Welcome Everyone!

OSM
Blasting
Seminar

November
2007

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What is Vibration ?

A traveling disturbance, the transfer of energy between two points.

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Vibration – Particle Motion

- Newton's Second Law - F=MA The resultant of all the forces acting on a particle is proportional to the acceleration of the particle.
- Ground Particle ? - Molecular or Particulate (a continuous medium with constant thermodynamic and acoustic variables)
- Particle motion is spherical. Tri-axial geophones measure the X, Y and Z vectors of spherical particle motion.

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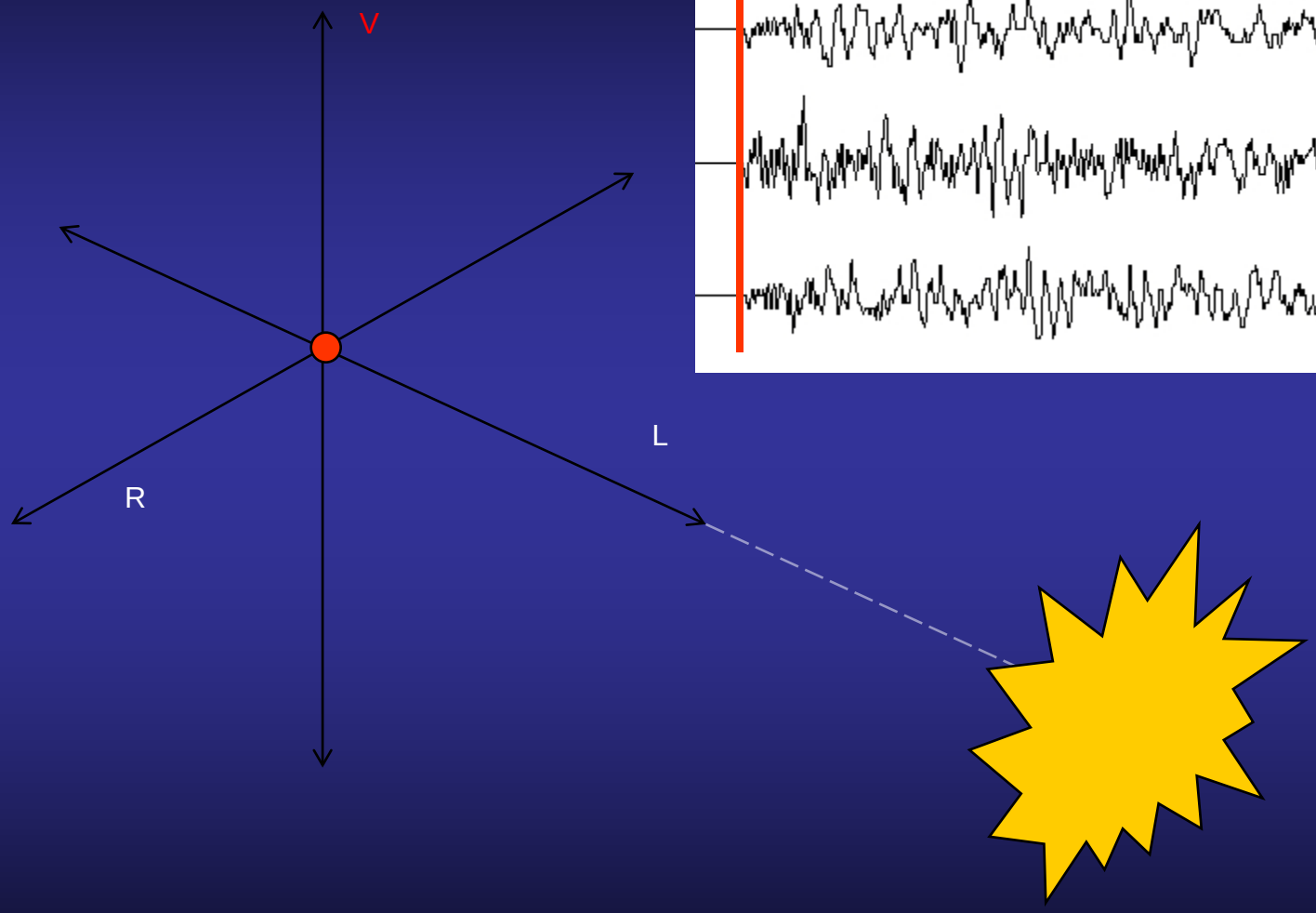
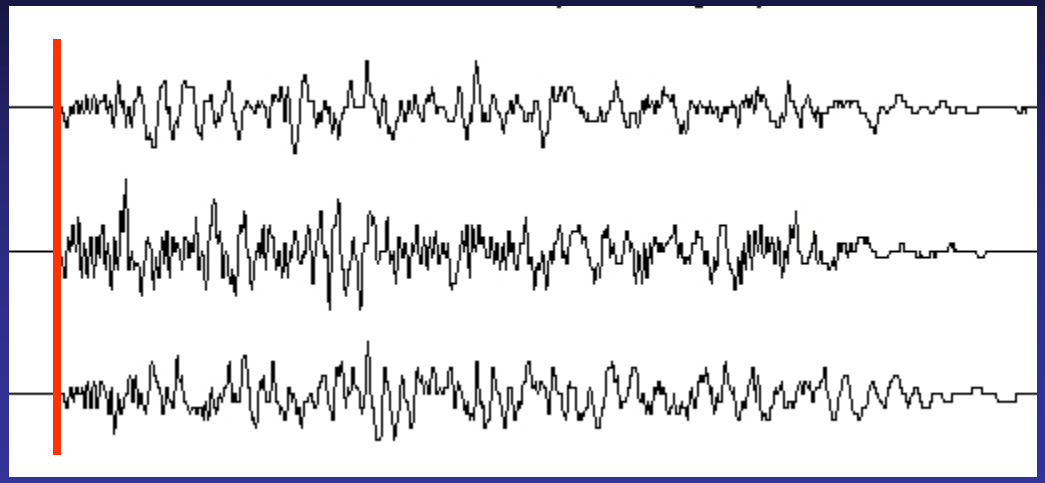
Particle Motion





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Vibration - Velocity

- Wave Velocity - The wave velocity is the rate at which the vibration wave travels within the rock mass.
- Particle Velocity - The Particle Velocity is the measure of the rate of change in the displacement of the ground particle $\Delta d / \Delta t$.

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Vibration Characteristics

- Wave Motion
  - Transient - Transient wave motions are typically complex short duration impulse events.
  - Periodic - Periodic wave motions are typically sinusoidal events of a discrete frequency.
  - Random - A transient event usually within a periodic wave.

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Vibration Characteristics

- Wave Medium - The wave medium is the material in which the wave exists and propagates. A wave medium can be solid, liquid or a gas.
- Solids store energy in shear and compression. Liquids only store energy in compression.

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Vibration – Wave Properties

- Velocity – Wave Velocity and Particle Velocity
- Wave Motion – Transient, Periodic, Random
- Wave Medium – Elastic or Non-Elastic

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Blast Induced Vibrations

- The detonation process. The source of vibration?
  - The potential energy of explosives is converted to kinetic energy during a blast.
- A blast detonation can be discussed and analyzed as a system.

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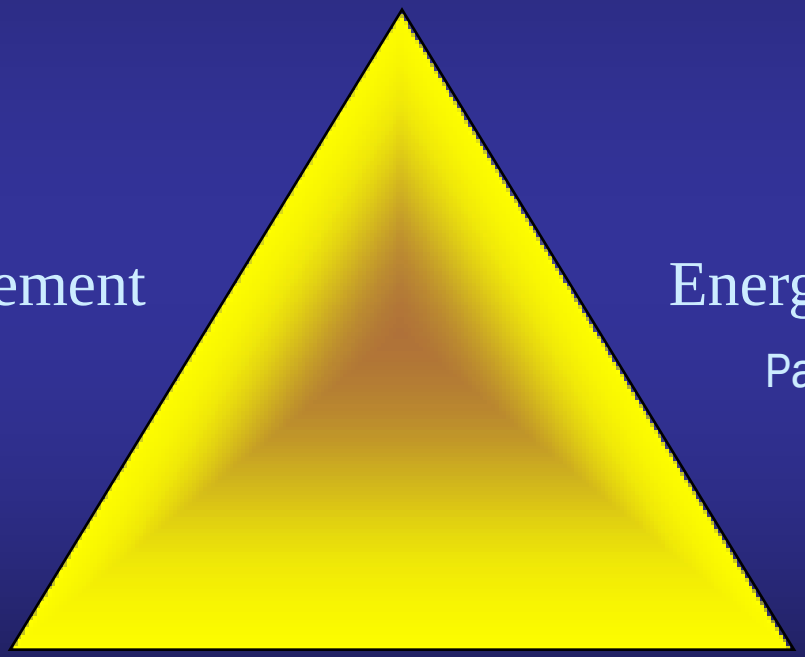
Blast System Analysis

Energy



Energy Confinement

Timing

Energy Distribution

Pattern / Loading

Energy Level

Product Type

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Systems Analysis

INPUT → BLACK BOX → OUTPUT

Energy In	Energy Loss	Effective Energy
Available potential Energy of explosive product.	Product Degradation Venting	Blast performance. Breakage Movement Vibration

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The Stages of Blast Detonation

- Stage 1 - Pressure propagates outward from the borehole as a compressive shock wave.
- Pressure drops quickly with increased distance from the borehole.
- Radial cracking will appear from 1 to 2 hole diameters out from borehole

