## Wuhan University of Technology

# Excellent course

# Blasting Engineering

# Chapter 5: Mechanics of rock blasting

Contents:


5.1 Fundamental theory of rock failure

5.2 Blasting action of single charge

5.3 Blasting action of extended charge

5.4 Characters of rock failure when detonating multi-charges

5.5 Principle of energy balance and charging calculation

5.6 Main influencing factors on blasting effect

# Section 1: Fundamental theory of rock failure（1）

**Expansive action of expansion gases**

**Tensile action of reflective stress wave**

**Comprehensive action with expansion and tension**

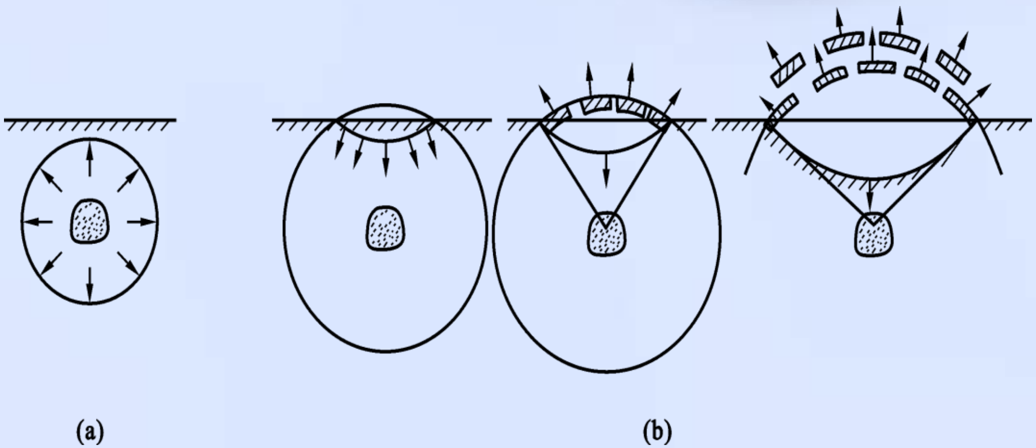
**Expansion of explosion gases**

# Section 1: Fundamental theory of rock failure（2）

**Expansive action of expansion gases**

**Tensile action of reflective stress wave**

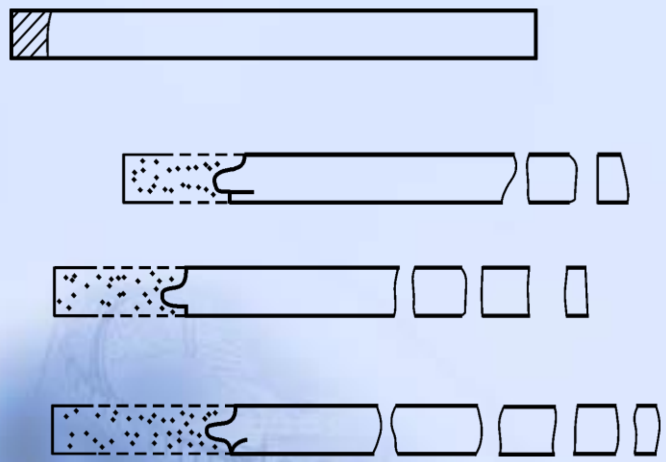
**Comprehensive action with expansion and tension**



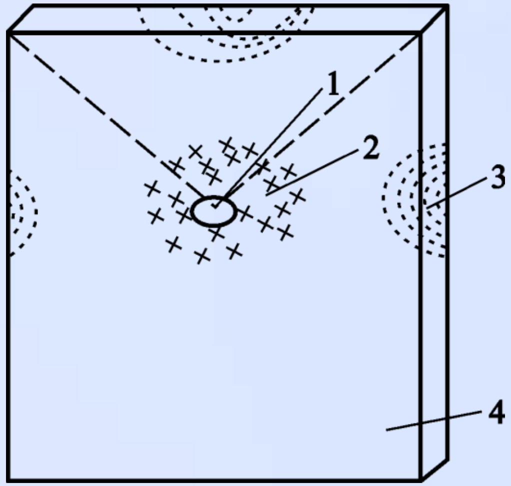

**Tensile action of stress wave reflection**

***(a)*** Wavefront of incident pressure wave
***(b)*** Wavefront of reflective tensile stress wave

# Experiments for testing tensile action of reflective stress wave



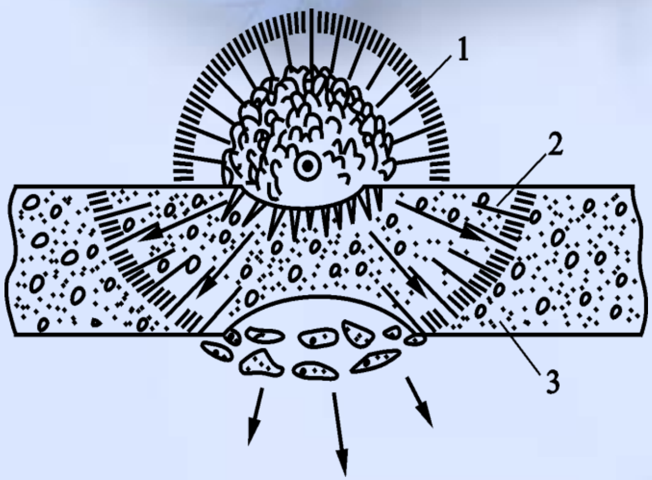
blasting experiment of rock bars




blasting experiment of plate

1—blasthole 2—crushed zone

3—tensile zone 4—vibrative zone




detonation experiment of cement plate

1—wavefront of air shock wave

2—wavefront of shock wave in cement plate

3—cement plate

# Section 1: Fundamental theory of rock failure（3）

**Expansive action of expansion gases**

↓

**Tensile action of reflective stress wave**

↓

**Comprehensive action with expansion and tension**

→

**Essence of comprehensive action：**

The initial crack is produced by shock wave and stress wave and filled with explosion gases which force the crack to grow further with quasi-static pressure. Quasi-static energy, produced by explosion gases, is the main force of rock failure.

**By А.Н.Ханукаев , three classifications of rock :**

**(1)** Rock of high impedance(MPa·s/m), from 15 to 25, is failed main by incident and reflective stress wave.

**(2)** Rock of medium impedance, from 5 to 15, is failed mainly by comprehensive action of incident stress wave and explosion gases.

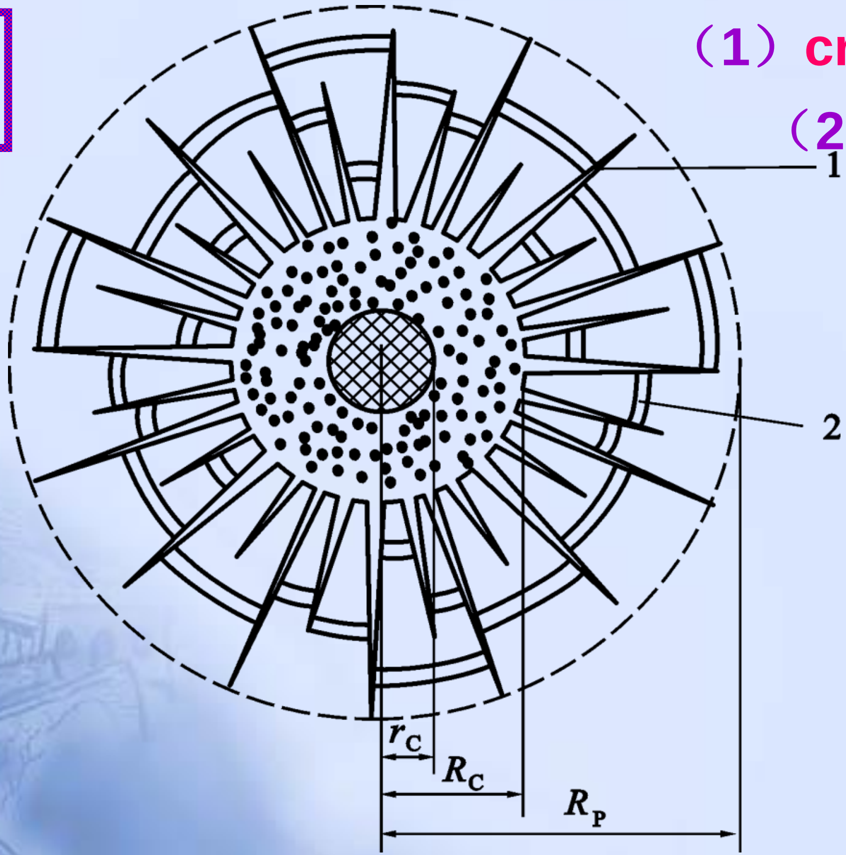
**(3)** Rock of low impedance, lower than 5, is failed mainly by expansive action of explosion gases.

