Chapter 17

Mechanics of blast fragmentation

17.1 INTRODUCTION

Previous parts of this book dealt exclusively with rotary blasthole drilling, as is practiced in large surface mines. In mining operations the drill and blast operations are so closely associated with each other that a book on either subject is likely to be considered incomplete without adequate coverage of other. Therefore, chapters hereinafter cover theoretical and practical aspects of blasting in large surface mines.

Blasting is a very devastating form of rock destruction. As these operations are extremely dangerous, they are subjected to very stringent regulations imposed by controlling authorities – usually Governments of the countries. These regulations not only apply to blasting operations but also for transporting, storing and handling of explosives. All the persons carrying out blasting operations are required to be specially trained. Without a certificate from an appropriate training institute, nobody is allowed to undertake blasting operations.

Blasting is not only dangerous in practice but even as a subject it is far more vast and relatively complicated than drilling. In fact, this is the reason for which almost every other book on drilling and blasting published so far has laid far more emphasis on blasting.

Adequate knowledge of blasting is very important for everybody involved in blasthole drilling. This chapter is devoted to elaborating different aspects related to the process of explosion.

17.2 EXPLOSION PROCESS

Any inflammable material filled in a hole in the ground, will burn continuously so long as the supply of oxygen necessary for the burning process continues. The process of burning propagates at a certain speed from the point of initiation to the end point after which no more inflammable material is available for burning.

When an inflammable material burns, the most common byproducts are oxides. Therefore, oxygen is very essential for the process of burning.

If a material burns by taking oxygen from the atmosphere, it does not burn quickly. But if it generates an adequate quantity of oxygen by self-decomposition, it can burn much faster.

Actual burning always takes place within a small layer confined by two surfaces. This layer always moves to burn new material. Behind this layer the material is in burnt form and ahead of the layer the material is in unburnt form.

The thickness of the burning layer depends upon the burning material itself and also on the physical extent of the burning material in continuum.

Deflagration and detonation are the two distinct types of burning.

When the speed of propagation of the burning layer is less than the speed of sound, the burning is called deflagration. In deflagration the burning layer advances by transferring heat energy to the adjacent layer in the unburnt portion.

When the speed of propagation of the burning layer is in excess of 2000 m/s the burning is termed detonation. In detonation the burning layer advances by transferring energy through a shock wave.

The speed of propagation of the burning front depends upon the intensity of heat with which the burning process has been started and how quickly, and also how much oxygen the burning process gets. Therefore, some explosives merely deflagrate when brought in contact with a common match-stick fire but detonate and explode if brought in contact with a spark that has very high intensity of heat.

Usually all materials that detonate are called explosives. Detonation of all the explosives results in a very large volume of gases and a very large quantum of heat. Most of the explosives are chemicals formed by carbon, hydrogen, oxygen and nitrogen. When they detonate, they mainly generate common and harmless chemical compounds such as H_2O (Water), CO_2 (Carbon Dioxide), N_2 (Nitrogen) with a very small quantity of poisonous gases such as NO (Nitrous Oxide), CO (Carbon Monoxide), NH_3 (Ammonia), CH_4 (Methane).

Figure 17.1 shows the propagation of a burning layer in a blasthole that has uniform diameter through out its length. In the case of explosives the velocity of propagation of the burning layer is called the velocity of detonation. The frontal surface of the burning layer, more commonly called the detonation zone, is termed the shock front and the rear surface is called the Chapman-Jouguet surface.

The length of the detonation zone depends upon the components of the explosive, particle size, density and confinement of the explosive. The width of the detonation zone is proportional to the length of detonation zone.

For every explosive there is a certain blasthole diameter called the 'critical diameter'. If the particular explosive, filled in a blasthole having a diameter smaller than the critical diameter is detonated, there is a likelihood that detonation of the

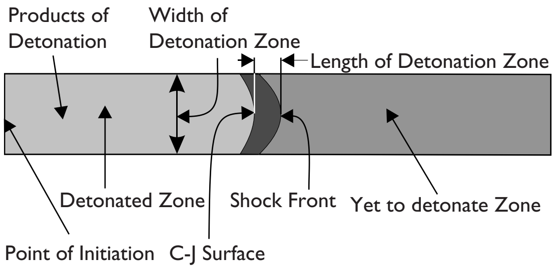

Figure 17.1 Propagation of detonation.

explosive will be incomplete and blasting will be ineffective. Thus for effective use of the explosive, the actual blasthole diameter must be more than the critical diameter.