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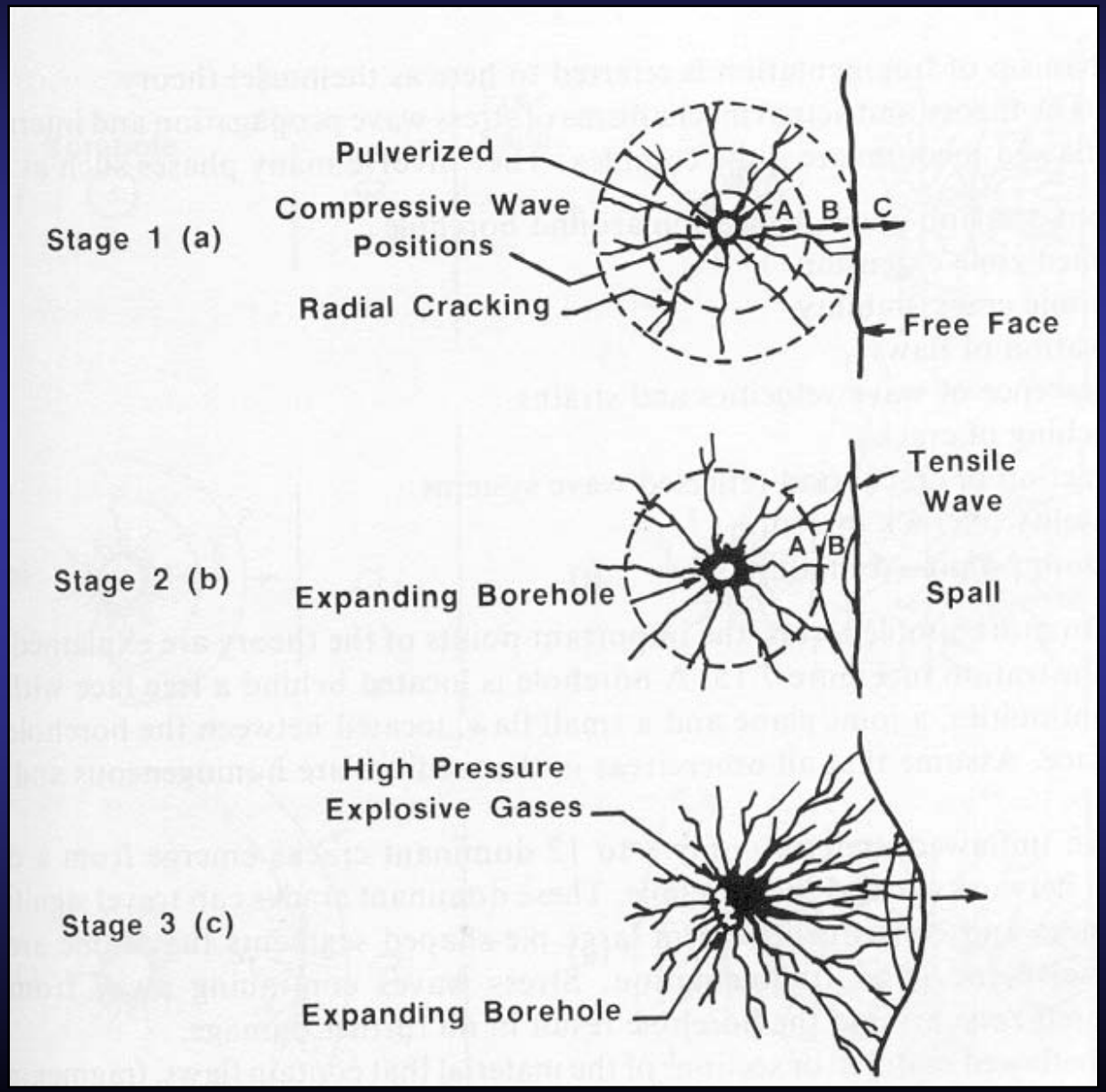
The Stages of Blast Detonation



The Stages of Blast Detonation

- Stage 2 - The compressive shock wave is reflected back from a free surface as a tensile wave
- At this point in time the radial cracks typically extend 25% of the distance between the hole and the free surface parallel to the blast hole.
- Explosive gasses, seeking the path of least resistance, expand into the rock mass, tearing apart the rock and displacing the burden

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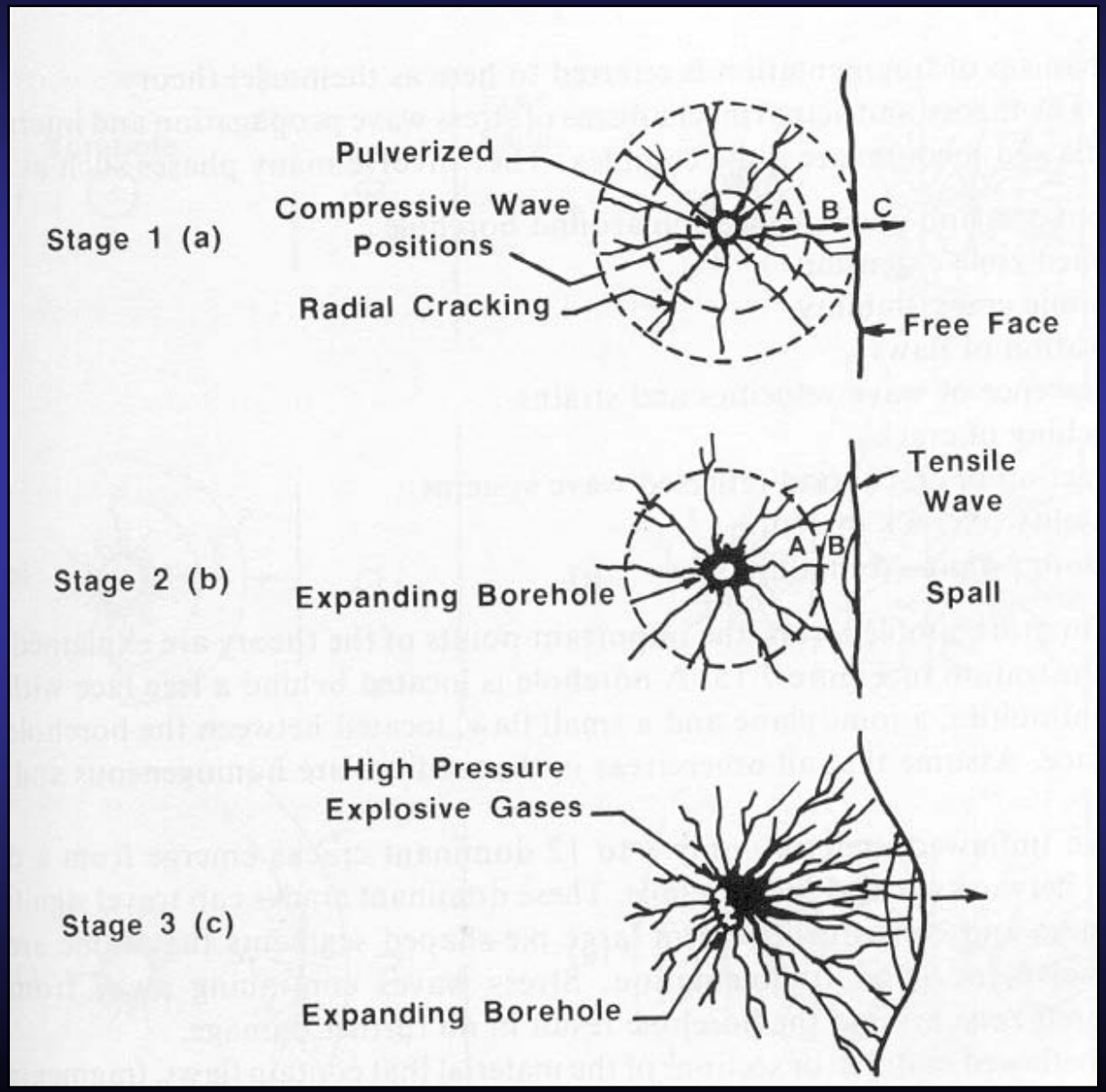
The Stages of Blast Detonation



Elastic Vibration

- Elastic Vibration - When the is Earth rapidly displaced or distorted at some point, the energy imparted into the Earth by the source of the distortion can be transmitted in the form of *elastic waves*. A wave is a disturbance that propagates through, or on the surface of, a medium. Elastic waves propagate through the medium without causing permanent deformation of any point in the medium. Sound propagates through the air as elastic waves and water waves propagate across the surface of a pond as elastic waves.

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Non Elastic Vibration

- Non-Elastic Vibration – Non elastic vibrations result in permanent deformation of the rock mass. They are usually within close proximity of the borehole.

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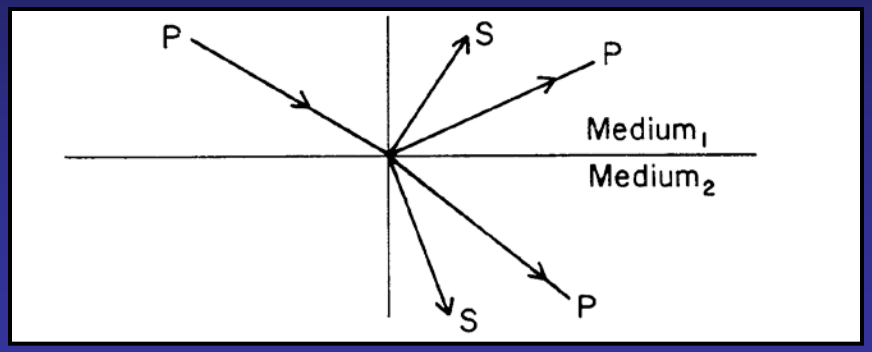
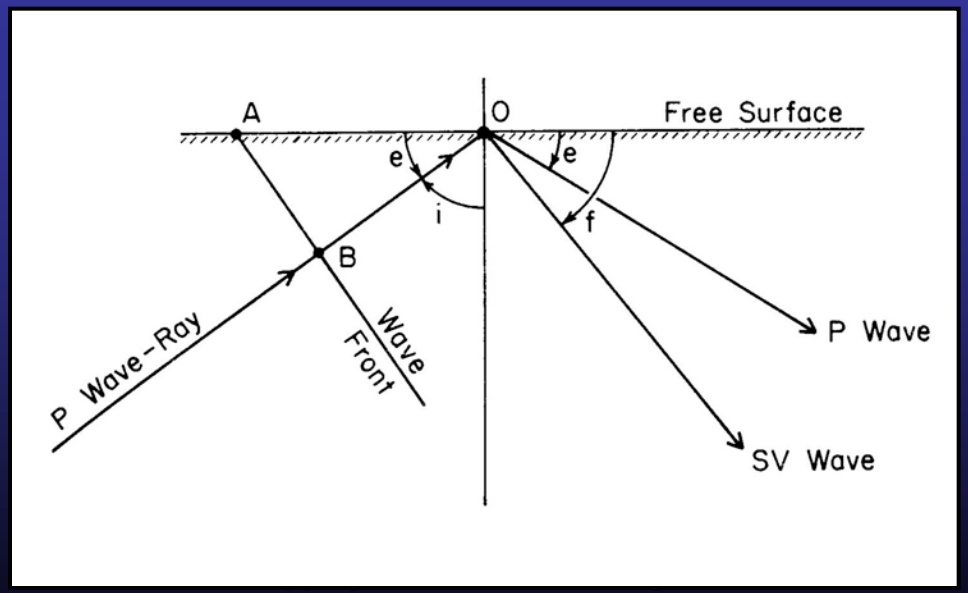
Wave Action at Boundary





