Source Wave Design for Downhole Seismic Testing

Downhole seismic testing (DST) has become a very popular site characterizing tool among geotechnical engineers. DST methods, such as the Seismic Cone Penetration Test (SCPT), are utilized to determine low strain ($\varepsilon < 10^{-4}\%$) interval velocities and attenuation or absorption values from compression as well as horizontally and vertically polarized shear seismic waves (P, SH and SV respectively), which are generated near the surface and travel down to one or more seismic sensors installed downhole. An ASTM standard for DST has been published (ASTM D 7400–08), covering important DST issues, such as seismic sources, receivers, and recording systems.

Seismic sources for DST are often designed to generate either predominantly P and SV waves or predominantly SH waves due to the fundamentally different behavior of these wave types at a boundary. When a P or SV wave strikes a boundary, four outgoing waves are generated (reflected P and SV waves as well as transmitted P and SV waves), while an SH wave will only generate reflected and transmitted SH waves, thus simplifying the interpretation of the recorded seismic time series. Irrespective of the source type, it is very important that the source-sensor geometry is configured optimally and designed such that “point source” events are created and that the energy generated by the source is maximized to allow for investigations to a greater depth.

SH Wave Sources

Figure 1 outlines the particle motions of an S-wave propagating along the x axis. As is shown, an S-wave has two degrees of freedom:

1) particle motions perpendicular to the ray path and those in the horizontal plane (θ_Z)
2) particle motions perpendicular to the ray path and those in the vertical plane (θ_Y).

By convention, the first type of S-wave is referred to as an SH-wave (horizontally polarized) and the second type of S-wave is referred to as an SV-wave (vertically polarized). As is shown in Figure 2, the SV-wave is a shear, transverse, or rotational wave where the particle motions are perpendicular to the ray path.

A shear wave type source requires an asymmetric ground displacement. A popular DST SH source is the hammer beam, where a hammer blow is applied laterally to the sides of specially designed plates fixed at the surface. The hammer beam generates excellent polarized SH waves and is typically used when reverse polarity analysis is applied (since this analysis method requires a reversible source). The SH wave particle motions are orthogonal to the raypath and restricted to the horizontal plane; therefore, the optimal SH wave source is one where the ground surface is sheared orthogonally to the borehole or the seismic cone extension rods as illustrated in Figure 3. Figure 4 is an illustration of the source body waves impacting upon a triaxial seismic sensor package.

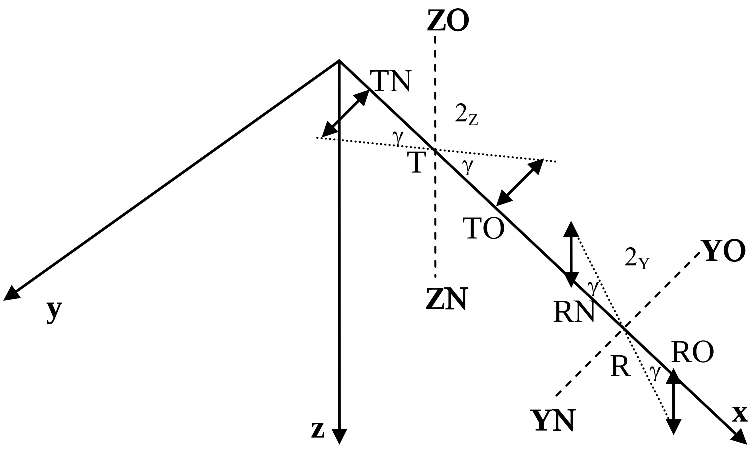

Figure 1. Particle motions (θ_Z and θ_Y) associated with an S-wave propagating along the *x* axis.

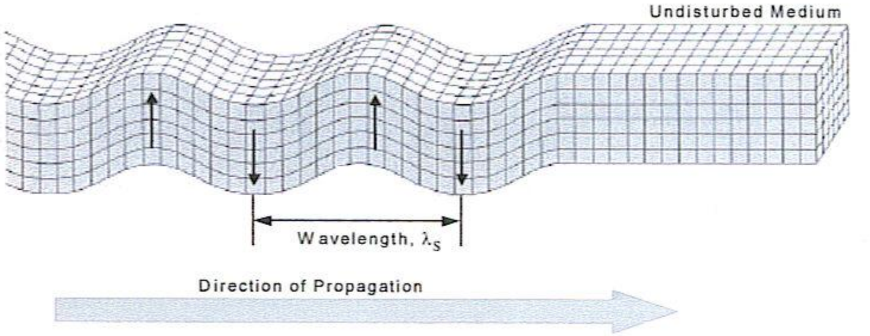

Figure 2. Shear wave particle motion and ray path (after Bolt (1976)).