Dangers of blasting operations are many and arise From:

1 Generation of poisonous gases
2 Throw of rock pieces in the air
3 Pollution of atmospheric air by dust
4 Vibrations caused in the ground mass
5 Propagation of air shock waves.

Improper transportation, storing and handling can cause even more dangerous explosions than the explosion engineered through proper blasting operations. Accidental explosions are always unexpected and without any control, whereas the proper blasting operations are expected and controlled.

17.3 FORMATION OF A CRATER BY A BLAST

The most fundamental action behind disintegration of the rock mass by a blast is the formation of a crater.

A crater is formed when a projectile of any heavy object impinges upon a rock mass. Such a crater is observed very commonly.

A crater is also formed when an anchor embedded in the rock mass is subjected to a pull-out force that is sufficient to break the rock mass. Such a crater is shown in Figure 17.2. The pullout force actually exerts pressure on the rock mass through the plate as shown by small arrows in the figure. These forces in turn generate shear stress in the rock mass along the surface AB. Eventually the failure occurs at this surface when the stress exceeds the strength of the rock mass.

When an explosive, confined in a spherical cavity inside a rock mass, is detonated, the pressure created inside the cavity exerts forces in the radial direction. Further, the extreme rapidity with which the pressure inside the cavity is generated causes a compressive stress wave moving radially in all directions. As the compression stress wave travels, the magnitude of stress decreases. When this compressive stress wave

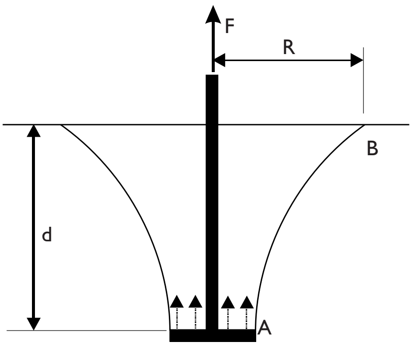

Figure 17.2 A crater formed by pullout force exerted on an anchor embedded in rock mass.

reaches the free surface it rebounds backward in the form of a tensile stress wave. The magnitude of tensile stress in this wave depends upon the compressive stress wave.

As a result of the tension wave, the failure of the rock mass occurs in the volume enclosed by the free surface and the curved surface in the form of a crater shown in Figure 17.3.

The depth and volume of the crater is at a maximum for a certain depth of the explosive cavity below the free surface. This depth is called the critical depth d_c.

When the depth of the explosive cavity is much higher than the critical depth, no fragmentation at the free surface takes place and there is no crater. As the depth of the cavity of explosive below ground level d approaches d_c, the crater forms and the volume of the crater keeps on increasing till $d = d_c$. All this is shown in Figure 17.3. When $d = d_c$ the corresponding crater is called a full crater.

The radius R_1 on the free surface, in the case of a full crater formed by an explosion, is much larger than the radius R observed in the crater formed by anchor pull-out. This is shown in Figure 17.4.

The critical depth depends upon the properties of the rock mass as well as properties and weight of the explosive.

The depth d_c for full crater increases with increasing mass of the explosive, W. A relation between the two is as under.

$$W \propto d_c^n$$

where

W = Mass of the explosive
d_c = Depth of the full crater from the free surface.

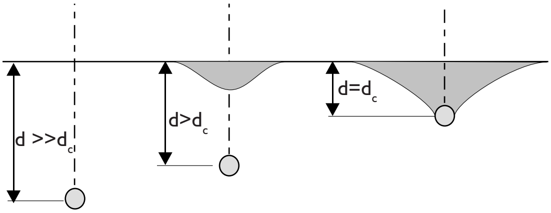

Figure 17.3 Progressively increasing depth of crater formed in the rock mass by explosive in a cavity below free surface.