# Section 2: Blasting action of single charge

**internal action**

（1）**crushed zone**（compression zone）

（2）**cracked zone**（fractured zone）

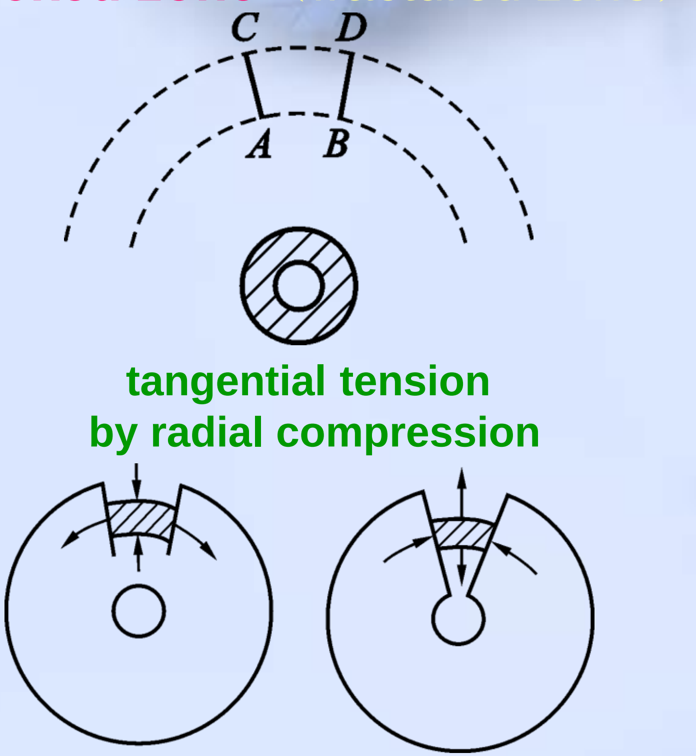



**Internal action**

**1**—radial crack **2**—circumferential crack

**rc**—radius of charge **Rc** —radius of crushed zone

**Rp** —radius of cracked zone

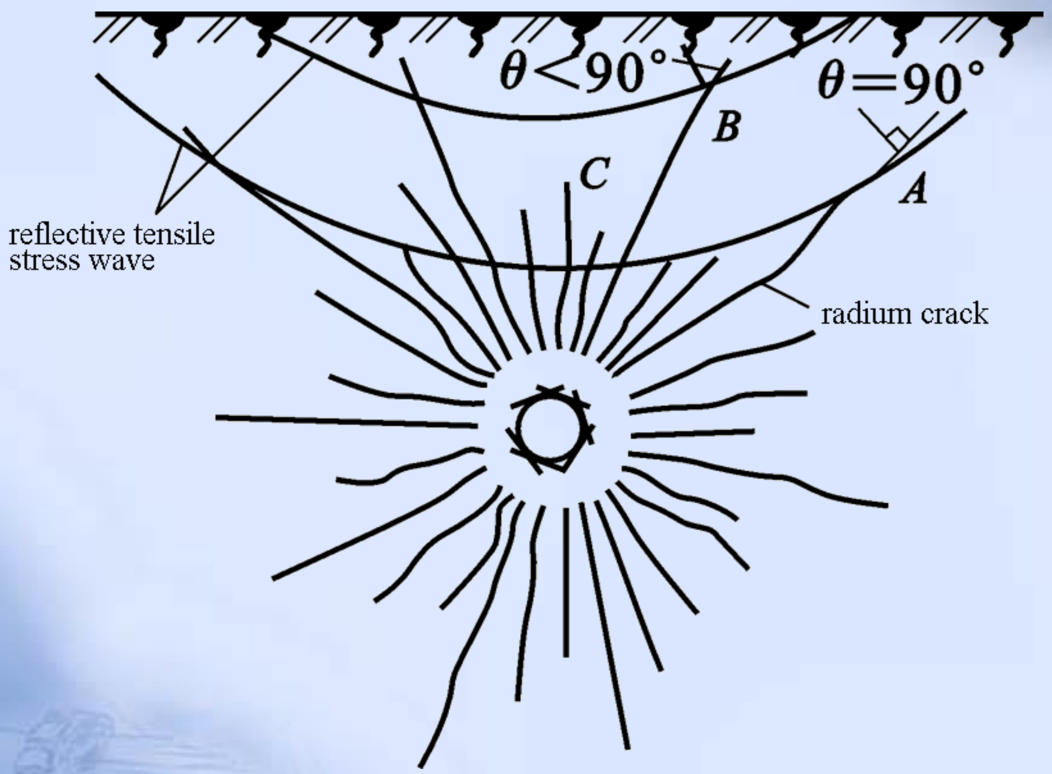



**Formation mechanism of radial crack and circumferential crack**

# external blasting action by single charge （2）

**External action**

**（2） reflective tensile stress wave makes radial crack grow**

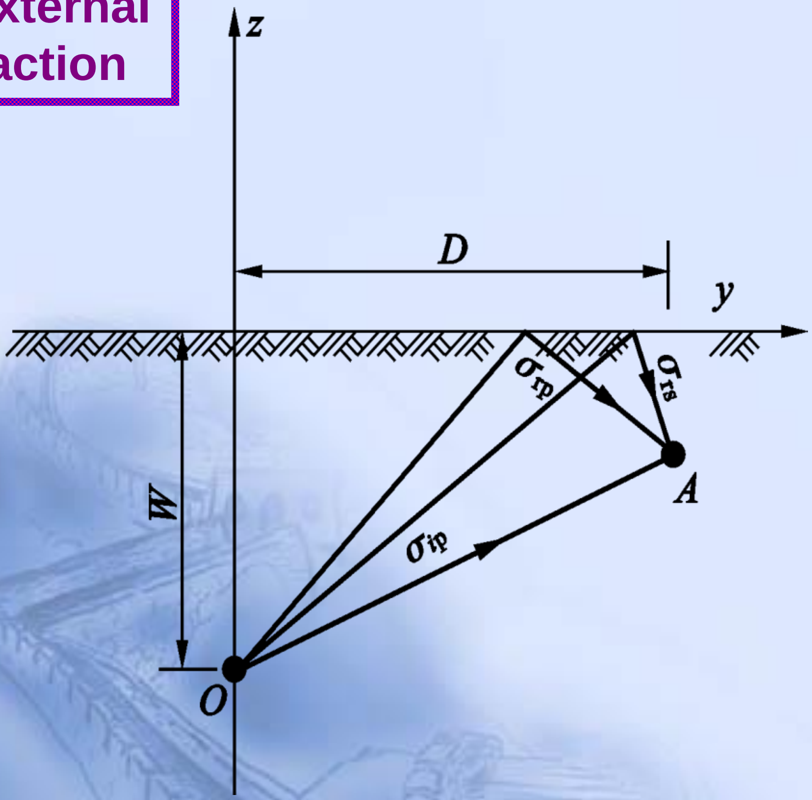



**Effect of reflective tensile stress wave on radial crack**

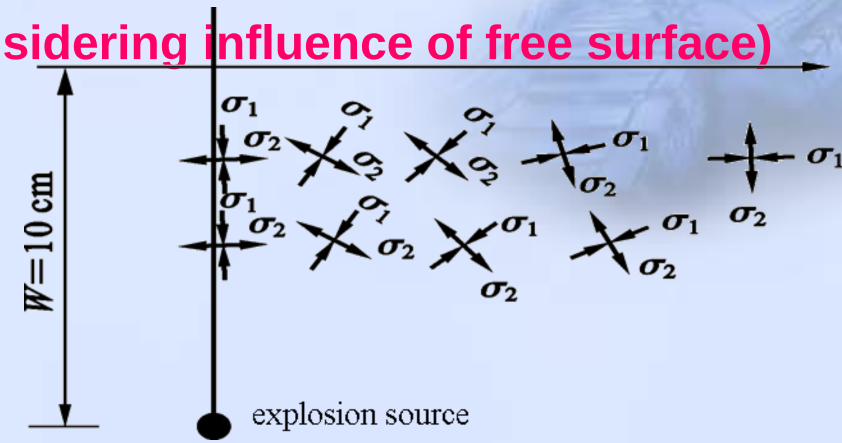
# external blasting action by single charge （3）

## （3）analysis of stress field (considering influence of free surface)

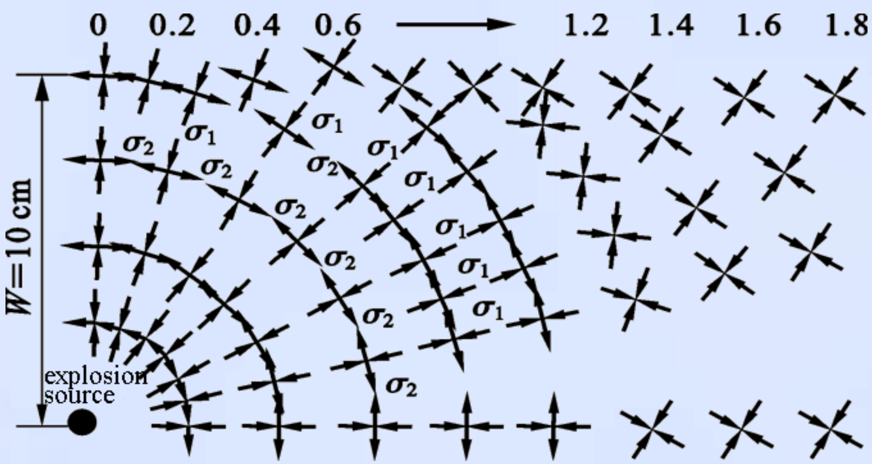
**External action**




Stress analysis on point A in rock mass




Direction of $\sigma_1$ and $\sigma_2$ when tensile stress $\sigma_2$ takes a maximum value




Direction of principle stress $\sigma_1$ and $\sigma_2$

# Process of rock failure when blasting happens

**A**
**Stage one**

Shock wave makes rock compressed on radial direction.

