilling rigs are mounted upon individual mobile frames, which permit the drilling of a row of blastholes, and by moving the frame itself, the next row can be drilled in the same manner. This facilitates the drilling of a large area with having to change the position of the platform, which reduces the work cycle time.

The rafts are anchored to various fixed points to avoid lateral movements and allow, when necessary, a change in position. The vertical effect of the waves can be overcome with special devices in the drilling rigs which maintain a constant pressure against the bottom of the blasthole, The winches and anchor wires are moved by compressed air, hydraulic or electric energy. Special precautions must be taken in this last case to avoid chance ignition of the electric detonators derived from the stray current.

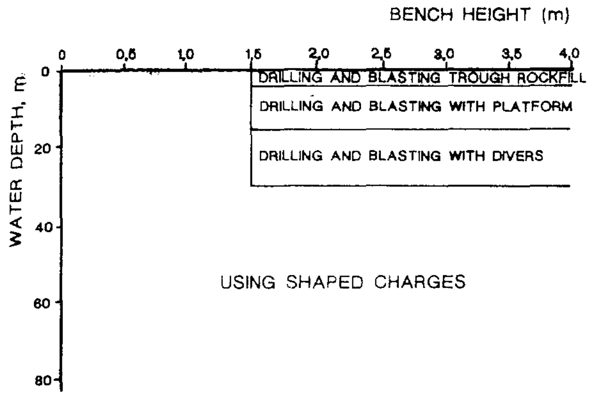

Fig. 26.1. Fields of economic application for the different drilling methods in relation to the bench heights and water depth.

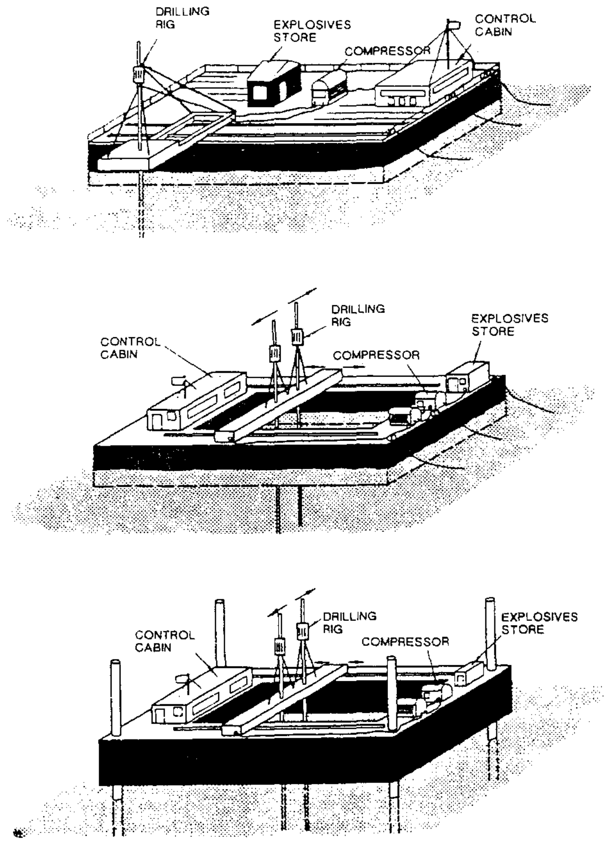

Fig. 26.2. Types of floating pontoons or rafts and self-elevating, spudded platform.

The main advantages of these methods are:

– Drilling and charging of the blastholes from the surface in more favorable conditions.

– The visiblity in the water does not affect the work.

– Lower costs because of fewer diver hours.

On the other hand, the main inconvenience is the high initial investment in the building of the structures and their equipment.

As to the drilling procedure, usually special OD or ODEX rigs, described in the first part of this handbook, are used. The first one has an outer casing tube with a ring bit of cemented carbide at the lower end with which the surface is drilled, and once the rock bed is reached it penetrates around 10 to 30 cm and the rest of the blasthole is drilled with the inner drill steel and is not affected by loose material.

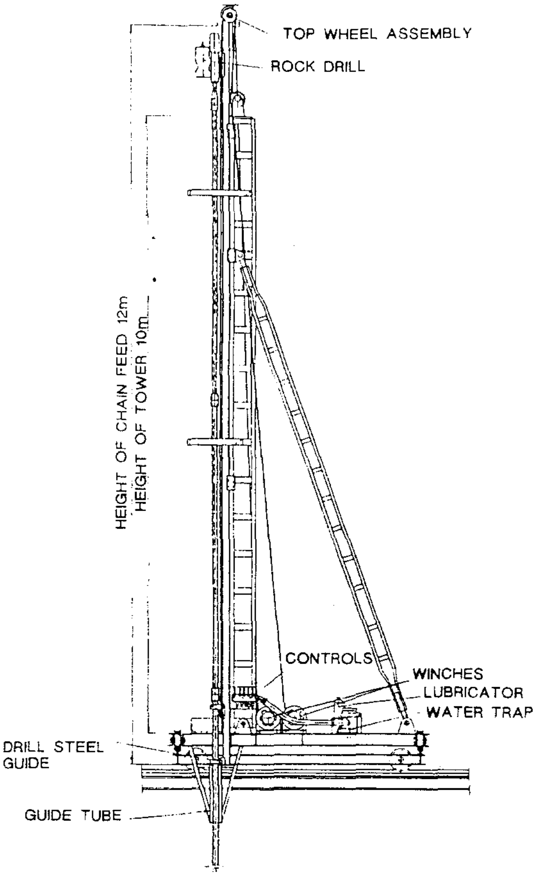

Fig. 26.3. Drilling mast (Atlas Copco).