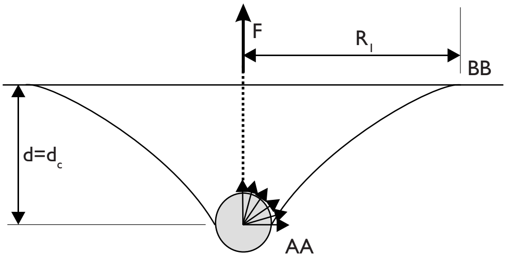

Figure 17.4 Geometry of a full crater.

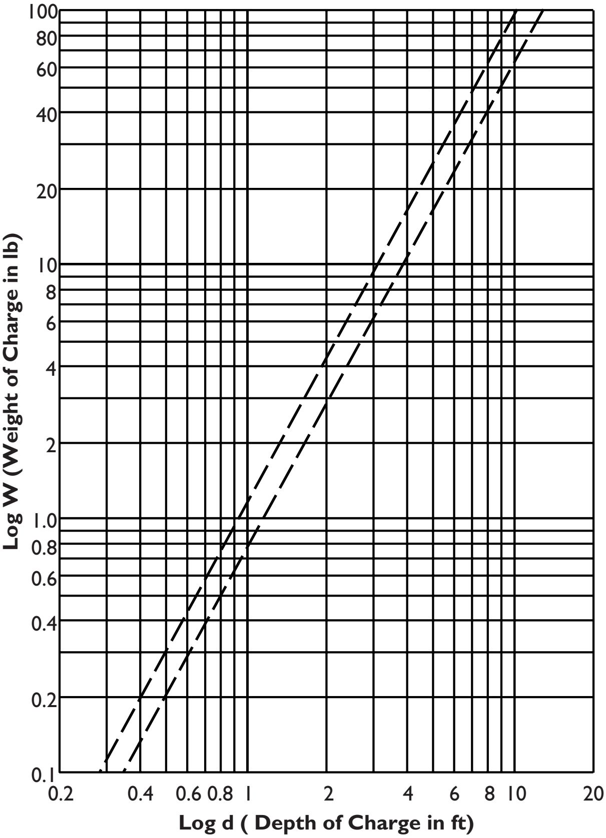

Figure 17.5 The plot of relationship between weight of explosive w and critical value of depth of explosive.

If the explosive is contained in a long horizontal blasthole instead of a spherical cavity, then the depression made in the ground by the explosion is in a long canal-like shape rather than a conical crater.

Experiments were carried out on a gneiss rock mass at Idaho Springs to ascertain various parameters of the geometry of a full crater. The plot for various values of mass of explosive and corresponding depth of the crater was as shown in Figure 17.5.

It was found that the value of n is 1.85 for the particular rock mass. It was also found that $R_1 = 2.8d_c$.

Experiments have indicated that the value of n is between 1.5 for elastic and 3.4 for plastic rocks.

17.4 BLAST FRAGMENTATION MECHANISM

A very rudimentary idea of rock fragmentation by blasting is contained in the first chapter of this book. It needs to be elaborated.

The many disintegration modes that contribute to the process of rock fragmentation are as under.

1 Crushing of Rock
2 Radial Cracking
3 Circumferential Cracking
4 Spalling
5 Radial Push by Gases
6 Cracking by Flexure
7 Collision of Fragments
8 Separation of Beds

Each of the above points is elaborated below.

17.4.1 Crushing of rock

Explosive filled in a blasthole is called the charge. The process of systematically filling charge in a blasthole is called charging.

Initially when the explosive charge is detonated by a spark at the bottom of the blasthole the detonation zone starts moving up the blasthole at a speed of 2500 to 7000 m/s. The energy released and the gases generated in the detonation zone exert an extremely high pressure against the walls of the hole. Simultaneously the heat generated in the detonation gives rise to very high temperatures.