**B**
**Stage two**

Reflective stress wave makes spall fall

**C**
**Stage three**

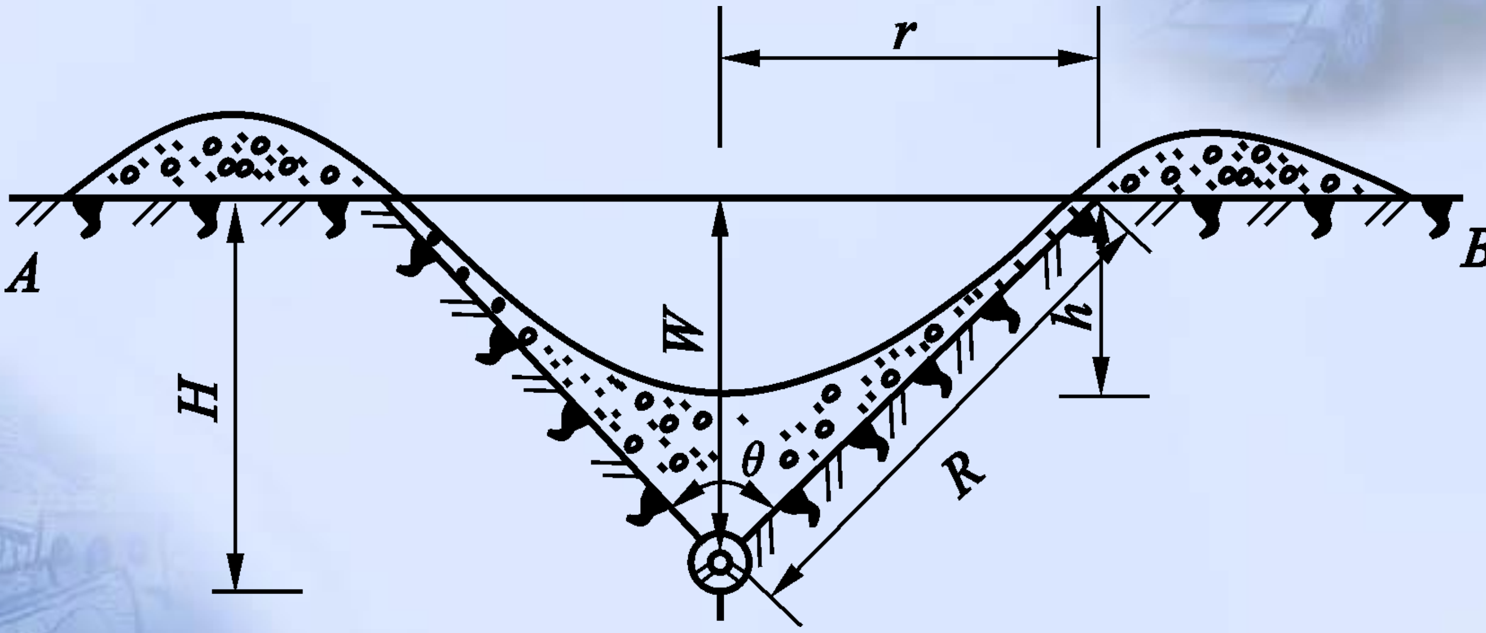
Expansion pressure of explosion gases makes radial crack grow

# Patterns of rock failure when blasting happens

**Five patterns of rock failure**

1. Rock wall of blasthole is crushed by compression.
2. cracked on radial direction.
3. cracked on circumferential direction by unloading.
4. Reflective tensile wave makes spall fall and radial crack grow.
5. cracked by expansion stress of explosion gases.

# Explosion crater





Crater index *n* is a ratio of radius *r* to line of least resistance *W*.

$$n = \frac{r}{W}$$

# Patterns of explosion crater

**a**

**n = 1.0**

Crater of standard blasting for throwing rock

**b**

**n > 1.0**

Crater of strengthened blasting for throwing rock

**c**

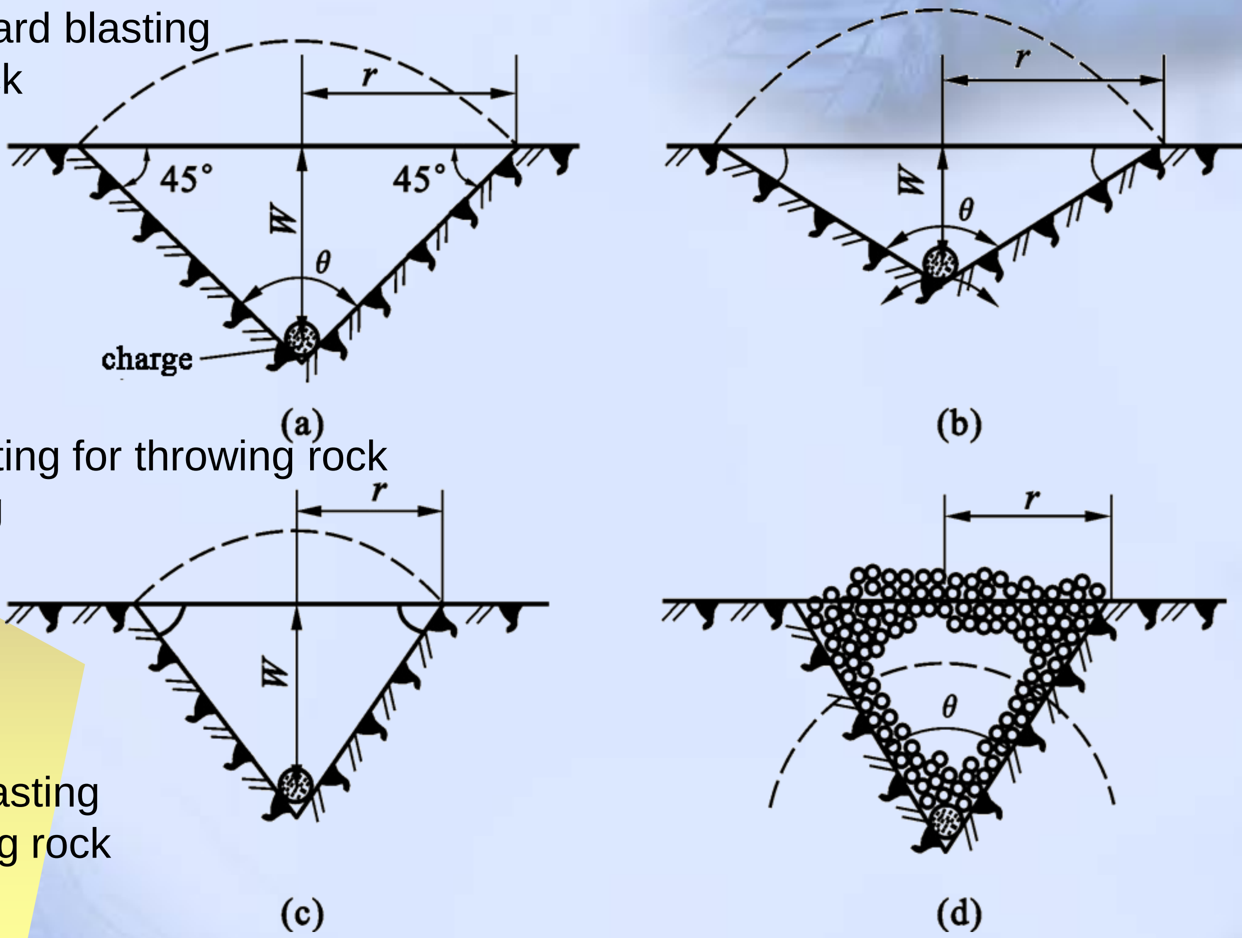
**0.75 < n < 1.0**

Crater of weaken blasting for throwing rock（strengthened blasting for loosening rock）