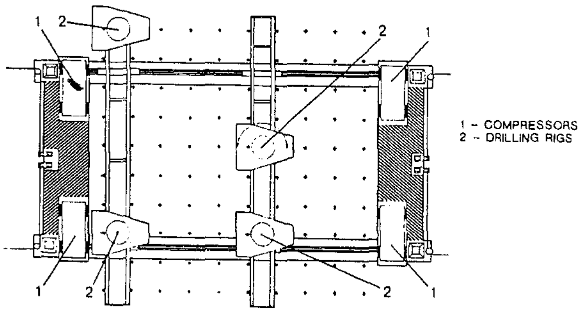

Fig. 26.4. Scheme of a self-elevating platform with a mobile frame.

The ODEX rig consists of a reamer that is used with a excentric bit which drills a larger opening, permitting the continuous use of casing in the blasthole. The drilling can be stopped at any given moment in order to change to the regular equipment. In this case either a top hammer or down-the-hole can be used.

Finally, fragmentation without use of blastholes will be studied in headline 7 of this chapter.

26.3 CALCULATIONS FOR CHARGES AND DRILLING PATTERNS

The basic differences between bench and underwater blasts are that the latter only has one free face, that the water and the overburden that rests upon the rock create a force or pressure and that the collaring errors and blasthole deviation can provoke a poor rock breakage and, there is risk of flash-over between charges.

To calculate the powder factor, the following equation is used:

$$CE = 0.5\,(\text{kg} \times \text{m}^{-3}) + 0.1\,(\text{kg} \times \text{m}^{-3}) \times H_e \times 1\,(\text{m}^{-1})$$

where H_e is the equivalent height of the column of water and covering material expressed in height of rock:

$$H_e = \frac{\rho_a}{\rho_r} \times H_a + \frac{\rho_{mr}}{\rho_r} \times H_{mr} + H_r$$

having: ρ_a, ρ_{mr}, ρ_r = Densities of the water, overburden and rock, H_a, H_{mr}, H_r = Heights of water, overburden and rock.

The powder factors oscilate between 0.5 and 3 kg/m^3 but, apart from this, there is another determining factor in the calculation of these values, the dredging equipment used to dig up the broken material from the blasts. In Table 26.1, the maximum granulation and mean powder factors which are common for each type of dredge.

The phases to calculate the drilling and charging patterns are the following:

1. *Powder factor CE* (kg/m^3)

$$CE = f\,(H_a, H_{mr}, H_r, P_a \ldots)$$

2. *Choice of the blasthole diameter, D (mm)*
In Table 26.2, the recommended drilling diameters are shown for different bench heights.

3. *Lineal charge concentration, q_l (kg/m)*

$q_l = f\,(D, P_e, P)$ where P is the charge pressure of the explosive.

Table 26.1.

Type of dredge	Maximum block size (cm)	Powder factor CE (kg/m^3)
Bucket dredger	60	0.5-3
Cutter section dredger	30	1
Crab dredger	30	1
Dipper dredger	80	0.5-2.5

Table 26.2.

Drilling diameter D (mm)	Bench height H (m)
30	0-3
40	2-5
51	3-8
70	5-15
100	6-20

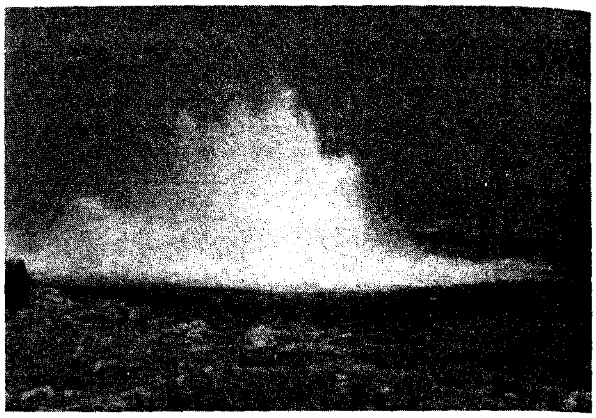

Photo 26.1. Underwater blasting

Table 26.3.

Type of pattern	Angle of breakage		
	90°	80°	70°
Square	0.70 B	0.88 B	B
Staggered	0.56 B	0.70 B	0.90 B

4. *Area of effective breakage, A_a* (m^2)

$$A_a = \frac{q_l}{CE}$$

5. *Drilling pattern, B and S (m)*
The normal practice is to place the blastholes on a square pattern, $S = B$, therefore $B = \sqrt{A_a}$.