The formulation of velocity of detonation, detonation pressure and detonation heat is dealt with in one of the forthcoming sections. In most cases the pressure ranges between 7 to 10 GPa and temperature ranges between 2500 to 4500°C. Such high temperature and pressure act together to pulverize and crumble a thick cylindrical layer around the blasthole wall. This is called the crushed zone. The thickness of the crushed zone depends upon the magnitude of the detonation pressure, heat of detonation, and the strength and porosity of the rock.

All this culminates in an increase in the volume of the blasthole. If V_O is the original volume of the blasthole and V_E is its volume after explosion, the increase in ratio V_E/V_O with time is as shown in Figure 17.6. This ratio is of the order of 2 to 4 for strong rocks and of the order of 10 for weak and porous rocks.

As much as 30% of the energy generated in the detonation zone is spent in the crushing of rock.

17.4.2 Radial cracking

A compression wave is also created at the detonation zone. It starts moving away from the blasthole in all directions at the velocity of a sound wave in that medium, as shown in Figure 17.7A.

All rocks are formed by minerals of different composition. Therefore, planes of weakness are left during the process of formation of a rock mass. The cracks, which are in a direction tangential to the wave propagation, remain nearly unaffected by the compression wave. The compression wave generates shear stress along the radial planes of weakness because the response of different crystals to compressive stress

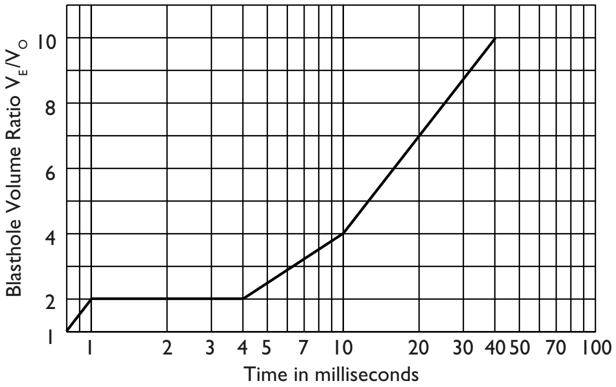

Figure 17.6 Increase in blasthole volume after detonation.

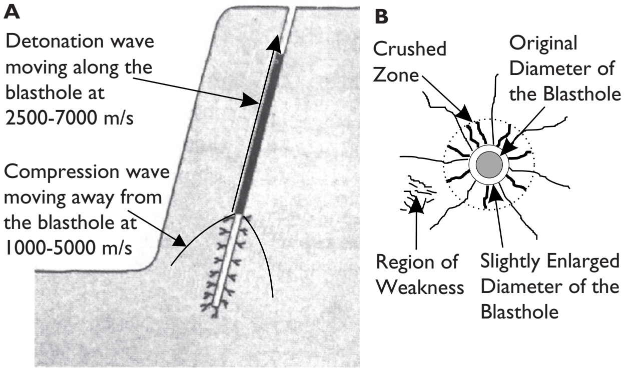

Figure 17.7 Initiation of rock fracture by blasting.

differs. The number of cracks in the region adjacent to the walls of a blasthole is higher, but at longer distances from the blasthole the formation of cracks is lesser as shown in Figure 17.7B. This happens because there is a significant reduction in the energy contained in the compression stress wave.

As the rock mass on the rear side of the blasthole is in horizontal confinement, there is no significant radial cracking on the rear side of the blasthole.

17.4.3 Circumferential cracking

Within a very short period the compression wave reaches the free surface at the bench face and gets reflected as a tension wave. The speed at which the tension wave travels backward is about half of the speed of the compression wave, i.e 500 to 2500 m/s. The lower speed of the tension wave is due to the fact that a significant part of the energy contained in the compression wave is lost as it moves to the bench face.

The quantum of energy lost depends upon many factors such as composition of the rock mass, the distance between the blasthole and the free surface nearest to the blasthole at the time of detonation (i.e. the burden), the distribution of pre-existing cracks in the rock mass, the porosity of the rock mass etc.