Stress and Strain

- Deformation – Compressional and Shear Strain
- Recovery of body size and shape after the removal of deforming forces is proportional to the Strain.
- Hookes Law –
  - (Stress) = (Elastic Moduli) X (Strain)
- Tensile Failure

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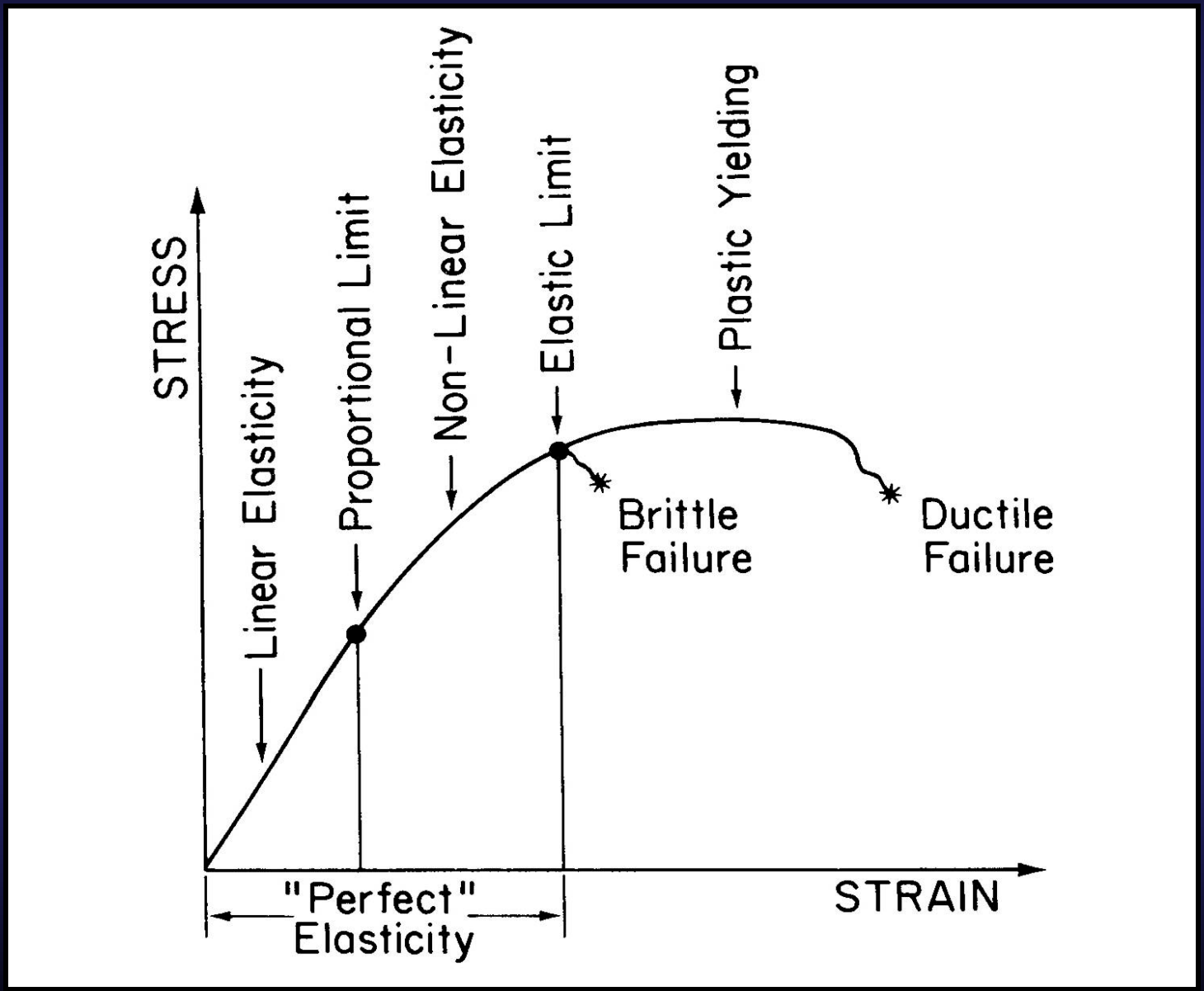
Particle Stress and Strain



Dispersion

- Dispersion - Dispersion is the separation of a wave into its spectral components having different wavelengths.

- Rayleigh waves in the Earth are dispersive: Rayleigh waves with a higher frequency travel more slowly than those with a lower frequency. This occurs because a Rayleigh wave of lower frequency has a relatively long wavelength. Long wavelength waves "see" more deeply into the Earth than waves with a short wavelength. Since the speed of waves in the Earth increases with increasing depth, the longer wavelength (low frequency) waves can travel faster than the shorter wavelength (high frequency) waves.

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Wave Types

Surface Waves – A seismic wave that travels on the surface of the Earth, moving either up and down or from side to side. These waves are commonly referred to as Love and Rayliegh Waves.

Body waves - A seismic wave that travels deep into the earth. These waves are commonly referred to as $P_{primary}$ and $S_{secondary}$ Waves.

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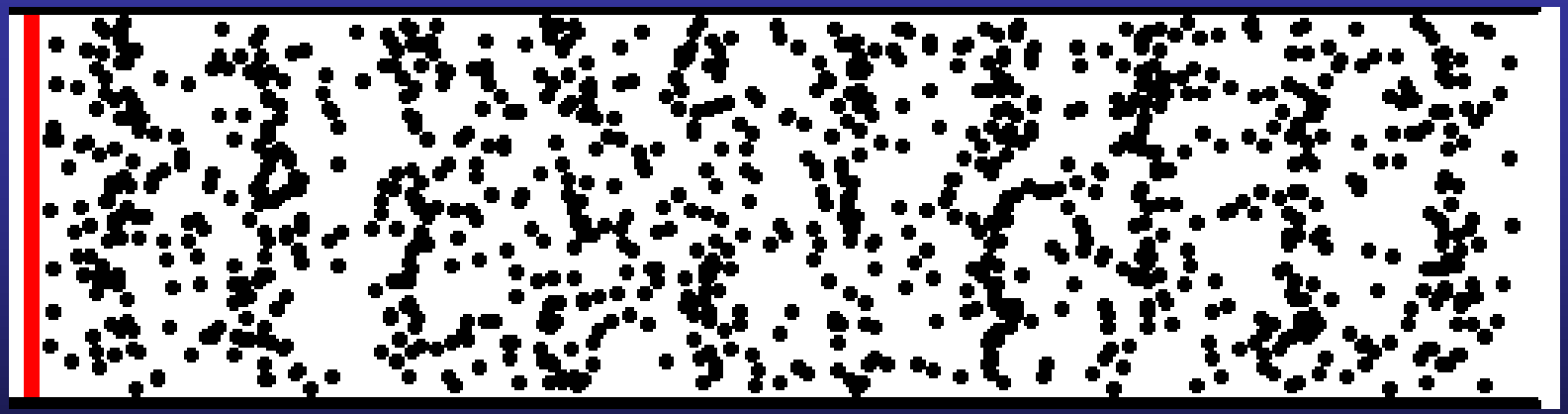
Surface Wave Types

- Love Waves – Love waves exist in the horizontal plane in the transverse direction. Love waves are very damaging. It tells the surface to move forward and backward.



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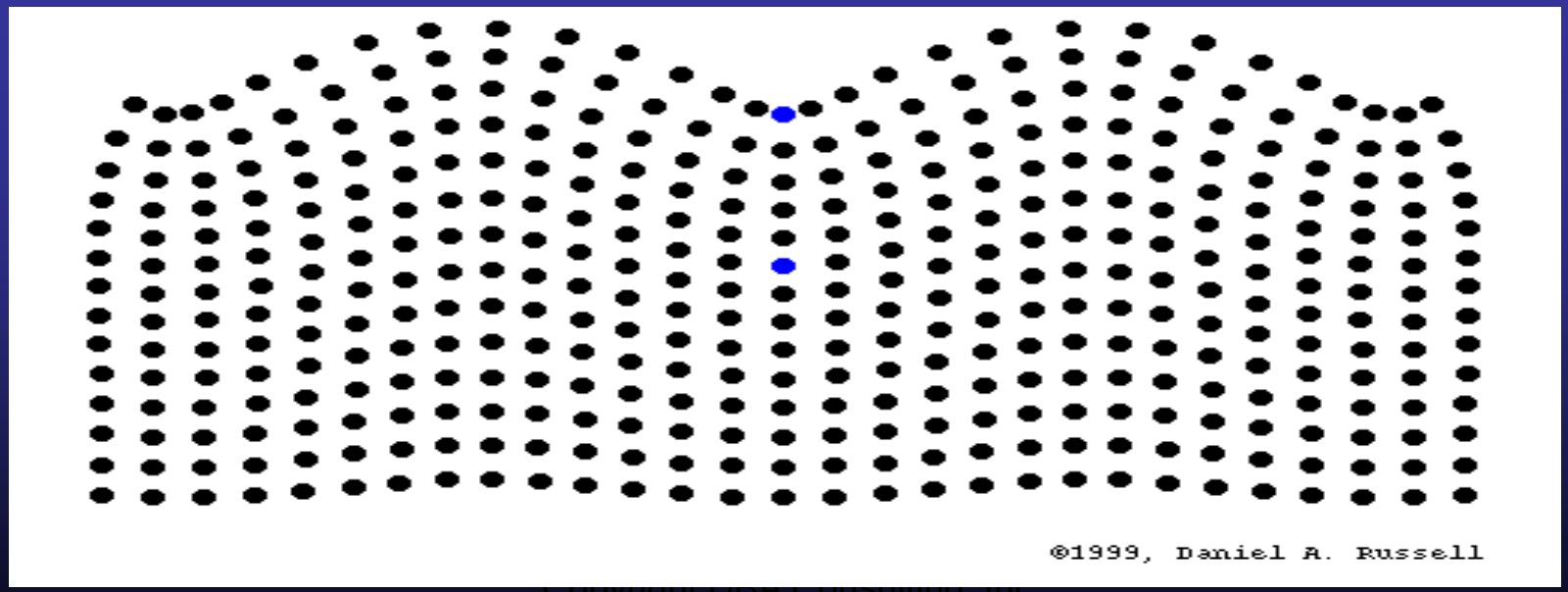
Surface Wave Types

- Rayliegh Waves – Rayliegh waves exist in the vertical and horizontal plane and have both longitudinal (movement parallel to the direction of travel, like sound waves) and transverse motion.