**d**

**n < 0.75**

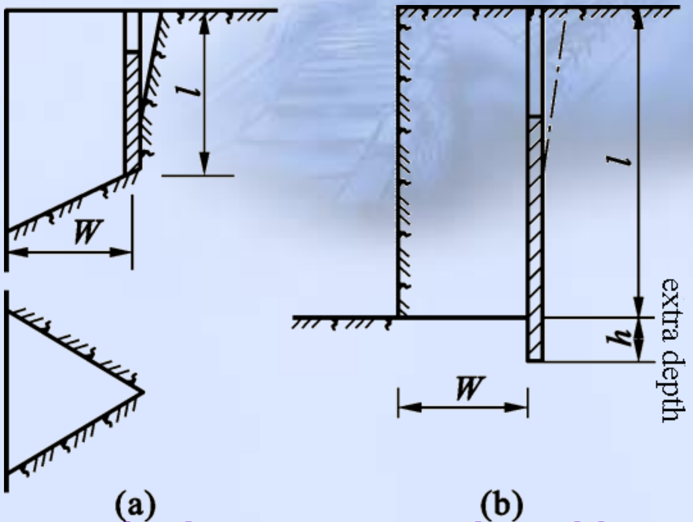
Crater of blasting for loosening rock



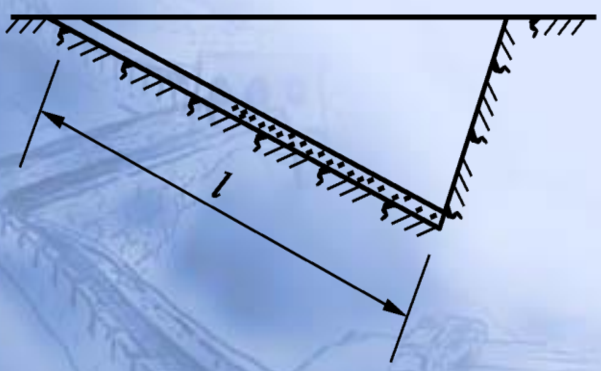
# Section 3: blasting action of extended charge

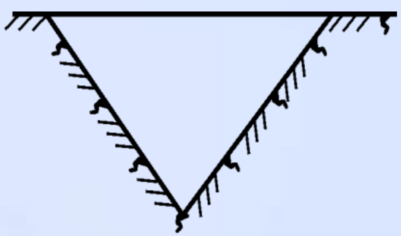
Extended charge

The ratio $\varphi$ of charge length to its diameter of cross section is higher than a particular value.

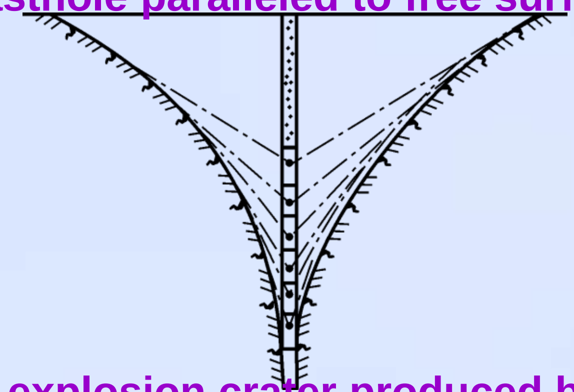



explosion crater produced by blasthole paralleled to free surface



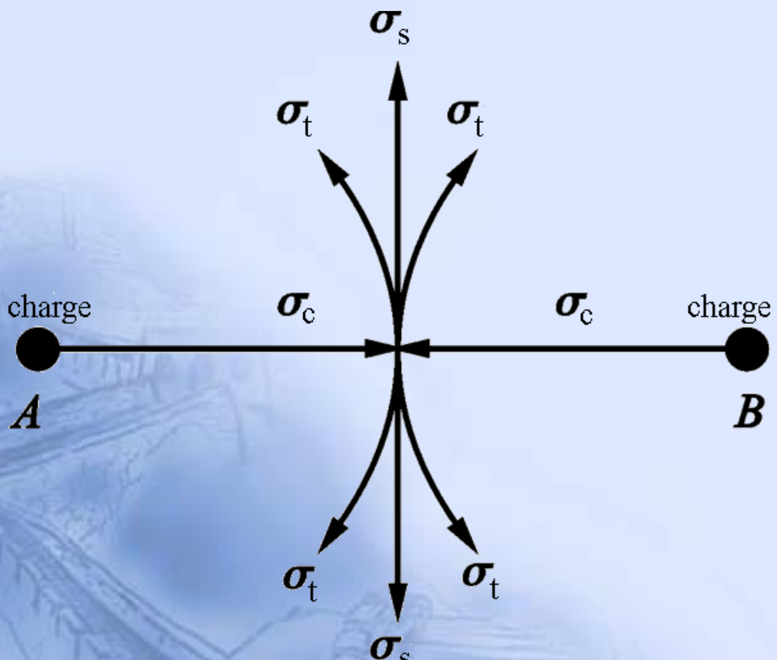
explosion crater produced by an oblique blasthole to free surface



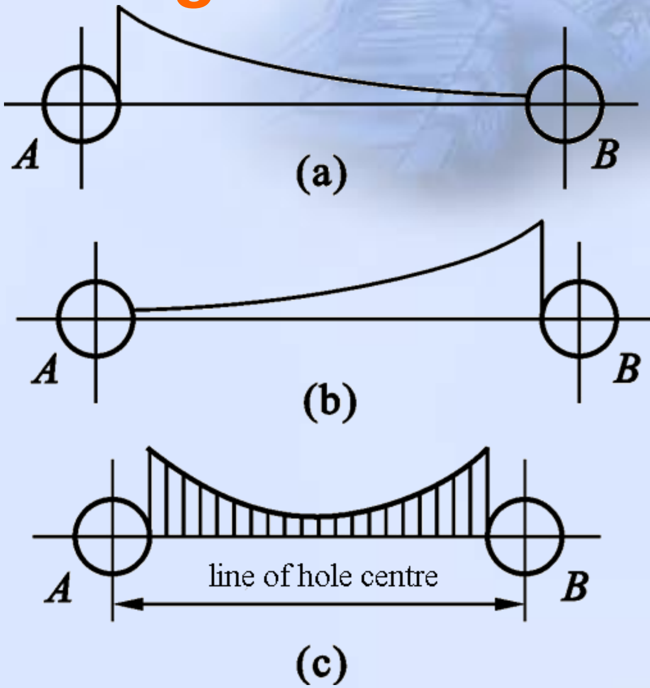
explosion crater produced by an vertical blasthole to free surface

# Section 4: Characters of rock failure when detonating multi-charges

When detonating two adjacent charge, stress on the line of hole center will be strengthened. However, stress on two sides of middle section of the line will be reduced.




**Superposition of stress wave produced by detonating two adjacent charge**



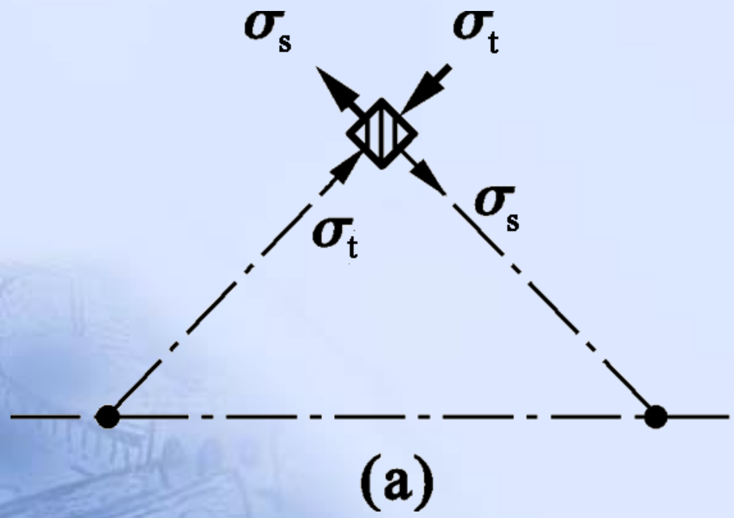

**Analysis on quasi-static stress on the line of hole center**

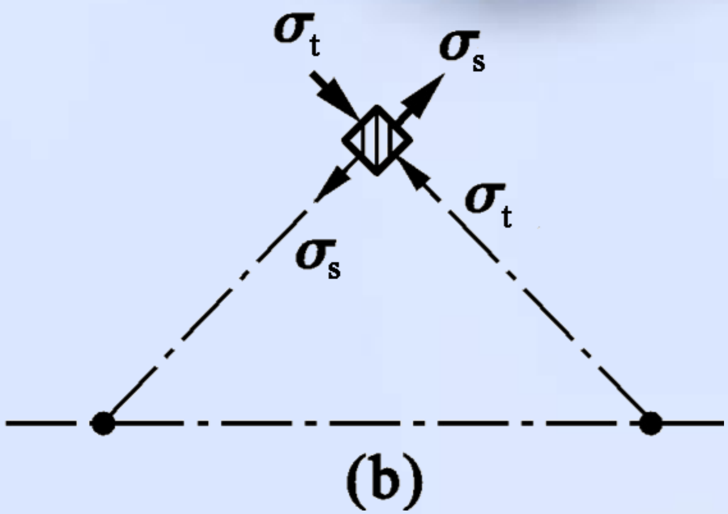
**（a）** tangential associated tensile stress produced by A