6. *Subdrilling, J (m)*
Usually $J = B$ for square patterns, but if the pattern is staggered and the rock breaks well on the bottom, then the following modifications should be made as in Table 26.3.

7. *Volume of blasted rock, VR (m)*
This is the nominal volume plus that of the subdrilling, that is produced in the shape of an inverted cone.

$$VR = A_a \times H + \frac{A_a \times J}{3} = A_a \times (H + J/3)$$

8. *Charge per blasthole, Q_b(kg)*

$$Q_b = CE \times VR$$

9. *Height of the charge column, l (m)*

$$l = \frac{Q_b}{q_l}$$

10. *Stemming Length T (m)*

$$T = L - l$$

Normally the collaring distance is 15 D with a minimum value of 50 cm, but if there are no environmental limitations the blastholes can be charged to their total length, as the water pressure will confine the gases from the explosion. This will also allow a a more ample drilling pattern.

Example

An underground blast is to take place in a rock bench of 5 m high that is under an overburden of 10 m. The drilling diameter is 51 mm and a pneumatic charger is available with which the explosive reaches a density of 1.3 g/cm^3 in the blastholes. The rock has a mean density of 2.5 t/m^3.

1. $$H_e = \frac{1}{2.5} \times 10 + 5 = 9\,\text{m}$$

$$CE = 0.5 + 0.1 \times 9 = 1.4\,\text{kg/m}^3$$

2. $$q_l = \frac{\pi \times 5.1^2}{4} \times 100 \times 1.3 \times \frac{1}{1000} = 2.66\,\text{kg/m}$$

3. $$A_a = \frac{2.66}{1.4} = 1.9\,\text{m}^2$$

4. $$B = \sqrt{1.9} = 1.38\,\text{m}$$

$$S = 1.38\,\text{m}$$

5. It is considered that the drilling pattern is staggered with a breakage angle of 70°.

$$J = 0.9 \times 1.38 = 1.24\,\text{m}$$

6. $$VR = 1.9 \times \left[5 + \frac{1.24}{3}\right] = 10.28\,\text{m}^3$$

7. $$Q_b = 1.4 \times 10.28 = 14.39\,\text{kg}$$

8. $$l = \frac{14.39}{2.66} = 5.41\,\text{m}$$

9. $T = (5 + 1.24) - 5.41 = 0.83$ cm, which is equivalent to 16 D approximately.

26.4 CHARGING THE BLASTHOLES AND PRIMING SYSTEMS

This operation can either be done by hand or with charging devices that are powered by compressed air or water pressure. The advantages of the charging devices are numerous but above all in the charge concentration acheived. As a consequence, the drilling pattern can be more widely spaced, which reduces the drilling costs as well as the danger of flash-over between blastholes, Fig. 26.5, which is, on many occasions, due to lack of alignment of the same.

With these charging devices the charge concentration increases between 15 and 40% more than when done by hand.

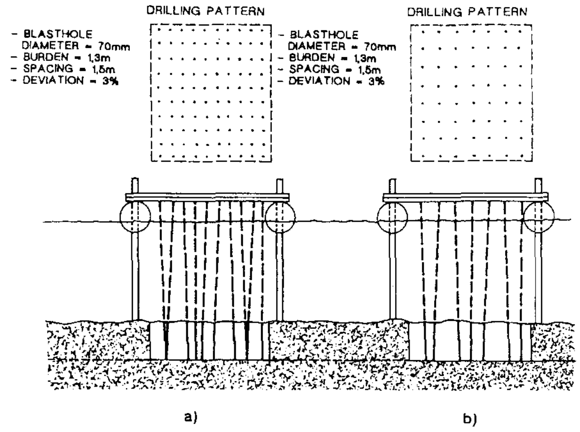

Fig. 26.5. Manual charging (a) Mechanized charging (b).

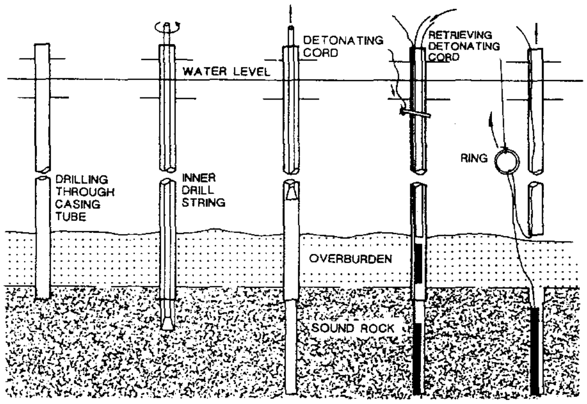

Fig. 26.6. Charging of the blastholes.