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Body Wave Types

- Primary Waves - Primary waves also called P waves, because they propagate through the medium faster than the other wave types. P waves are longitudinal waves that have vibrations along or parallel to their direction of travel. The wave medium is being extended and compressed as P waves propagate through the material. P waves are analogous to sound waves propagating through the air.

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Body Wave Types

- Secondary Waves - The S-wave or shear wave, sometimes called an elastic S-wave, are sometimes called secondary waves, because they propagate through the medium slower than P waves. In S waves, particles constituting the medium are displaced in a direction that is perpendicular to the direction that the wave is propagating.

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P and S Wave Velocities

Material	P Velocity (feet/sec)	S Velocity (feet/sec)	Density (gm/cc)
Granite	13 - 20 k	7 – 11 k	2.67
Limestone	10 – 20 k	9 – 11 k	2.65
Shale	6 – 13 k	3.5 – 7.5 k	2.35
Soil	0.5 – 2.5 k	0.3 – 1.8 k	1.1 - 2
Clay	3.7 – 8.2 k	1.9 k	1.4
Till	1.3 k	---	1.5 – 2.0
Schist	14.9 k	9.5 k	2.8

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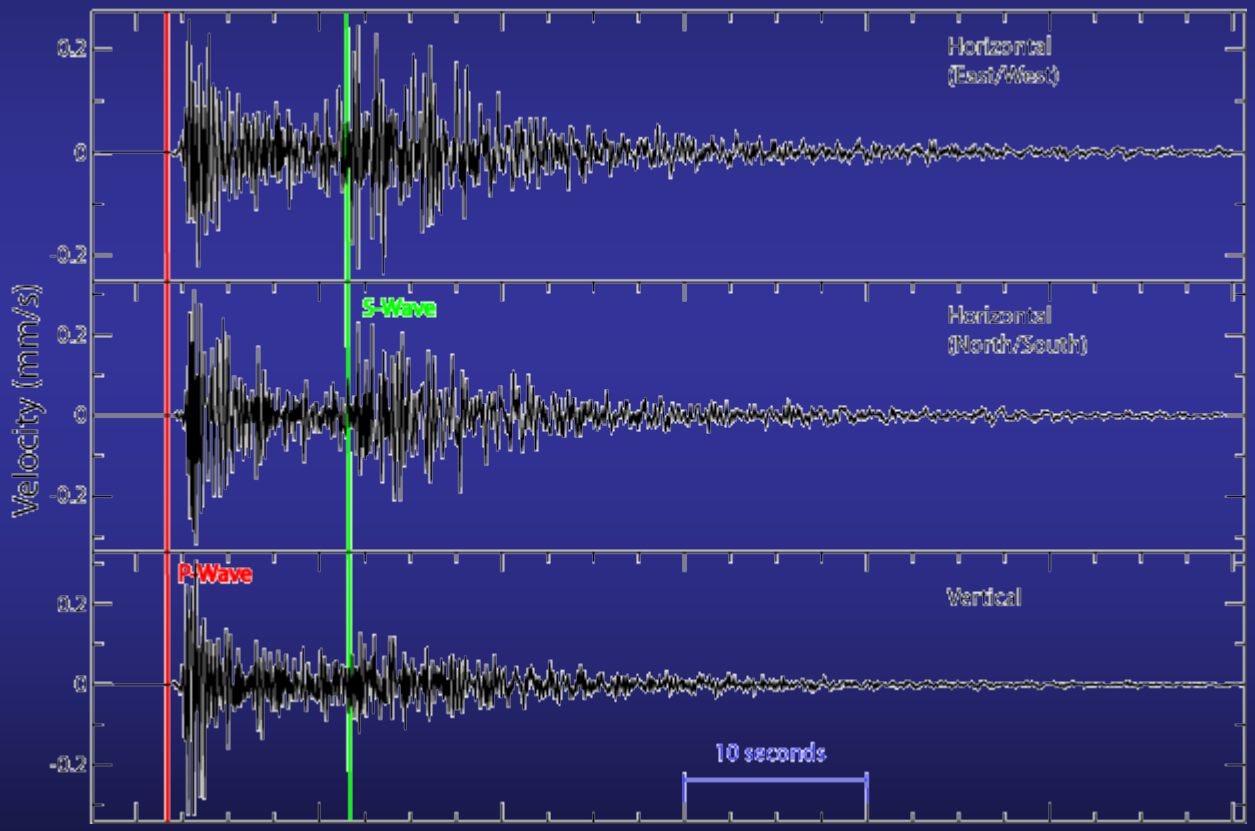
Body Waves



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Blast Induced Vibrations - Generation Zone

- Rapid release of chemical energy
- High pressure and temperature in a very short time duration
- High percentage of chemical energy consumed in non -elastic rock fragmentation and displacement
- Remainder of energy propagates from source in medium as elastic vibration

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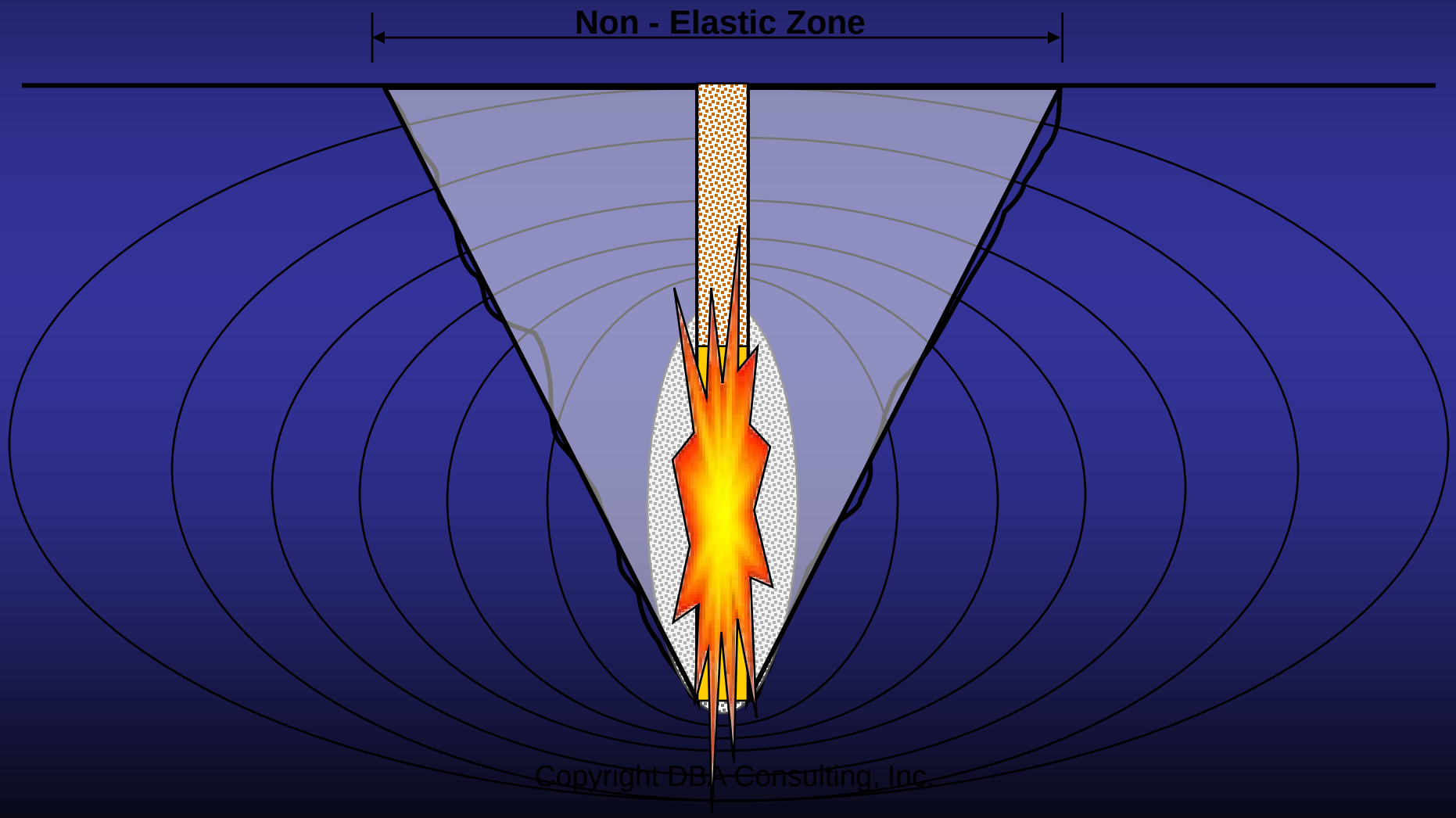
Crater Zone



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Seismic Transmission Zone

- This is the area around the blast that propagated ground vibrations can be perceived and measured.
- Near Field Vibrations – These vibrations are typically high frequency and amplitude vibrations within 300 feet of the blast.
- Far Field Vibrations – Far field vibrations are vibrations monitored outside of 300 feet of the blast. Far field vibrations are greatly influenced by the properties of the wave medium.