Tension waves are very important from the viewpoint of blasting because they generate circumferential cracks in the rock mass as shown in Figure 17.8A. Without such circumferential cracks there cannot be any significant fragmentation in the rock mass. The portion between the blasthole and the bench face is heavily cracked by the tension wave as shown in Figure 17.8B.

The reason for large scale circumferential cracking in the rock mass by the tension wave is that all the rocks have very low tensile strength as can be seen from Table A14.5 in Appendix 14.

Since there is no free surface on the rear side of the blasthole there is no circumferential cracking on the rear side.

17.4.4 Spalling

When a compression wave reaches the bench face and reflects as a tension wave, in the very initial stage circumferential radial cracks develop near the bench face. Since there is no confinement of the rock fragments on one side of the bench, they separate from the bench face and fall down. This fragmentation is called spalling.

17.4.5 Radial push by gases

After the radial and circumferential cracking the rock mass on the front side of the blasthole is already loosened, but remains without significant movement. Gases formed in detonation and held at exceedingly high pressure start flowing to the circumferential cracks through the radial cracks and exert outward pressure. This causes throw of the rock fragments in an outward direction i.e. away from the bench face as shown in Figure 17.9.

17.4.6 Cracking by flexure

In a blasthole the detonation process is almost invariably started at the bottom of the blasthole. In the initial stages gases form at the bottom and exert upward pressure.

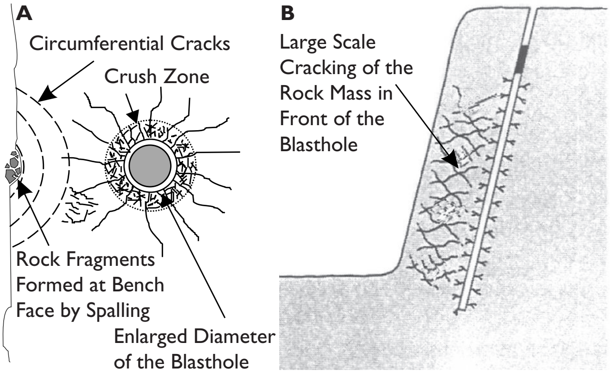

Figure 17.8 Rock mass cracking by tension wave.

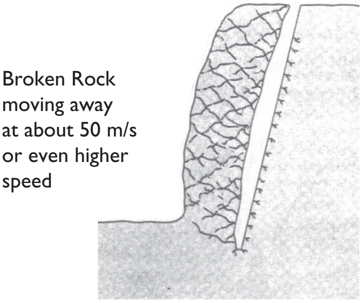

Figure 17.9 Throw of rock fragments.

Figure 17.10 A blast in a large mine.

As the detonation layer moves upward, the gases formed in the upper region also add to this pressure. Thus, the pressure in the middle of the blasthole length is higher than the pressure at the bottom. This differential pressure creates a bending moment on the burden wall as shown in Figure 17.9 and as is evident from the photograph in Figure 17.10.

With such flexure given to the burden wall, horizontal cracks form in the wall on the outer side i.e. near the bench face.

A photograph of a blast carried out in a mine bench is shown in Figure 17.10. Minute observation of the photograph reveals that the rock mass portion towards right side has bulged more whereas the rock mass at the middle portion of the photograph has not bulged to that extent. This is because the middle portion actually represents the boundary between the non-blasted area on the left side of the photograph and the blasted area on the right side. Further, the right side portion appears to have vents through which explosion gases have escaped along with fine material. The fine material has formed a clearly visible cloud of dust.

17.4.7 Collision of fragments

When fragments formed by blasting are thrown away from the rock mass in burden, they collide with each other. Such collisions result in further fragmentation of the pieces of rock.

17.4.8 Separation of beds

If the rock mass consists of different layers, as usually happens in sedimentary rock formations, the response of different layers to the action of the compression wave is different. For this reason, in many cases the beds on two sides of the bedding plane get separated by cracks formed at the bedding plane. Such cracks invariably add to the process of fragmentation by blasting.

The speed at which the fragments are thrown away depends upon the pressure and rock mass characteristics.

All the modes of rock fragmentation described in earlier sections take place in such a short time interval that it is very difficult to give any sequence.