The charging method consists of, once the drill steel has been removed, introducing a plastic or aluminum hose into the blasthole, connecting the device to the compressed air system by way of a reduction valve which lowers the pressure to 300 kPa, giving impulse to the cartridges deposited in the chamber, where there is a safety valve and automatic closing. The productivity can reach 300 kg/hour per worker with 25 mm cartridges. For depths of more than 20 m, it is advised to use water pressure to give impulsion, as this reduces the counterpressure.

If this system is not used, the explosive can be placed by using prefabricated charges that consist of special plastic charging tubes with the cartridges inside.

The priming of the blastholes is carried out normally with detonating cord which is left along the wall of the same and is recuperated by threading it into a ring that is lowered on the outside of the casing, Fig. 26.6.

The initiation of each cord is done from the outside by placing an electric detonator after the drilling and charging of the whole round and always after removing the drilling pontoons. Connectors are used to assure isolation of the circuit and they are placed out of the water on buoys or floaters.

When electric or Nonel Type detonators are used, it is recommended that two be connected per hole, especially in very deep blastings. In these cases and for safety reasons, the primer cartridge should be placed last of all.

The detonating cord and electric detonators for this type of blasts should be specially designed with optimum insulation characteristics and resistance to water.

26.5 TYPES OF EXPLOSIVES

The explosives used for this type of work should have a chemical composition that does not alter the initiation sensitivity even after various days underwater. This can usually be acheived with a higher nitroglycerine content but, on the other hand, there is a serious risk of increasing the flash-over sensitivity from hole to hole and danger in the dredging operations if any explosive is left. According to Langefors, the following should exist:

$$q_l\,(\text{kg/m}) \geq 0.75\, DS^2\,(\text{m})$$

so that at a distance *DS* no *self-excitement* can exist.

Nowadays, the development of explosive slurries and emulsions has brought about greater safety and productivity in blasting, as well as reducing vibrations due to less chance of sympathetic detonation.

26.6 ENVIRONMENTAL EFFECTS ASSOCIATED WITH UNDERWATER BLASTINGS

The principal problems caused by underwater blastings are:

a) *Ground vibrations.* These are more important when the explosive is inside blastholes that are drilled in rock. Also, the shockwaves are usually accompanied by low frequency components.

This type of alterations will be subjected to a detailed analysis in Chapter 32.

b) *Underwater shockwave.* Damage to nearby structures or vessels. to divers close to the blasts, as well as to the existing aquatic fauna.

In water, the explosive energy is transmitted with great efficiency, given the low compressibility of the liquid, which means that the shock wave has high destructive power, even over large distances. The propagation velocity decreases as the distance increases from the detonation point, until it reaches the sonic speed *VH* = 1435 m/s.

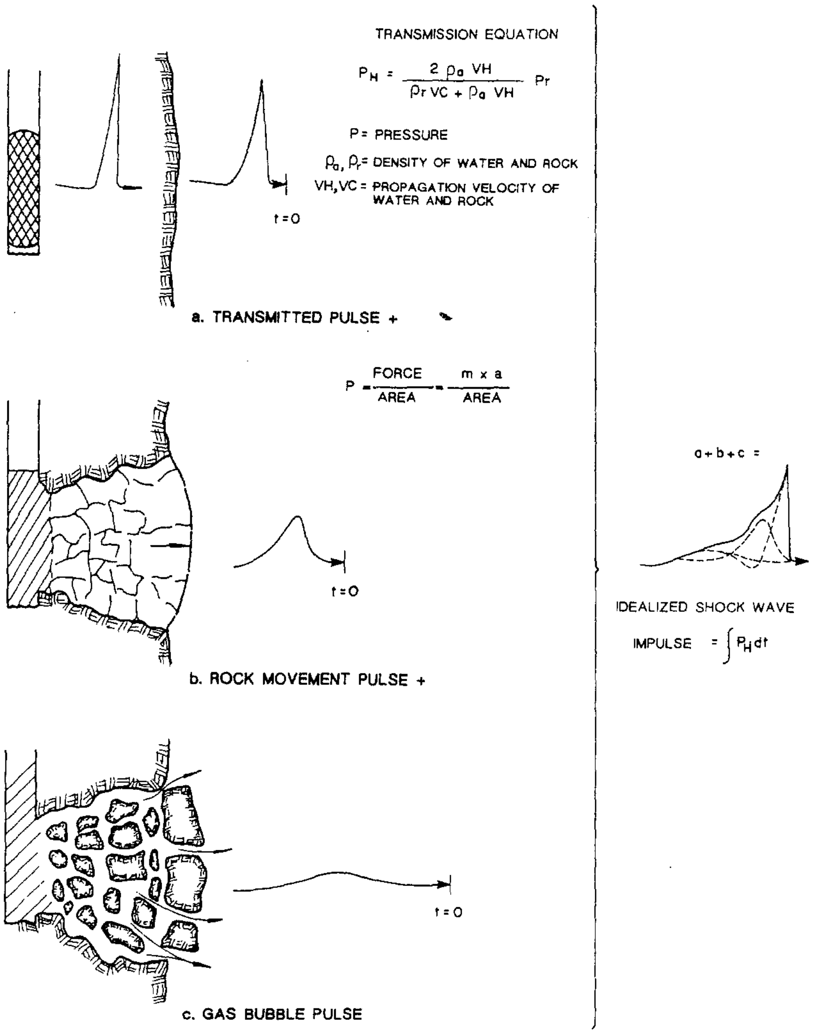

Fig. 26.7. Phases of shockwave formation.