**（b）** tangential associated tensile stress produced by B

**（c）** superposition stress produced by A and B

# Analysis on stress reduction




Analysis on stress reduction

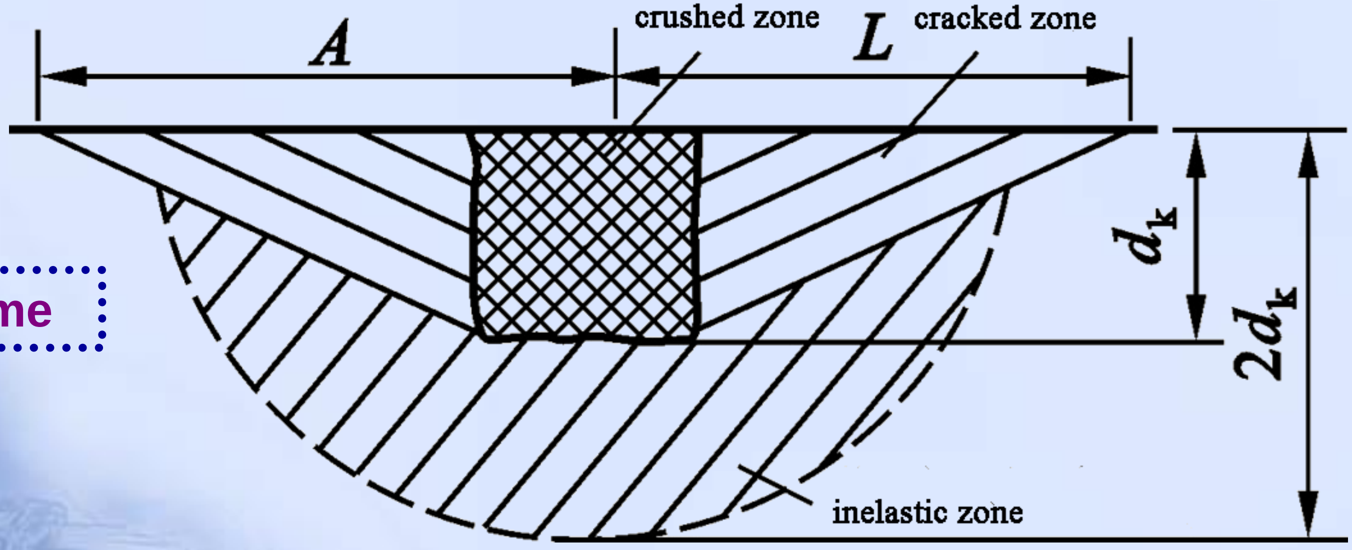
**The blasting effect of detonating multi-charges is poor, so it can't be applied in practice.**

# Section 5: Principle of energy balance and charging calculation

Principle of similarity

$$\frac{R'}{R} = \left(\frac{Q'}{Q}\right)^{1/3}$$

Principle of volume




Blasting effect of external charge

# Principle of energy balance and charging calculation

**Principle of volume**

**Principle of similarity**

With constant types of explosive and rock, the blasting volume of soil and rock is in proportion to charging. That is

$$Q=KV$$

For concentrated charge, the crater index *n* of standard blasting for throwing rock is 1. That means *r=W.*

The volume of explosion crater can be calculated by following formula.

$$V=\frac{\pi r^2}{3}W \approx W^3$$

The charging of standard blasting for throwing rock can be calculated by following formula.

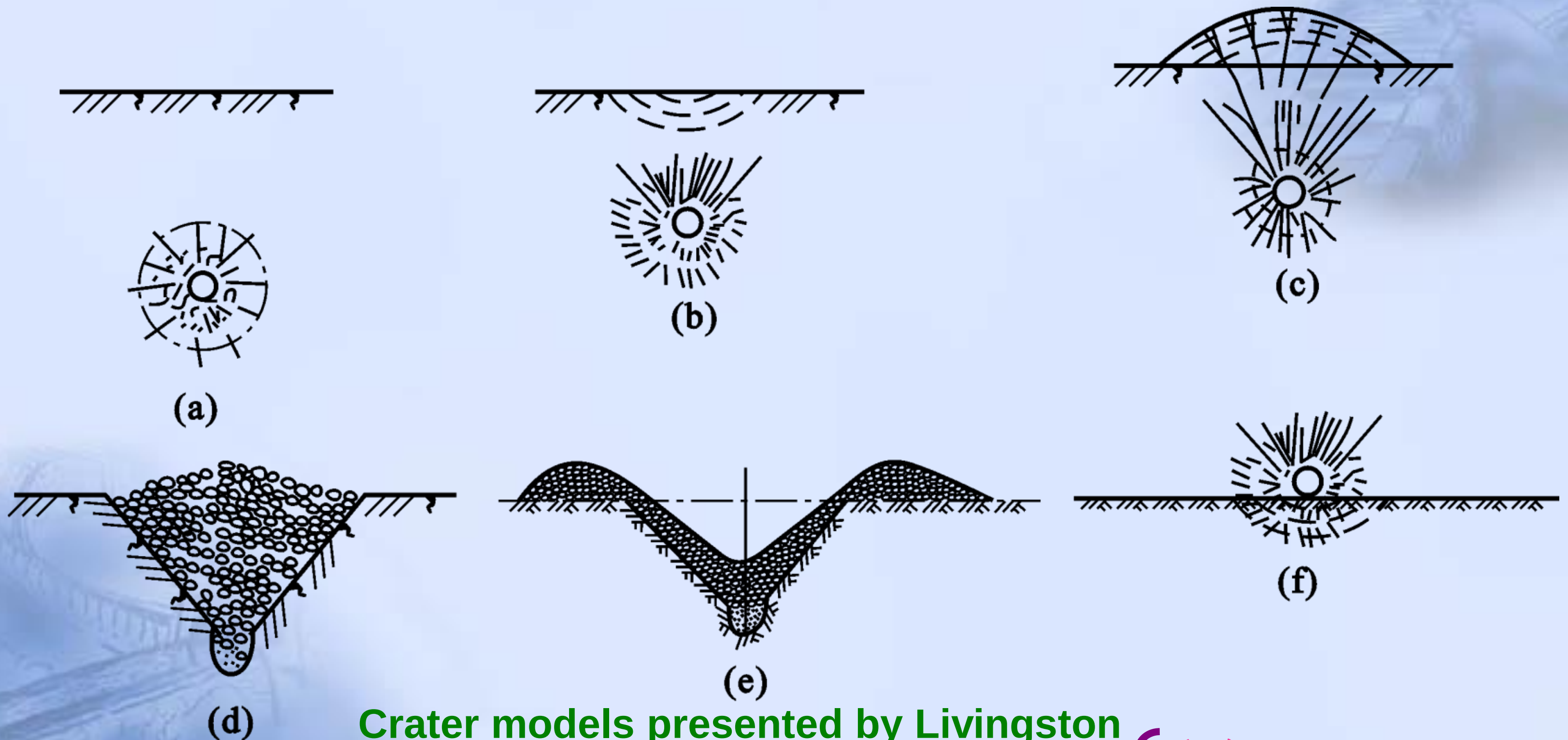
$$Q_{标}=KW^3$$

So:

$$Q_{抛}=f(n)KW^3$$

***f(n):*****function of crater index**

# Principle of explosion crater presented by Livingston




Crater models presented by Livingston

Four types of crater are classified by Livingston according to their deformation and failure patterns.