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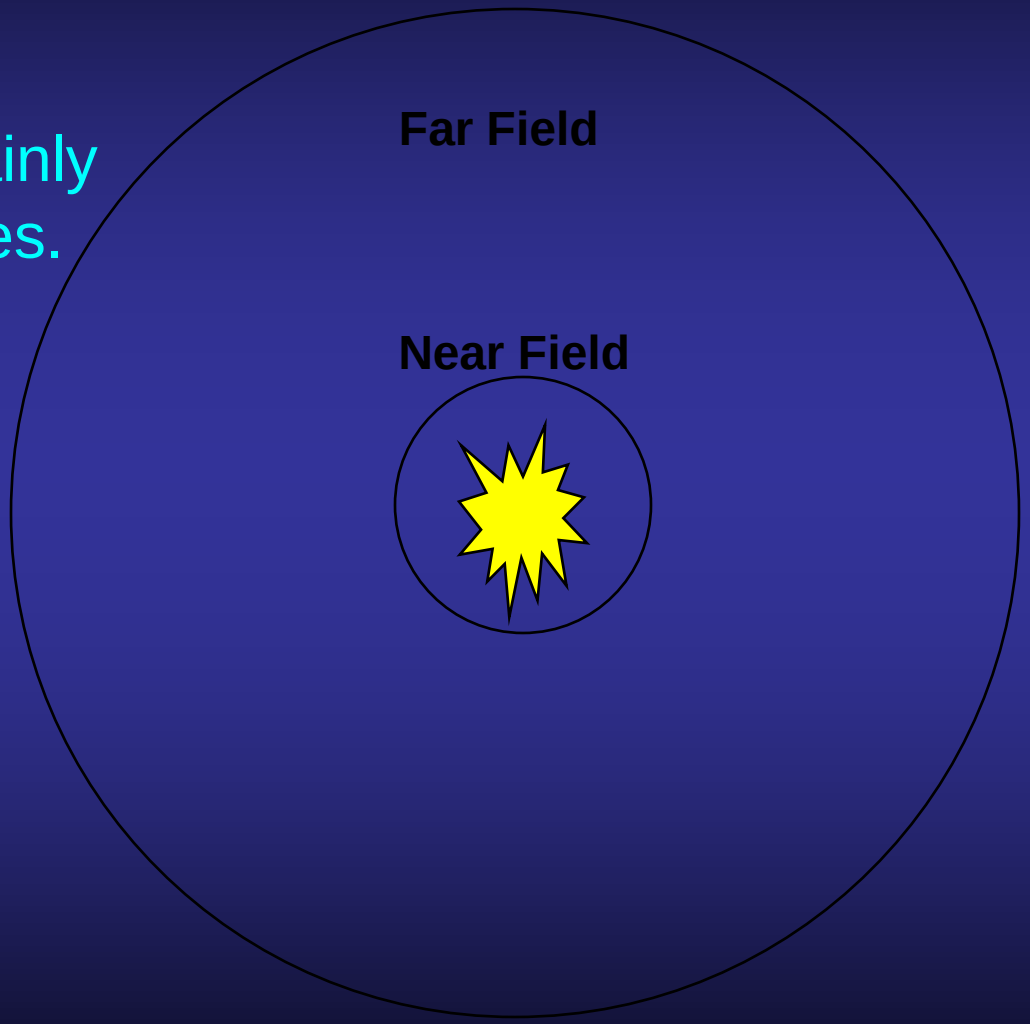
Seismic Transmission Zone

Near Field – Energy is mainly transported by Body Waves.

Far Field – Energy is transported by Surface Waves. (Boundary =1 λ)



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Factors Influencing Seismic Transmission

- Geology - The geology of the region has the most influence on the propagation and characteristics of the ground vibration.
- Topography - Rolling topography typically infers interruptions in geologic formations resulting in boundaries in the wave guide Horizontally bedded geologic formations in flat terrain will tend to more easily propagate ground vibration as the wave guide is more homogeneous.
- Water Saturation – Highly saturated soils will reduce the energy loss at waveguide boundaries yielding higher particle velocities.

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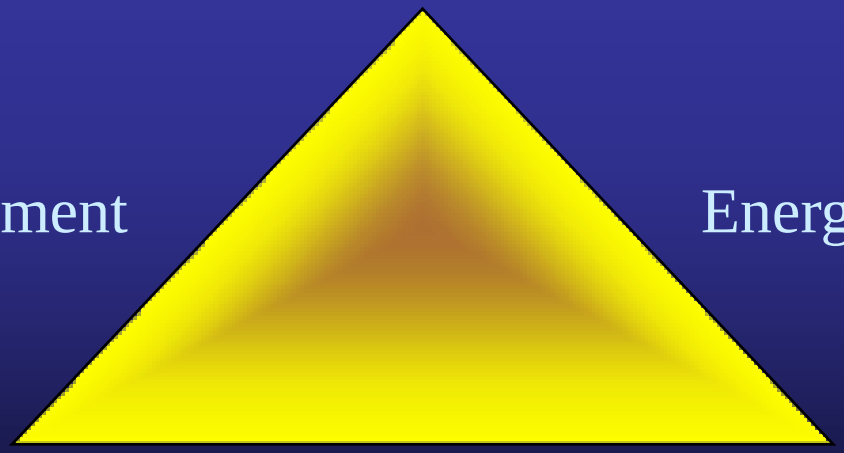
Factors Influencing Seismic Transmission

- Explosive Energy – The amount of potential energy is determined by the type and amount of explosives.



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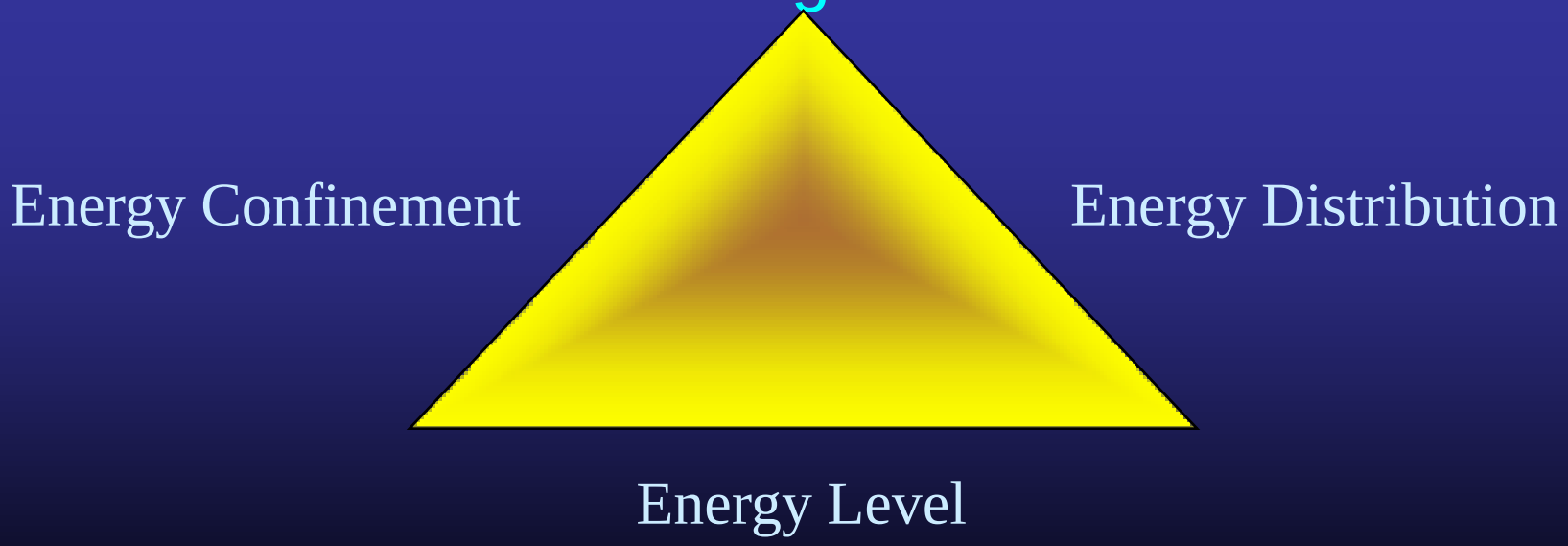
Factors Influencing Seismic Transmission

- Energy Confinement – The confinement level of explosive energy is determined by the geometry of the blast. If this energy can not be relieved in the process of breaking and moving rock the energy will be transferred into the ground as vibration.



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Acoustic Transmission Zone

- Transmission medium – The wave guide or propagation medium of air borne vibrations is the atmosphere.

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Acoustic Energy Transfer

Venting - Improper or insufficient stemming incapable of containing pressure.

Mud and Weak Seams – Mud seams and unconsolidated weak seams will not contain pressure and provide conduit for rapid escape of gas.

Light Face Burden – Light burden will provide for rapid release of gas pressure into atmosphere.

Burden Movement – Face displacement and overburden movement will displace air causing increased pressure.

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Factors Influencing Air Vibrations

Temperature – Air temperature will affect the propagation of air borne vibration. Warmer air will transmit vibration better than cold air. These effects are particularly important where sound is propagating over distances greater than a few hundred meters.

Isotherms – A layer of cool air above warm air will guide air vibration into the cooler air layer.

Inversions – A layer of warm air above cool air will reflect the air vibration back to the earth's surface.

Wind – Wind will bend the sound waves. Waves propagating upwind will be upwards and downwind propagating waves will be bend downward.

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Review of Key Points

- Particle motion is spherical. Tri -axial geophones measure the X, Y and Z vectors of spherical particle motion.
- Particle Velocity is the measure of the rate of change in the displacement of the ground particle $\Delta d / \Delta t$.
- The wave medium is the material in which the wave exists and propagates. A wave medium can be solid, liquid or a gas.