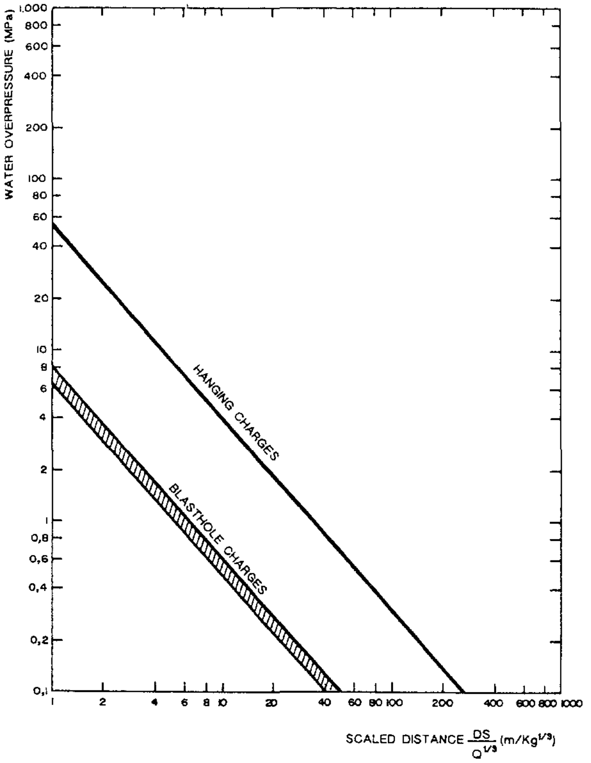

Fig. 26.8. Underwater overpressure produced by hanging charges of dynamite in water and confined in blastholes.

The peak pressure reached in the charge limit is 10^7kPa, a few meters away the pressure is reduced to 10^5kPa and at a great distance it can be 10^4kPa. However, the impulse lasts a very short period of time so that even in the most unfavorable cases it is measured in hundreths of microseconds.

The correct work plan for the blasts requires a basic knowledge of the laws of pressure, impulsion and duration of the underwater shockwaves.

In practice, for underwater blastings the usual equations applied are those given by Cole. For free hanging TNT charges ($P_{TNT} = 1.52$ g/cm^3), the equations for the pressure and impulsion are the following:

$$P_H\,(\text{MPa}) = 55.5 \times \left(\frac{\sqrt[3]{Q}}{DS}\right)^{1,\,1.3}$$

$$I_H\,(\text{Pa}\cdot\text{s}) = 5760\,\sqrt[3]{Q}\,\left(\frac{\sqrt[3]{Q}}{DS}\right)^{0.89}$$

If other explosives are used, the correction factor C^* to be applied is:

$$C^* = \frac{VD^2 \times \rho_e}{VD^2_{\text{TNT}} \times \rho_{\text{TNT}}}$$

The primary peak pressures of charges that detonate inside blastholes opened in rock, are 10 or 15% lower than those corresponding to hanging charges, Fig. 26.8.

De Raadt has introduced a new empirical method based upon the concept of the *Bubble Boundary* from which he estimates the maximum distances and quantities of hanging charges permitted so as not to damage submerged objects in the vecinity. The calculation of said parameter is taken from the equation:

$$R_b\,(\text{m})\,j = 1.5 \times Q^{1/3}\,(\text{kg})$$

where: Q = Explosive charge.

As damage can occur under that distance, the following condition will have to be satisfied:

$$R_o\,(\text{m}) = FS \times R_b$$

where FS is the Safety Factor defined in function with the type of structure or object that is to be protected and its underwater depth, Table 26.4.

The values indicated above should be increased when the objects are at greater depths than those shown, as well as when the hanging charges are larger.

Table 26.4. Recommended safety factors.

Constructions	
Hydraulic constructions, bridge pillars, steel constructions or similar, for a submerged depth and depth of charge of up to:	
6 m	2-3
15 m × 3-4	
Vessels	
Including dredgers, pontoons or similar, for a depth of charge of up to 15 m and a draught of up to:	
1 m	4- 5
2 m	5- 8
4 m	8-12
10 m	12-18

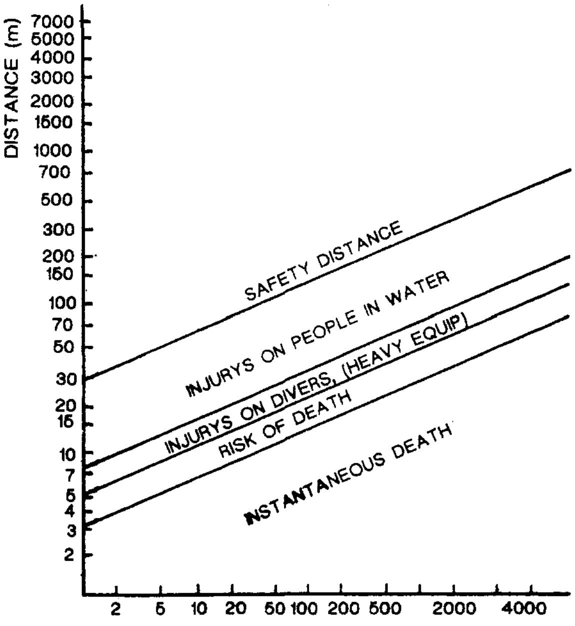

Fig. 26.9. Safety distances for charges in blastholes.