**Related terms**： critical depth, optimum depth, turning depth.

（1） elastic deformation

（2） shocked fragmentation

（3） crushed fragmentation

（4） explosion on surface

# Charging calculation of concentrated charge

**A empirical formula presented by M.M.Bopeckob**（applied to charging calculation of blasting for throwing rock）：

$$f(n) = 0.4 + 0.6n^3$$

**Charging calculation of blasting for throwing rock:**

$$Q_p = (0.4 + 0.6n^3)k_b W^3$$

$$Q_p = (0.4 + 0.6n^3)\varphi k_b W^3 \quad \varphi = \begin{cases} 1 & W \le 25m \\ \sqrt{W/25} & W > 25m \end{cases}$$

**Charging calculation of blasting for loosening rock:**

$$Q_s = (0.33 \sim 0.5)k_b W^3$$

# Charging calculation of extended charge

**A** Extended charge is vertical to free surface.

$$Q = k_b f(n) W^3$$

$$W = l_{\mathrm{d}} + \frac{1}{2} l_{\mathrm{e}}$$

**B** Extended charge is parallel to free surface.

$$Q_{\mathrm{n}} = k_b W^2 l$$

# Unit explosive consumption

**Main parameters：**

**$K_b$** — ***standard unit explosive consumption index,*** abbreviation of ***unit explosive consumption index of standard blasting for throwing rock***, means the consumption of 2# rock AN-TNT containing explosive for blasting 1m$^3$ of rock or soil when crater of standard blasting for throwing rock (**n=1**) is produced by detonating a single concentrated charge.

**$K_s$** — ***unit explosive consumption index of blasting for loosening rock*** means the consumption of 2# rock AN-TNT containing explosive for blasting 1m$^3$ of rock or soil when crater of blasting for loosening rock (generally **n<0.75**) is produced by detonating a single concentrated charge.

# Methods to take values of $K_b$ and $K_s$

| lookup | engineering analogy | experiment |
| --- | --- | --- |
| For normal rock blasting, $K_b$ and $K_s$ can be taken by lookup. | $K_b$ and $K_s$ can be taken according to unit explosive consumption used in analogous project. | $K_b$ can be taken by experiment of standard blasting for throwing rock. |

**In experiment of standard blasting for throwing rock, formula to calculate $K_b$ is:**

$$k_b = \frac{Q}{(0.4 + 0.6n^3)W^3}$$

# Unit explosive consumption of multi-charges

**explosive ratio**

**Explosive ratio, which is represented by *q*, means the ratio of total charging quantity to blasting rock volume when detonating multi-charges. The calculating formula is:**

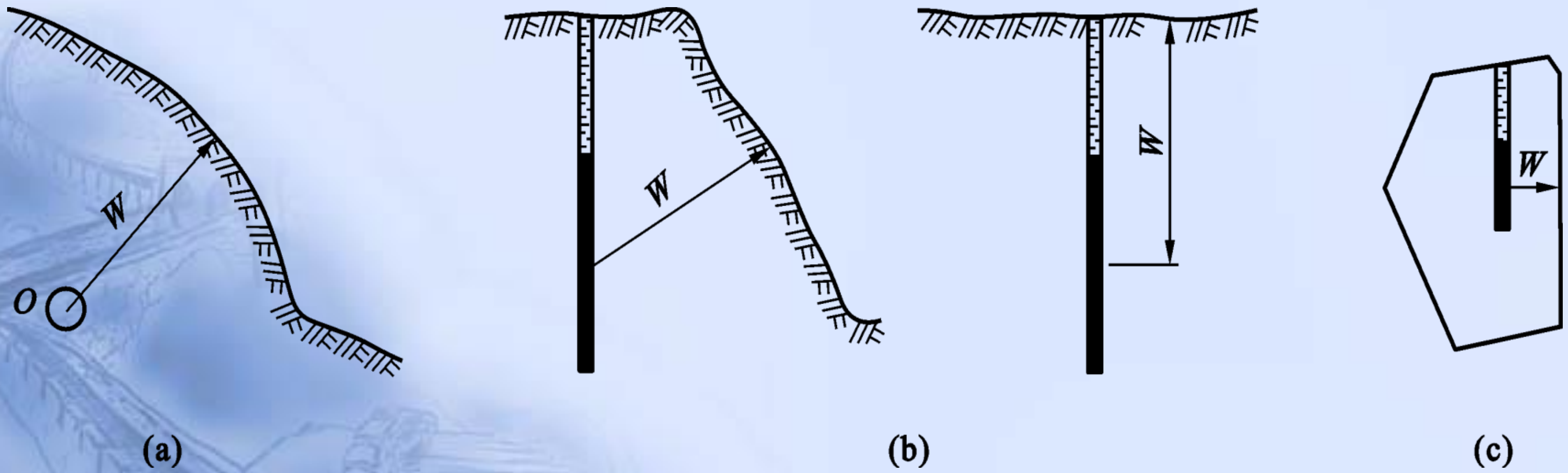
$$q = \frac{\Sigma Q}{\Sigma V}$$

**Above $K_b$ and $K_s$ are relative indexes between charging quantity and blasting rock volume when detonating a single concentrated charge.**

# Resistance line（1）

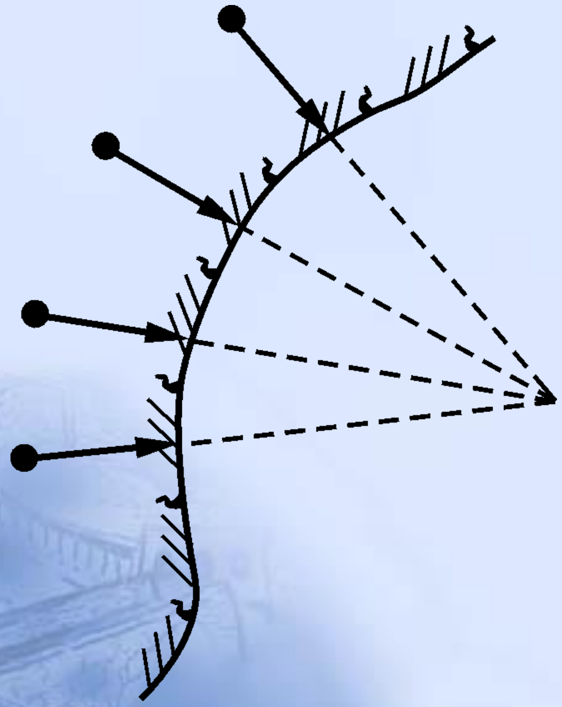
**Direction of the line** —— general direction of crushing, throwing and stacking

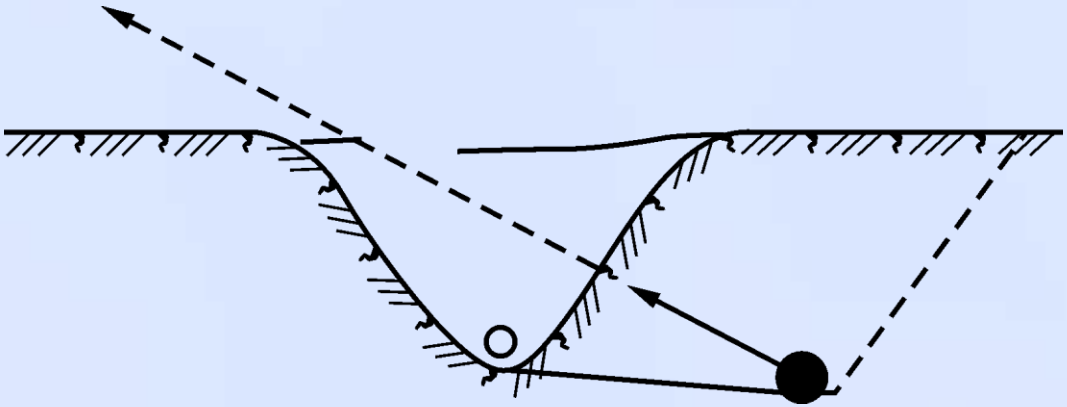
**Principle of the line** —— relationship between throwing and the line and between stacking and the line




**Line of least resistance for different blasting**

# line of least resistance（2）

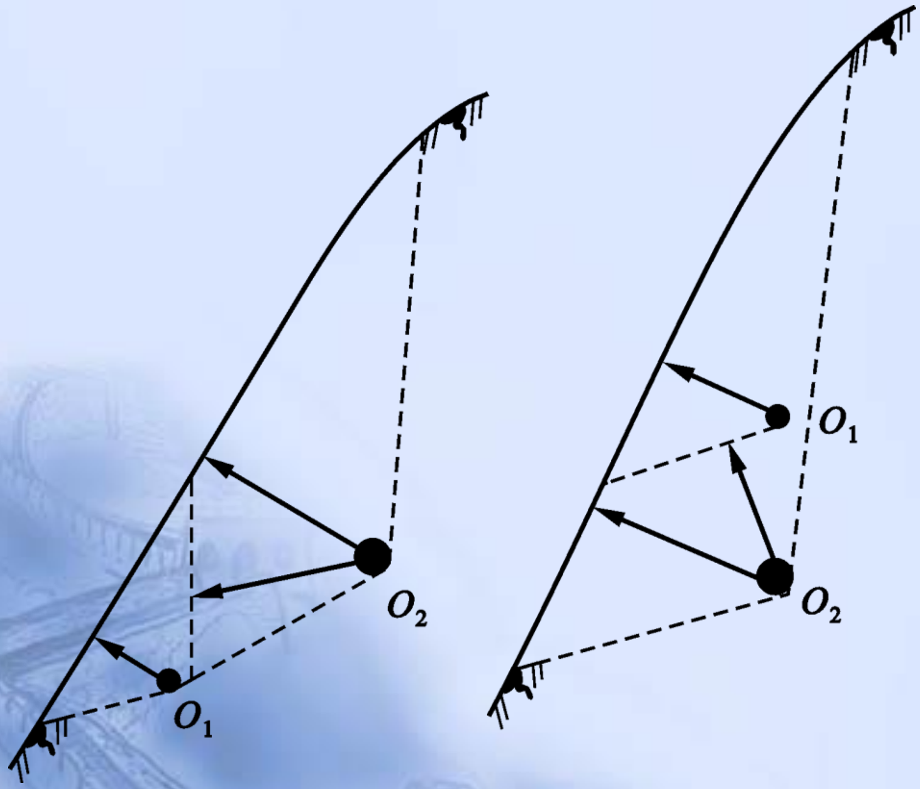




**Concave Surface**
**good for concentrated throwing and stacking**

**Assisted Charge**
**to change direction of the line**

# smallest resistance（3）




Influence of charging position and initiating sequence on direction of the line

Line of least resistance leads the direction of rock crushing, throwing and flying.