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Review of Key Points

- Elastic waves propagate through the medium without causing permanent deformation of any point in the medium.
- The geology of the region has the most influence on the propagation and characteristics of the ground vibration.
- Far field vibrations are vibrations monitored outside of 300 feet of the blast. Far field vibrations are greatly influenced by the properties of the wave medium.
- A large percentage of a blasts chemical energy is consumed in non - elastic rock fragmentation and displacement. The remainder of energy propagates from source in medium as elastic vibration.

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Review of Key Points

- The following are contributors to air borne blast vibrations:
  - Venting - Improper or insufficient stemming incapable of containing pressure.
  - Mud and Weak Seams – Mud seams and unconsolidated weak seams will not contain pressure and provide conduit for rapid escape of gas.
  - Light Face Burden – Light burden will provide for rapid release of gas pressure into atmosphere.
  - Burden Movement – Face displacement and overburden movement will displace air causing increased pressure.

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Blast Vibration Characteristics

- Thank You

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Modulus of Elasticity

Typical Values of the Elastic Moduli*

Material	Young's Modulus (E)	Bulk Modulus (K)	Shear Modulus (μ)	Lame's Constant (Λ)	Poisson's Ratio (σ)
	Dynes/cm^2 x10^{11} (except where noted)				
Steel	20	17	8	11	0.30
Aluminum	7	7½	2½	5½	0.35
Glass	7	5	3	3	0.25
Rubber	2x10^7	1x10^{10}	7x10^6	1x10^{10}	~0.50
Granite	7	3	2	2½	0.25
Limestone	5½	3½	2	3½	0.20-0.32
Sandstone	4½	3	1½	2½	0.23-0.28
Shale	3	2	1	1	0.22-0.40

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Wave Types

- Body and Surface
- Body Waves
  - Primary Waves (P Waves)
    - Compressional, Longitudinal, Fastest
  - Secondary Waves (S Waves)
    - Shear, Transverse, Rotational, Slower
- Waves are guided by a boundary.
  - Surface Waves
    - Exponential attenuation with increased distance

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Surface Waves

- Love Waves and Rayliegh Waves
  - Love Waves exist in the horizontal plane only in the transverse direction.
  - Rayliegh Waves exist in the vertical plane.
- Discontinuities and variations in the elastic medium alters the wave velocity.

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Shear Wave Motion

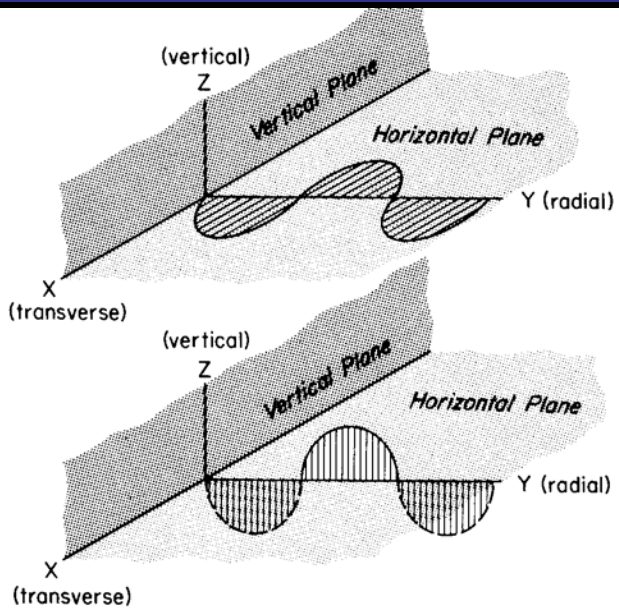

Figure I-4. Types of Shear Wave Motion

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P and S Wave Velocities

Material	P Velocity (feet/sec)	S Velocity (feet/sec)	Density (gm/cc)
Granite	13 - 20 k	7 – 11 k	2.67
Limestone	10 – 20 k	9 – 11 k	2.65
Shale	6 – 13 k	3.5 – 7.5 k	2.35
Soil	0.5 – 2.5 k	0.3 – 1.8 k	1.1 - 2
Clay	3.7 – 8.2 k	1.9 k	1.4
Till	1.3 k	---	1.5 – 2.0
Schist	14.9 k	9.5 k	2.8

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Wave Motion

- Harmonic Motion – $X = A \sin\omega t$
  - X = Displacement at time (t)
  - A = Maximum value of X (peak)
  - $\Omega = 2\pi f$ (f=frequency)

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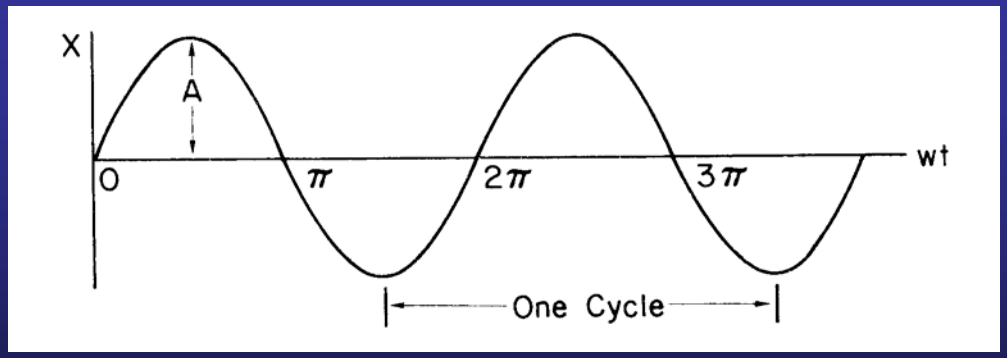
Harmonic Motion
Simple Sine Wave



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Blast Induced Vibration Waves

- The Generation Zone
- The Seismic Transmission Zone
- The Acoustic Transmission Zone
- The Recording Site

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The Generation Zone

- Rapid release of chemical energy
- High pressure and temperature in a very short time duration
- High percentage of chemical energy consumed in rock fragmentation and displacement (non-elastic)
- Remainder of energy propagates from source in medium as elastic vibration

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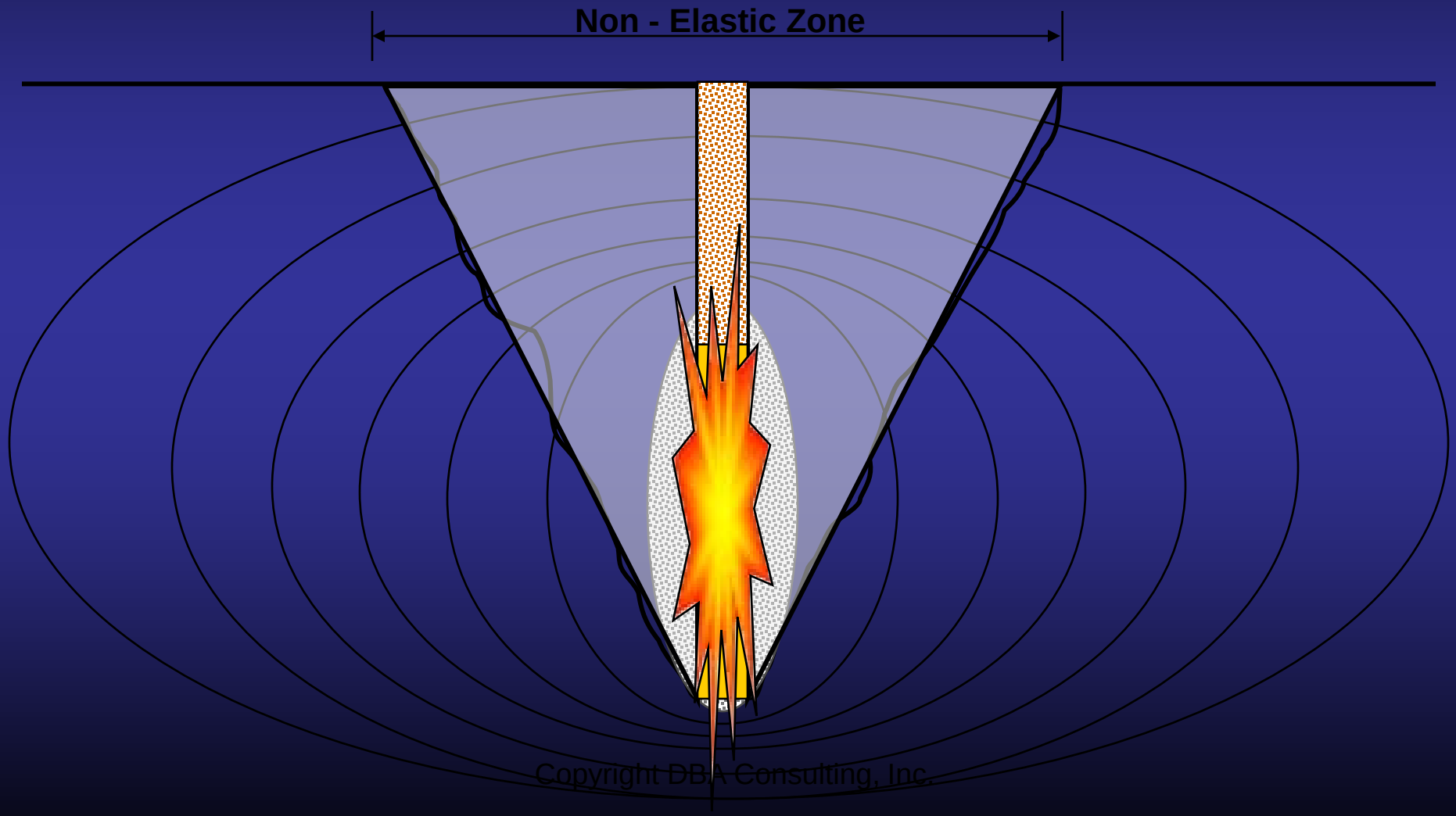
Crater Zone



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Seismic Transmission Zone

- Elastic zone of perceived seismic disturbance
- This is the zone of most interest
- Principal items of interest are the variations in amplitude and frequency of disturbance at varying distances from source