In another context, the underwater shockwaves can harm divers, if they are close enough to the blastings. H. Wolff, from his experiences in the US Navy, established an empirical formula to calculate the safety distances when firing free hanging charges:

$$DS_s = 225\sqrt[3]{\frac{Q}{\rho_e}}$$

where: DS_s = Safety distance (m), Q = Weight of the explosive (kg), ρ_e = Density of the explosive.

In the nomograph of Fig. 26.9, the recommended safety distances are indicated for different explosive charges fired in blastholes.

The maximum pressure that a diver can withstand, without special protection, varies between 0.172 MPa and 0.34 MPa, and the threshold of probable death is found in 2.06 MPa.

One of the most common procedures to combat the pressure of the shock wave is to surround the blasting zone with an air bubble curtain to isolate it from the rest of the contour. It has been experimentally demonstrated that for a flow of air of 1 l/m.min. the overpressure is reduced ten times, whereas for double the flow, it is reduced about 70 times. This is logical, not only because of the larger volume of air but because the smaller bubbles have a correspondingly larger effective sufrace than the bigger bubbles, for the same quantity of air, Fig. 26.10.

The air bubble curtain is produced by placing one or two parallel steel pipes on the bottom through which compressed air is pumped. The air escapes through small perforated openings, forming the bubbles that flow towards the surface.

Below, the dimensions for these installations are given:

– Diameter of the pipeline	50 mm
– Separation of the openings	100 mm
– Diameter of the openings	1.5-3 mm
– Air pressure	686 kPa – 7 kg/cm^2
– Air flow per meter	0.13 l/m.s.

c) *Airblast.* This alteration is not very important in underwater blastings, but its effects can be taken into consideration for charges hanging in the water, with an explosive of ρ_e = 1.75g/cm^3 and VD = 7200 m/s, according to the nomograph in Fig. 26.11.

26.7 SHAPED OR CONCUSSION CHARGES

When it is not possible to drill blastholes or it is very difficult, there is the possibility of shaped or concussion charges. The principal condition for application of this method is that the area to be blasted be far away from any type of construction or vessel, because the devastating effects of the water shockwave and, in lesser degree, the vibrations, can cause great damage.

The blasting patterns are usually square, firing all the charges instantaneously. To speed up the placing operation, the charges are frequently prepared on rectangular frames, such as in Fig. 26.12.

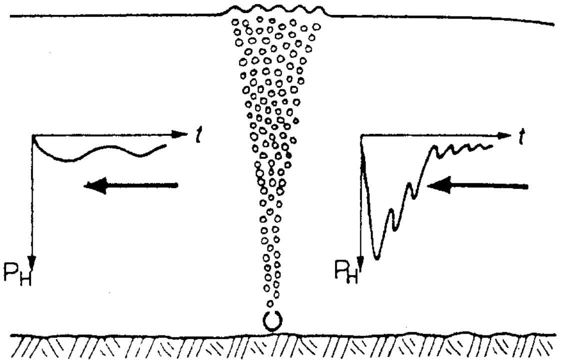

Fig. 26.10. Shock absorbing effect of the air bubble curtain.

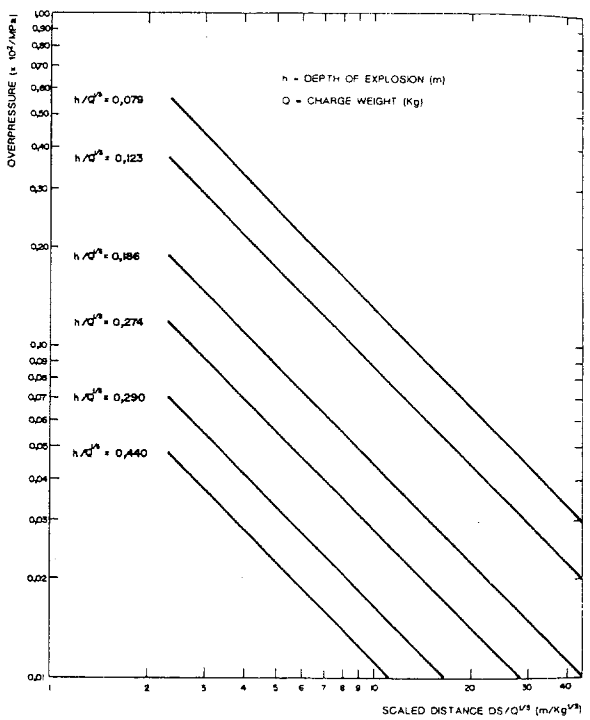

Fig. 26.11. Airblast pressure from underwater blasting with hanging charges.

