Shock Waves In Snow – Interaction of Explosives With Snow

J. B. Johnson
Institute of Northern Engineering
University of Alaska Fairbanks

November 11, 2010
Presentation Goals and Outline

• Goals
  – Describe the properties of explosives important for snow engineering
  – Describe how explosive generated shock waves interact with snow
  – Explain the various possible outcomes of using explosives in snow of interest to avalanche control specialists.

• Outline of the talk
  1. Overview of methods of using explosives in snow engineering
  2. Explosive properties important to snow engineering
  3. Explosive shock wave interaction with snow
  4. Use of explosives in snow to maximize their effectiveness
1. Overview of Methods of Using Explosives in Snow

- Surface or in-snow Cornice burst
- Air burst (Gazex)
- Explosive charge placement effects

In-snow sequential or simultaneous detonation in stable snow
Questions Derived from Using Explosives in Snow

• How do explosives interact with snow?
• How do explosive affect snow instabilities?
• What are the best explosives to use?
• What are the most efficient methods?
• Why do post-control releases occur?
• Why are wet slabs so hard to release?
• What is in-place explosive slab stabilization?
• What are the limitations of explosive use?
2. Explosive Properties

- Detonation process
  - Initiation of explosive detonation
  - Detonation burn characteristics

- Explosive characteristics
  - Detonation velocity
  - Pressure
  - Energy
  - Impulse
Idealized Explosive Detonation

- Detonation wave consists of 4 parts
  - Shock compaction
  - Reaction zone (highest pressure, energy & density)
  - Equilibrium C-J state (decreasing P-density)
  - Rarefaction “Taylor” wave expanding gases)
Idealized Explosive Detonation

- **Detonation pressure**
  - Highest, but decreasing in the R-Z
  - Constant ($P_{cj}$)
  - Decreasing in the E-G
- Rate of decrease depends on explosive thickness & degree of confinement
C-J Pressure as Function of Density and Detonation speed

- C-J pressure ($P_{cj}$) is a function of Detonation velocity ($D$), explosive density ($\rho_0$), and the explosive gas constant ($\Gamma_{cj}$).

\[ P_{cj} = \frac{\rho_0 D^2}{\left( \Gamma_{cj} + 1 \right)} \text{ (GPa)} \]

Data from Dobratz and Crawford, 1985
Explosive Energy Density Versus Detonation Speed

- Energy density \( (e_d) \) is a function of \( D \)
- Higher \( e_d \) results in higher explosive work output
- Increasing \( D \) results in increasing \( P_{cj} \) and \( e_d \)

Data from Dobratz and Crawford, 1985
High failure or yield strength

Pressure

Explosive 1 (Exp 1)
High failure or yield strength

Explosive 2 (Exp 2)
Low failure or yield strength

Time

Shock Impulse

• \( P_{cj} \) and shock impulse (I) determine explosive effectiveness

• For \((P_{cj})_1 > (P_{cj})_2\) and \(I_1 = I_2\)
  - Exp 1 has greater effect on high strength materials
  - Exp 2 has greater on low strength materials
Shock Impulse Magnitude

- Impulse is increased by increase explosive energy density and/or mass

- The effect of spherical explosive charges of different size varies as the cube root of charge mass
Summary of Explosive Performance Information

- Effectiveness of action is a function of impulse and gas pressure
- Total energy determines impulse magnitude
- Total energy is a function of density, specific energy, and explosive size
- Gas pressure is a function of energy density ($e_d$), mass, and degree of confinement
3. Shock Wave Interaction With Snow

- Shock wave propagation
- Shock wave attenuation
- Scaling laws and equivalent explosive effects (Using larger explosive mass to affect larger areas)
- Explosives and snow engineering (avalanche control, cornice control, slope stabilization)
Explosive Effect in snow

Detonation Point
(Data from Gubler, 1976, 1977, 1978)

Air
Snow surface
Snow

Relative explosive effect vs. Total energy (MJ)

Relative explosive effect vs. Detonation speed (km/s)
Plane Shock Wave Propagation in Snow

- Two zones of propagation
  - Shock compression waves ($\sigma_{Sp}$ dominant)
  - Acoustic waves ($\sigma_{Ap}$ - propagating in snow frame and air pores)
Plane Shock Wave Attenuation

- Two sources of attenuation
  - Momentum Spreading in the shock compaction zone
  - Viscous dissipation in the elastic/acoustic Zone
- Air pore/ice frame interaction

Diagram:
- Pressure ($P$) vs. Distance ($D$)
  - $t = 0$: Explosive
  - $t = 1$: Unaffected bulk snow
  - $t = 2$: Elastic/acoustic
- Expanded phases:Expanding gases, Compacted snow, Elastic/acoustic
Momentum Spreading Attenuation

- Momentum (Q) is the product of mass (m) times particle velocity (v); \( Q = m \times v \)

- Spreading occurs when inelastic compaction occurs, reducing the particle velocity

- Pressure (P) decreases with \( v \); \( P = k \times v^2 \)
Viscous Dissipation Attenuation