Pay more attention to choosing the direction of the line and taking security protection on the direction. Measure value and direction of the line carefully before detonation.

Because charging quantity Q is in proportional to $W^3$, wrong measurement of W always leads to serious accident.

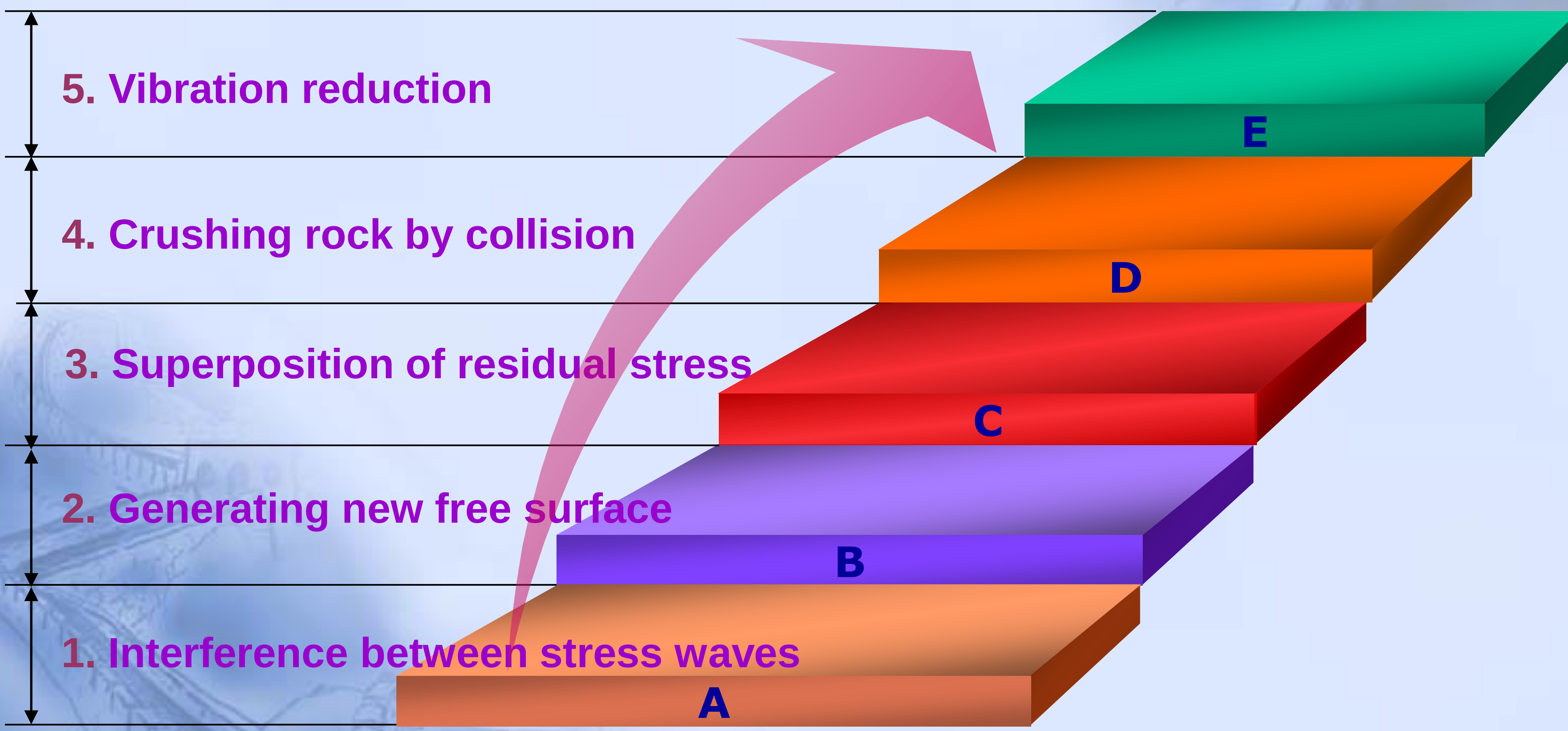
# Mechanism of MS blasting

**MS blasting**

MS blasting is also named delay blasting or MS delay blasting.

In MS blasting network, charges are sequentially initiated with a interval specified in milliseconds by MS detonators or other MS delay materials.

# Mechanism of MS blasting



# Calculation of interval

**A** According to interference of stress wave

**B** According to the new free surface

**C** According to the limit of vibration

**D** According to empirical formula

1） **presented by Changsha Research Institute of Mining and Metallurgy：**

$\triangle t = (20\sim40)W_0 / f$

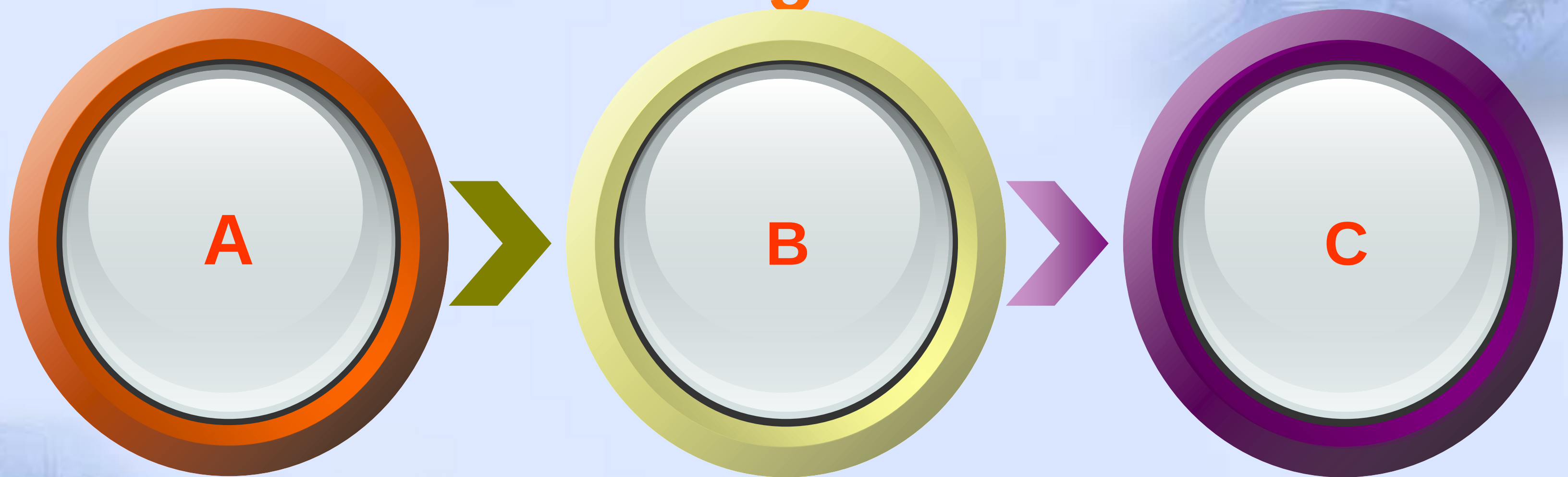
2） presented by **U. Langefors (Swede)：**