The explosive charges are placed in metallic or plastic receptacles divided in two parts, the lower is hollow and is where the sinker is attached to lessen the flotation effect, and the upper is where the cone shaped explosive is located, Fig. 26.13.

In trench excavations, fragmentation is achieved in depths of up to 5 m or even more, depending upon the type and size of the charge, their spacing and the strength of the rock. For excavations of up to 1.5 m and water depths of up to 100 m, shaped charges of 8 kg are used, placing them in function with the type of rock according to the following patterns:

Hard rock (granite, basalt, jointed, etc.)

1.0 × 1.0 to 1.5 × 1.5 m

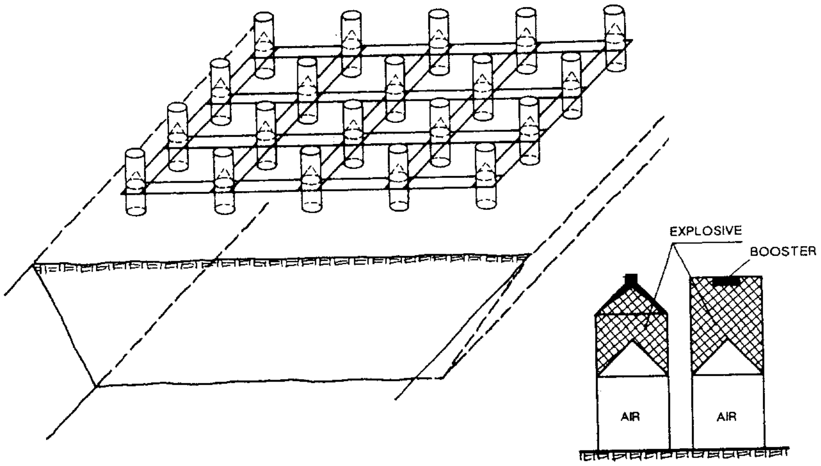

Fig. 26.12. The use of concussion charges in underwater blastings.

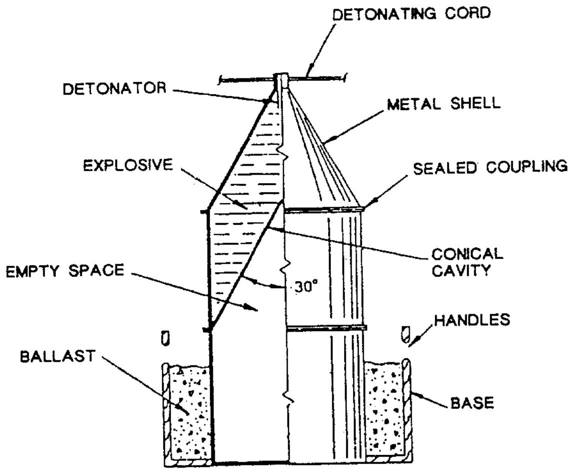

Fig. 26.13. Shaped charge.

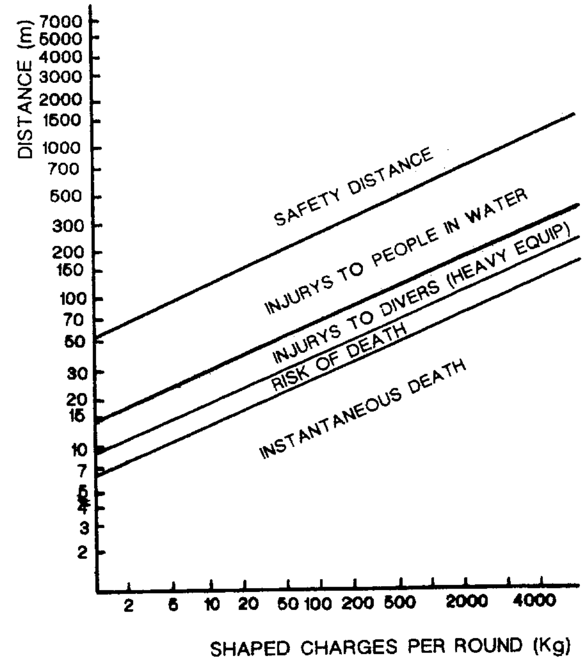

Fig. 26.14. Safety distances for shaped charges in underwater blasting.