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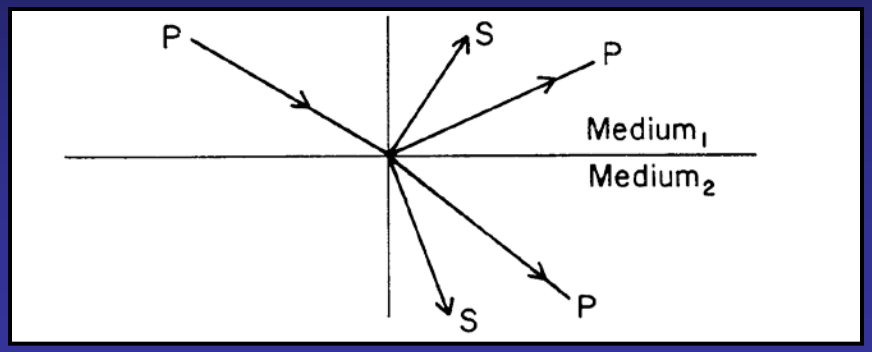
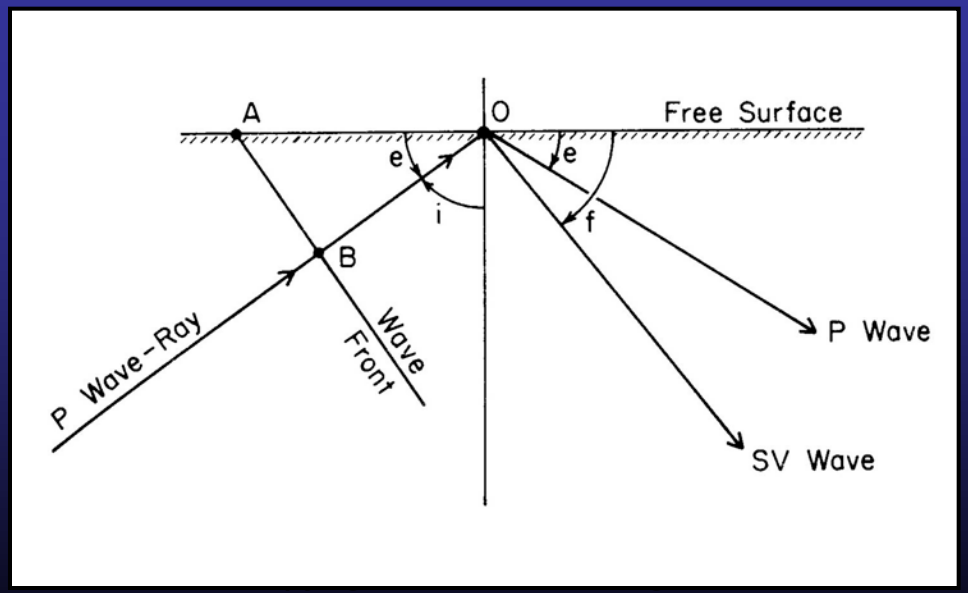
Wave Action at Boundary

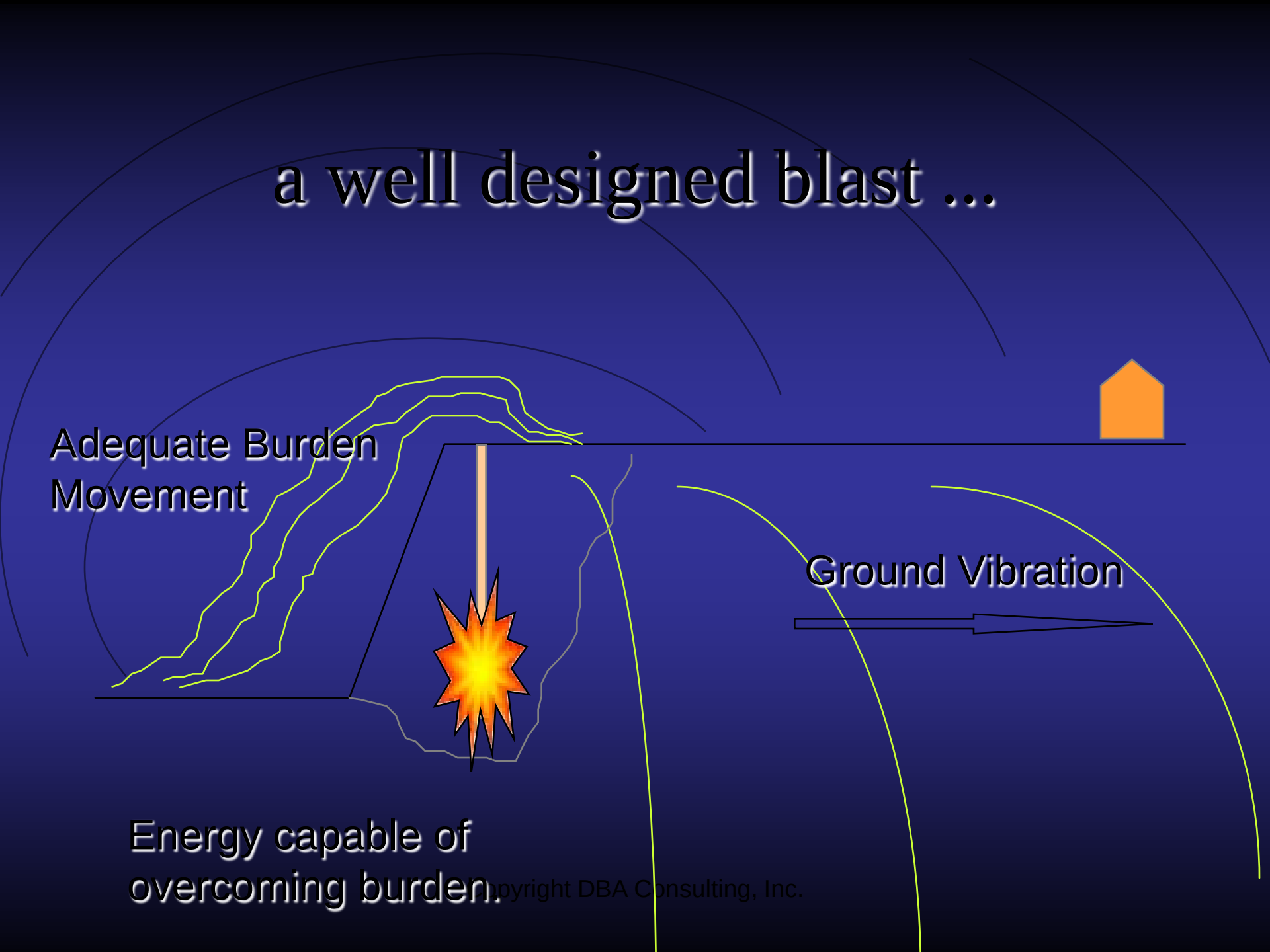




Typical Wave Velocities

SEISMIC EVENT	MEDIUM					
	CLAY		SANDSTONE		LIMESTONE	
	Velocity fps	Freq. Hz	Velocity fps	Freq. Hz	Velocity fps	Freq. Hz
Direct P	1000	25	3900	30	14,000	50
Refracted P	--	--	8200	40	--	--
Direct S	--	--	2600	40	7900	80-100
Refracted S	--	50	5600	--	--	--
Rayleigh	590-690	6-10	3000-4300	12-20	6900	25
Prograde Rayleigh	1150	10-12	4600	20	--	--
Love	670-850	5-10	3600-5300	15±	--	--

a well designed blast ...



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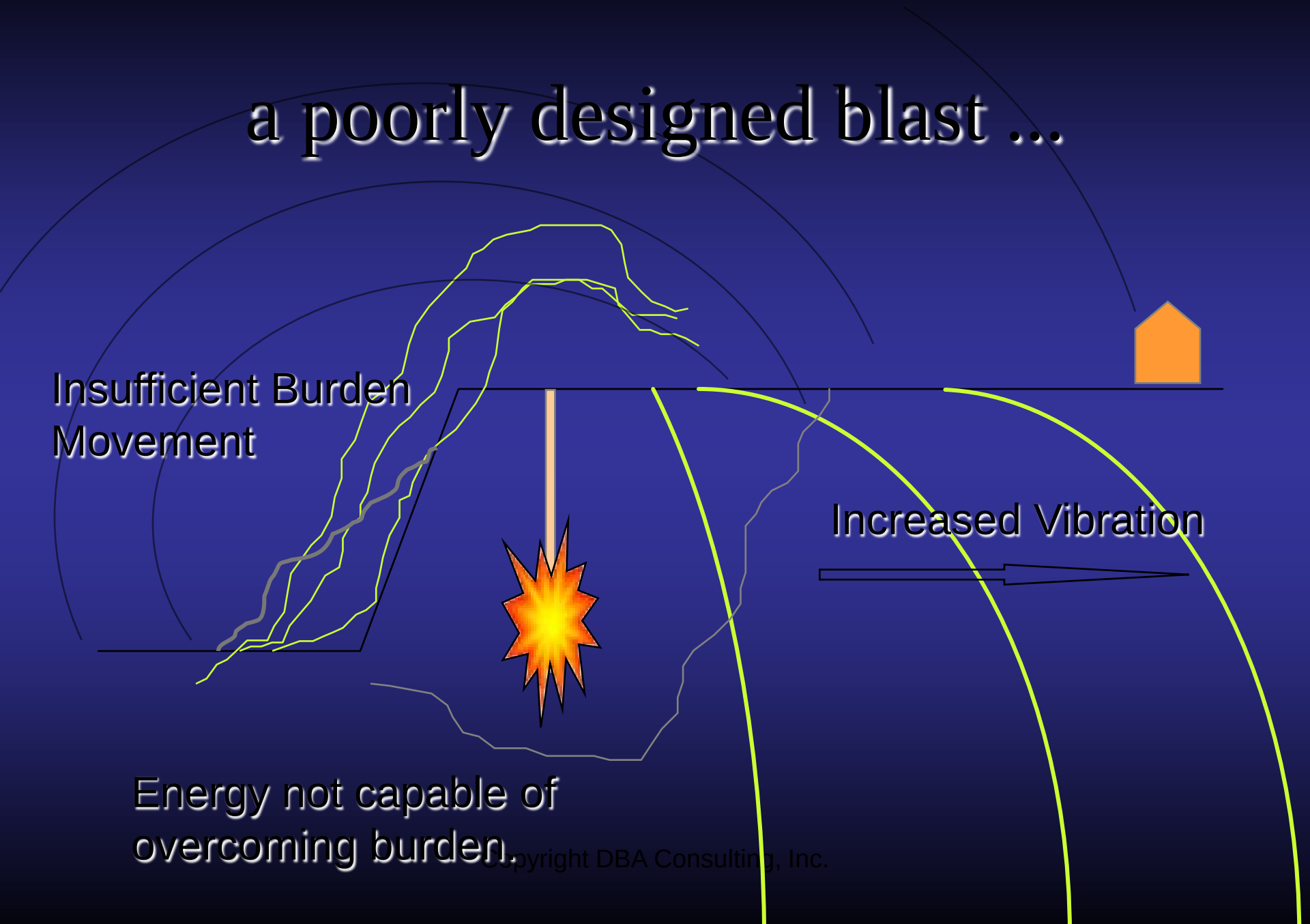
a poorly designed blast ...