- Viscous dissipation occurs because of air movement through snow in the pore space.
- The different velocity of air vibration compared to ice frame vibration produces friction heating and reduced momentum.
Plane Shock Wave Attenuation

\[ \rho_0 = 250 \pm 30 \text{ kg/m}^3 \]
Spherical Shock Wave Propagation

- Three zones of propagation
  - Shock compression waves ($\sigma_{Sp}$ dominant)
  - Fracture zone ($\sigma_t$ exceeds strength)
  - Acoustic waves ($\sigma_{Ap}$-propagating in snow frame and air pores)
Spherical Shock Wave Attenuation

- Three sources of attenuation
  - Momentum spreading
    - Snow compaction
    - Snow ejection (surface crater formation)
  - Geometric spreading
  - Viscous dissipation
Attenuation of Shock and Acoustic Waves

- Spherical shock in snow (M, G, & V)*
- Plane shock in snow (M & V)
- Plane acoustic in snow (V)
- 1-m above snow (G-in air, V-in snow)

*M – momentum spreading, G – geometric spreading, V – viscous dissipation
Explosive Detonations in Air

- For a given distance from ground zero (r), shock pressure (P) will increase with detonation height (H) to a maximum and then decrease.

- This defines the maximum pressure (P_{H_{max}}) – maximum detonation (H_{max}) curve.
Scaled Air Detonation

Pressure on snow

Pressure ratio as a function of scaled height of detonation

Scaled maximum Pressure curve
Detonation Above a Snow Slab

- Creates shear and compression stresses on snow layers
- Stresses on layers vary with Z
- Can cause weak layer collapse or shear failure
Detonation Above Snow: Bedding Plane Stresses

Shear

- Detonation height, $Z = 0.1$
- $Z = 1.0$
- $Z = 2.0$

Compression

- Detonation height, $Z = 0.1$
- $Z = 1.0$
- $Z = 2.0$

Radius

Shear stress

Compresssion stress
Summary of Explosive Interaction with snow

- Shock waves are rapidly reduced to low intensity (acoustic waves) due to momentum and geometric spreading.
- Acoustic wave attenuation is a function of viscous damping and geometric spreading.
- Detonation in air above the snow surface reduces attenuation rate (no momentum spreading).
- Optimal detonation height above snow depends on total explosive energy (charge mass).
  - Optimal detonation height produces the maximum pressure at a specified distance on the snow surface.
4. Explosives and Snow Engineering

- Attacking snow instabilities for dry and wet slabs and cornices
- Most effective charge placement
- The effect of charge size
- Recognizing the limitations of explosive use
Snow Instabilities

Cornice

Snow volume in tension at the ridge

Snow slab

Primarily – weak bedding plane, but also crown and flanks (especially with hard slabs)

Wet snow slab

Bedding plane with high water content from melt or rain
Cornice Hazard Control

- Tension stress instability
- Surface detonation crater to remove strength and allow gravity to induce tensile failure
- Subsurface detonation crater more efficiently reduces cornice strength
Weak Layer Snow Slab Control

- High local stresses
- Deep slab penetration
- Small areal extent

- Reduced local stresses
- Reduced slab penetration
- Increased areal extent

Stresses and slab penetration too small to have an effect

- Increase charge size
- Increased areal effect
- Increased slab penetration

Snow layers and potential failure planes
Potential Wet Slab Instability

- Wet slab instabilities are difficult to predict
  - Caused by zones of over saturated snow due to low or impermeable layer
- Simultaneous detonation to displace snow (increase flow pathways)
- Sequential detonation to move snow off slope

Potential wet slab with embedded explosives
Conjectures about Post-Control Delayed Slab Release

• Shock too weak to cause weak layer failure
  – layer continues weakening until failure occurs
  – Additional loading on slab causes layer failure

• Area of weak layer failure too small
  – Failure area continues growing under gravity loading until slab fails

• Hard slab strength in flanks and crown hold slab in place
  – Additional loading causes failure at crown or flanks
  – Progressive failure at flanks or crown cause failure
Conjectures About Slab Stabilization

• Weak layer collapse brings slab in contact with bedding plane
  – Friction holds slab on slope
  – Strength increases with time through sintering
• For wet snow – snow displacement
  – Better pathways for water flow
Conclusions (1/3)

• Total detonation energy, not detonation velocity, determines explosive effect

• High detonation velocity explosives have higher energy density than low velocity explosives (Higher energy for the same explosive weight)

• Targeting natural instabilities is the most effective method requiring the least amount of explosive (e.g., tension zones, weak layers)
Conclusions (2/3)

• Targeting deep slab instabilities, potential wet slab instabilities, or in-slope stabilization require more in-snow explosives to form craters and displace snow.

• Air burst detonations produce shear and compression stresses on weak layers to cause weak layer shear or collapse failure.

• Optimal air detonation above snow for weak layer attack is between $1 - 2 \, \text{m-kgf}^{1/3}$ in scaled units (for example – $1 - 2 \, \text{m for 1 kgf of explosive}$).
Conclusions (3/3)

- Understanding snow pack conditions is necessary to develop an effective explosive control use plan
  - To determine optimal type, amount and deployment method for explosives
  - To reduce risk of post-control releases
  - To determine if in-slope stabilization will be effective