$\triangle t = 3.3KW$

3） presented by **mining department of Soviet Union：**

$\triangle t = KW(24 - f)$

# Section 6: Main influencing factors on blasting effect




density、explosion heat and explosion velocity

detonation pressure and explosion pressure

utilization ratio of explosion energy

**difference:**

Detonation pressure — pressure on C-J surface

Explosion pressure — expansion pressure of explosive gases

# Action of free surface

**① reflecting stress wave**

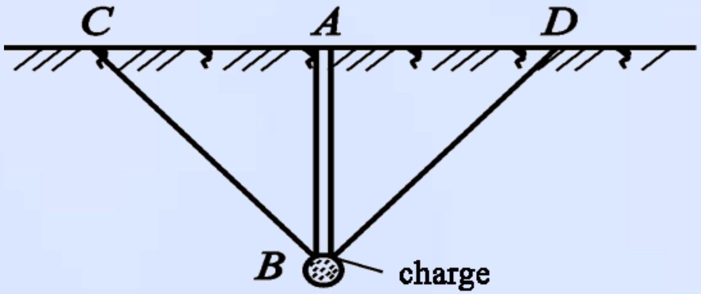
**Stress waves are reflected when they arrive at free surface. The reflection makes compressive stress wave converted into tensile stress wave. The tensile wave makes spall fall and radial crack grow.**

**② influence stress states and strength limit of rock**

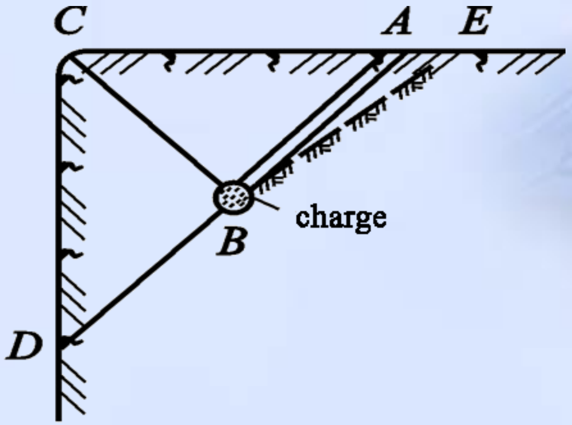
**In infinite medium, rock is in three-dimensional stress state. However, rock near free surface, which is in uniaxial stress state or planar stress state, takes uniaxial tensile strength or compression ultimate strength. Compared to rock in infinite medium, the strength of rock near free surface is several times, perhaps scores times lower .**

**③ Free surface is on line direction of least resistance. When stress wave arrivals at free surface, medium here moves faster because of resistance reduction. Following explosive gases moving to free surface make rock on surface bulged, crushed and threw.**

# Influence of free surface on blasting effect

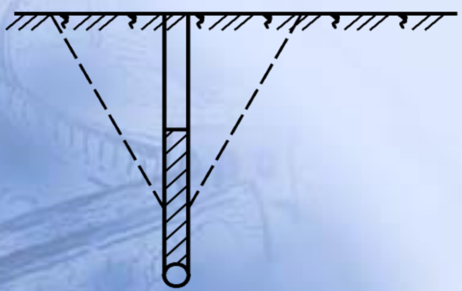



(a)

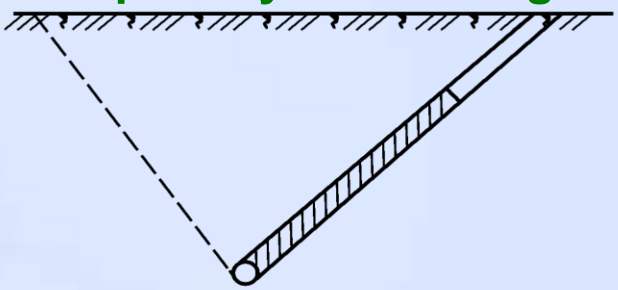



(b)

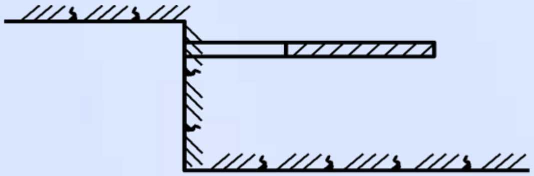
**Influence of surface’s quantity on blasting effect**



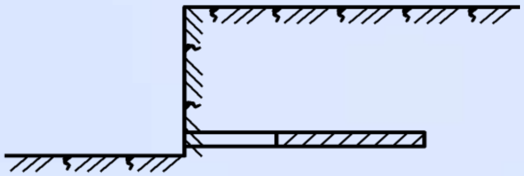
(a)



(b)



(c)



(d)

**Influence of surface’s and blasthole’s position on blasting effect**

（a）vertical blasthole（b）oblique blasthole

（c）surface is under blasthole（d）surface is over blasthole

# Influence of suitability of explosive to rock on blasting effect

**Wave impedance**

For rock or other medium, wave impedance means the product of their density and P-wave velocity.

**Charging structure**

- coupling charging
- decoupling charging

Formula for calculating decoupling index：

$$R_d = \frac{d}{d_e}$$

- decked charging
- continuous charging

(1) reducing the maximum shock pressure on hole wall.

(2) prolong the time of stress wave propagation.

(3) making the impulse of stress wave to rock larger and well-distributed.

# Influence of blasting technology on blasting effect

## Action of damming

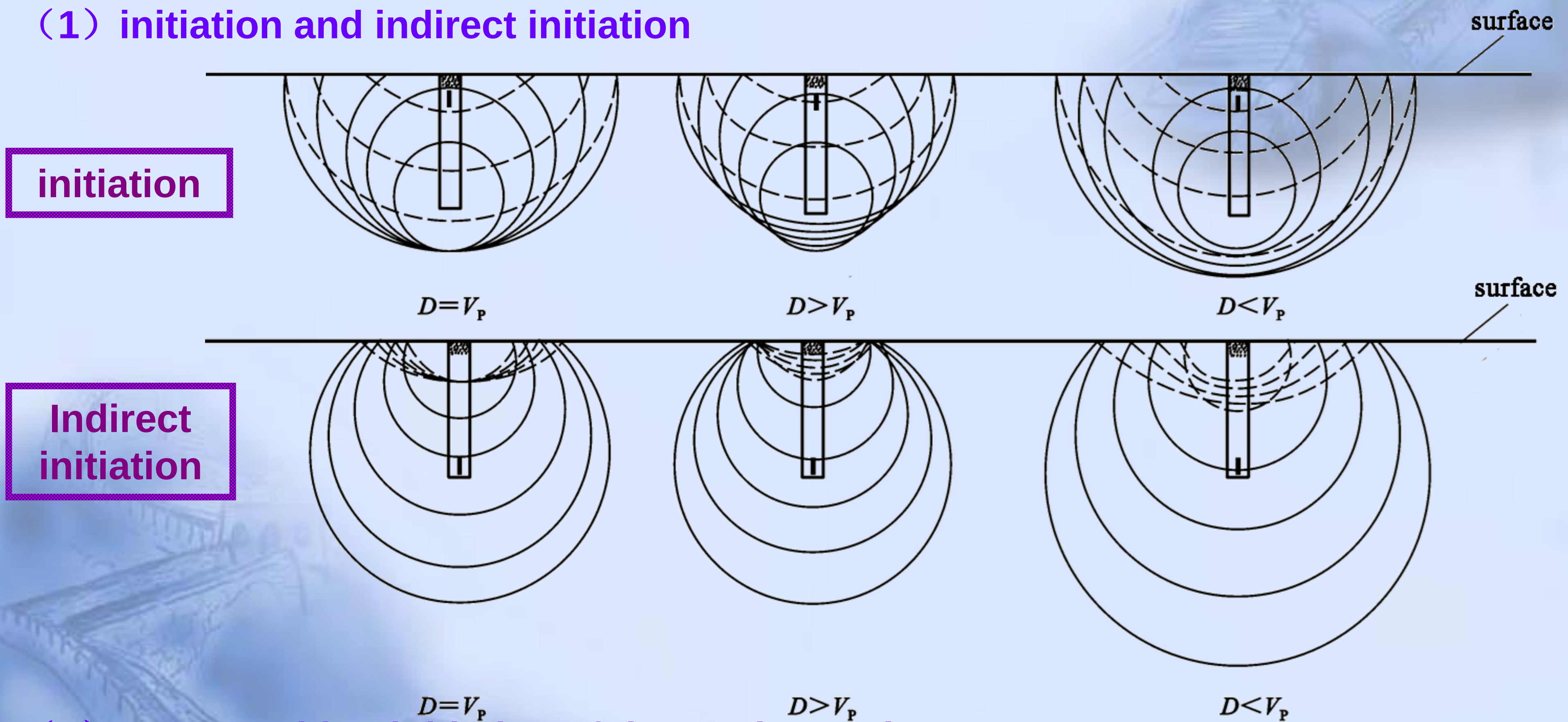
（1） Making explosive reacted completely. Releasing maximum heat and minimum poisonous gas.

（2） Reducing temperature and pressure of explosive gases. Improving utilization rate of explosion heat.

（3） Preventing burning solid particles(such as fragments of detonators) flying out of blasthole. Improving blasting safety.

# initiating methods

（1）initiation and indirect initiation




（2）superposition initiation of detonating code

superposition charge ——superposition of two types of explosive with different explosion velocity

# Thank You !

Wuhan University of Technology