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Acoustic Transmission Zone

- Explosion energy transferred into the atmosphere
- Vibration characteristics are similar to ground vibration - discontinuities
- Atmospheric Discontinuities - Focusing
  - Temperature and Pressure -3.5^{o}F per 1000 ft
    - Isotherm - Constant temperature with increased altitude
    - Inversion – Increasing temperature with altitude
- Wind and Wind Shear

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Recording Zone

- Subject of monitoring?
  - Above ground or below ground structure
- Above Ground – Will respond to vibration based on it’s Mass, Stiffness and Height
- SDF System

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Recording Method

- Magnitude Range of Measured Vibration
  - Frequency - 1 to 500 hz
  - Displacement - 0.001 to 0.5 inches
  - Velocity - 0.01 to 10 inches per second
  - Acceleration - 0.005 to 2 g.
- Displacement Seismographs (x)
- Velocity Seismographs ($\Delta x/\Delta t$)
- Acceleration Seismographs ($\Delta v/\Delta t$)

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Seismometers

- Displacement – Direct write
- Velocity – Electromagnetic
- Accelerometers - Pieziometric

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Velocity Geophones

- Frequency response
- Theory and Function
- Seismograph Fundamentals
  - Black Box
    - Signal In
    - Signal conditioning
    - Data storage

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Seismic Monitoring

- Field Use
  - Geophone location
    - Undisturbed soil
    - Adjacent to location of concern
    - Away from trees, underground objects, on soil (not concrete or gravel), properly coupled

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Seismic Monitoring

- Geophone placement
  - Poor coupling will always result in higher ground vibration readings.
  - Coupling
    - Spiked
    - Sand-bagged and spiked
    - Burial (spiked)
  - Proper orientation of geophone

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Seismic Monitoring

- Microphone Placement
  - Approximately 3 ft above ground
  - Mounted near geophone using wind screen
  - Away from barriers

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Wave Analysis
Initial Visual Review

- Simple or Complex?
- Interference Present?
- Frequency range
- De-Coupling?

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Wave Analysis Interpretation

- Peak Analysis
  - Half Wave
  - Peak to Peak
- Vector Sum Analysis
  - Pseudo Vector Sum Analysis
- FFT
- Integration and/or differentiation
- Response Spectra Analysis

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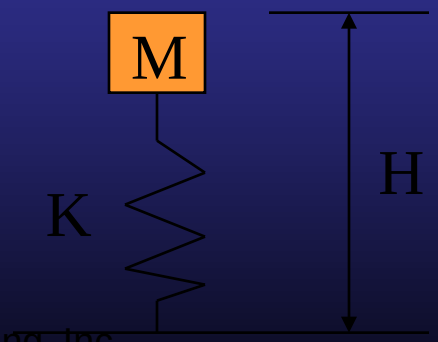
Frequency and Duration

- S.D.O.F. - Single Degree of Freedom
- Mass (M), Height (H) and Stiffness (K)



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Structural Response

- Resonance
  - Increased amplification
- Wave Duration
  - Reinforced amplification
- Axial Orientation of Structure
  - Mid-wall response
  - Areas of increased tensile failure
  - Damping

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Damage Classification

Tensile failure of a material when subjected to a stress or strain.

- Threshold - Loosening of paint: small plaster cracks at joints between construction elements ; lengthening of old cracks.
- Minor - Loosening and falling of plaster ; cracks in masonry and around openings near particians ; hairline to 3-mm (0- 1/8 in) cracks ; fall of loose mortar.
- Major - Cracks of several mm in walls ; rupture of opening vaults ; fall of masonry, e.g., chimneys; load support ability affected

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Comparison of Strain Levels Induced by Household activities, Environmental Changes and Blasting

Loading Phenomena	Strain Induced (µin./in.)	Corresponding Blast Level (ips)
Environmental Temperature, Humidity, Snow Loading, Soil Pressure	149 - 385	1.2 - 3.0
Walking	9.1	0.03
Heel Drops	16.0	0.03
Jumping	37.3	0.28
Door Slams	48.8	0.50
Nail Pounding	88.7	0.88

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Vibration Criteria

- Vibration Criteria
  - Damage Criteria - USBM RI8507
    - PPV most appropriate parameter
    - SD 70 – Conservative (0.08 – 0.15 ips)
    - Considered Frequency as Alternative Criteria
      - “Z Curve”
  - Perceptibility Studies
    - Human Response Criteria
      - Wiss and Parmelee
      - Reiher and Meister

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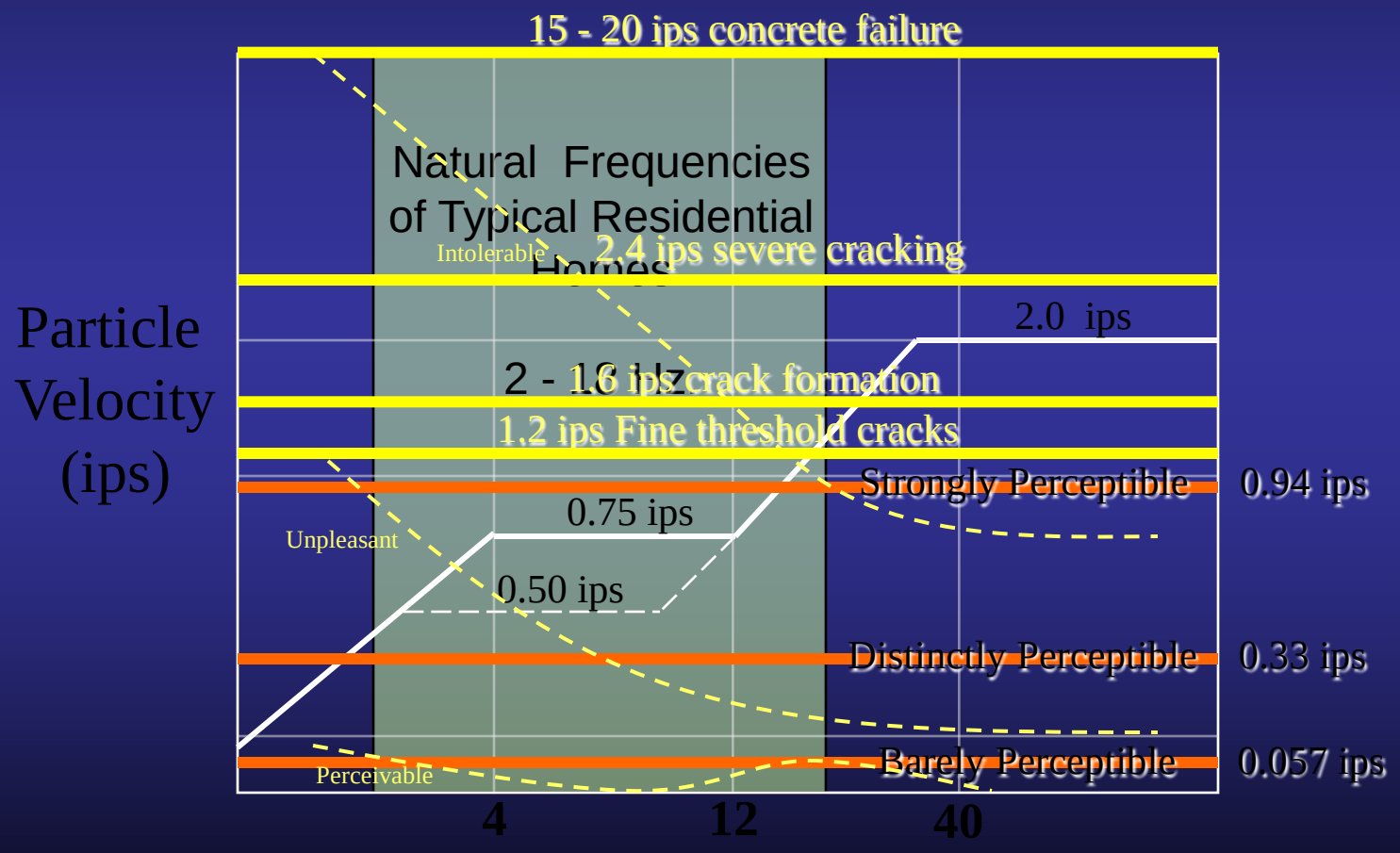
8507 vs. Human Response



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Vibration Prediction

- Scaled Distance
  - Square Root Scaled Distance $SD = D / W^{1/2}$
    - In a cylindrical charge (W) the blast hole diameter proportional to the square of charge weight ($W^{1/2}$).
    - SD is the ratio of the two distances
  - Cube Root Scaled Distance
- DuPont Prediction Equation
  - $PV = K * SD^{-1.6}$
- Regression Analysis

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Regression Analysis

- The geology is a vibration filter
- For best results:
  - At least 30 sets of data
  - Wide spectrum of recording distances (SD)
  - Narrow spectrum of blast designs
  - Multiple recording locations

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