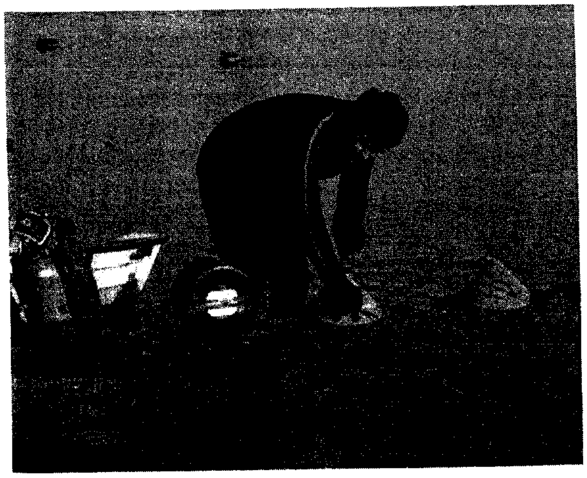

Photo 26.2. Preparation of a shaped charge (Courtesy of Nitro-Nobel).

Soft rock (Limestone, conglomerate, etc.)

2.0 × 2.0 to 2.5 × 2.5 m

When the depth of the water is under 2 m, special precautions should be taken, because flyrock can occur.

In the nomograph of Fig. 26.14 the safety distances recommended for different quantities of explosive for shaped charges fired underwater.

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CHAPTER 27

Initiation sequence and delay timing

7.1 INTRODUCTION

he group of controllable parameters least known by igineers and operators is the one that comprises the itiation sequences and the delay timings between the iarges of a blast. The nominal drilling patterns with a irden B and spacing S are radically modified with the itiation sequence, changing to other values B_e and S_e illed *effective* values.

The parameters indicated do not only have influence pon the fragmentation, but also upon other basic aspects ich as displacement and swelling of the rock, overbreak id intensity of vibrations. Therefore, the small extra cost using more complex initiation sequences is well worth ie expense, as the global economy of the whole opera-on benefits.

A large part of the theories exposed here are offered by ie specialists T.N. Hagan and A.B. Andrews, who have edicated their efforts over several years to study and ptimize blastings.

7.2 SINGLE-ROW DELAYED BLAST

or constant conditions of bench height, powder factor, pe of rock and blasthole diameter, and if the charges are red instantaneously, there is a relationship S/B in which ie displacement and the fragmentation are optimum. he ratio S/B in homogeneous materials oscilates be-veen 2 and 4 (Langefors, 1966) but, due to the fact that ie excavated volume per blasthole starts to decrease hen $S > 3B$, the optimum values of S/B are near 2.4.

If the spacing is under 2.4 B, as the charges act in nison, the radial cracks between blastholes intersect efore any others reach the free face, creating a splitting the plane of the blastholes, through which the gases scape prematurely to the atmosphere. This then pro-uces a simultaneous pushing of the rock mass in front of ie charges, with a pronounced horizontal shearing, egatively affecting fragmentation not only because the ropagation of the cracks is interrupted due to gas infiltra-on, but because there is almost no in flight collisions of ie projected rock and the breakage caused by shearing ccurs only along pit floor level and in the lateral planes B and CD, Fig. 27.1.

When very fine fragmentation is not necessary or when ie rock is intensly fractured and its displacement is nough to provoke the desired fragmentation, the blast can be fired instantaneously with a ratio S/B = 0.8 to 2.4, and with a burden dimension of 25 to 30% more than in sequenced blastings (Ash, 1969).

In pronounced bedding or joints parallel to the free face the ratio S/B can be above 2.4; on the other hand, if the orientation is normal to the face, the S/B value should be under 2.4. In homogeneous rock, if the relation S/B is larger than 2.4, the face will be very irregular as the cooperation between charges will not exist.

When the single-row blastholes are fired at intervals, the fragmentation increases considerably with respect to the instantaneous blasts, because the radial cracks that develop around each explosive column are almost totally formed before the next charge is detonated. In these situations, the charges create aditional free faces which means that each blasthole shoots to two faces, JK and KL, Fig. 27.2.

Fragmentation is better than in instantaneous blastings, because the heave energy is used in vertically shearing the burden and extending the cracks and the strain wave has a larger field of action.

When the interval of delay between adjacent blastholes is long, so that each charge can fragment and displace its corresponding share of the burden, the optimum spacing S_o is equal to 2.79 B_o, Fig. 27.3.

The value of the spacing is ample enough so that the cracks in the blastholes 0 and 1 develop totally without intersecting. When S diminishes to under 2.79 B_o, the effective burden B_e is somewhat less than optimum B_o and the fragmentation is poor, elevating the excavation costs, Fig. 27.4

If S = 2.79 B is maintained, and B exceeds B_o, Fig. 27.5, the crater angle is considerably less than 138° and the blasthole with delay nunber 1 will break towards face BD which is nearer than DC, resulting in a deficient fragmentation in the central region X. For this reason, the spacing should be less than 2.79 B. If, on the other hand, B is made less than B_o and S = 2.79 B, the hole 1 will break equally towards the faces DC and BD and the crater angle will remain at 138°, the fragmentation will be finer than required and, as the pattern is more closed, the drilling and blasting costs will be higher.

When B is considerably less than B_o, and S increases to above 2.79 B, in an effort to compensate the relatively small burden, the spacing becomes so great that the rock between the holes is not adequately displaced or frag-mented.

Even so, in practice the most common values of S