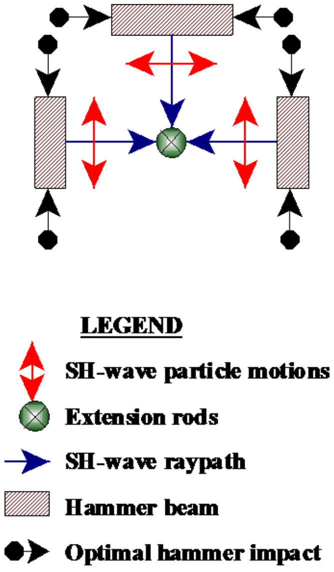

Figure 3. Plan view of optimal SH source wave generation utilizing a hammer beam configuration

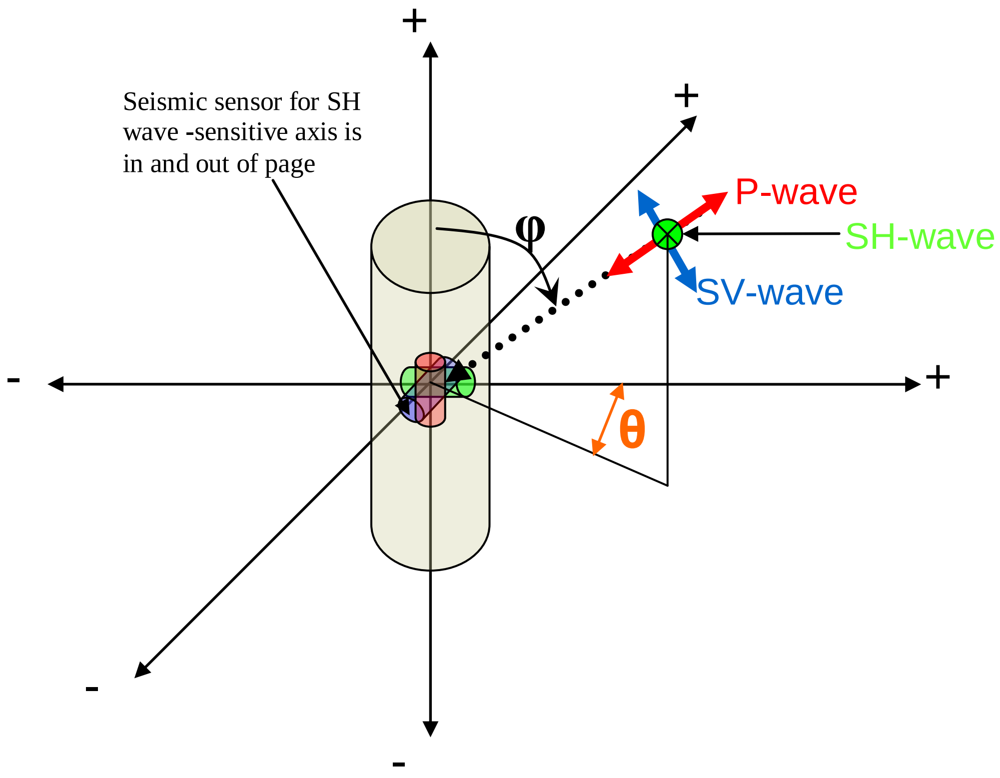

Figure 4. Source P, SV, and SH body waves impacting upon a triaxial sensor package.

ASTM D 7400-08 states that the center of the shear beam is placed on the ground between 1 and 3 m from the receiver borehole (or cone insertion point). This horizontal offset should be selected carefully since borehole disturbance, rod noise, and refraction through layers with significantly different properties may impact the test results. Larger horizontal offsets of 4 to 6 m may be necessary to avoid response effects due to surface or near-surface features and for normal move out (NMO) imaging. It should be noted that in case of a larger offset the possibility of raypath refraction must be taken into account.

SH-wave "point sources" should be utilized so that the source location can be quantified for subsequent interval velocity calculations. For example, if a large SH-hammer beam is utilized, it becomes difficult to specify the exact location of the seismic source. In addition, in case of complex stratigraphy it is preferable to excite a small area so that irregular and complex source waves are not generated.

Due to the "point source" concern, BCE has been specifying and manufacturing SH sources with limited dimensions (24" x 14") with traction ribs fixed to the underside (providing greater SH plate-ground coupling) for over 15 years. These dimensions were decided upon after detailed analysis of numerous DST seismic data sets obtained from variable SH plate dimensions. A fundamental concern in making the SH plates too small is that the plate may not sit flat upon the ground surface when loaded by the mast of drill rig or in-situ testing vehicle. While it is important to apply a significant vertical load onto the SH plates so that sufficient coupling between the SH plate and ground surface is generated upon impact (i.e., the plates do not "slip" upon impact), this load should not cause the plate to be unlevel. Non-level SH plates will not only result in the generation of "non-clean" SH source waves upon hammer impact, the embedded edges of the plate will also generate unwanted compression and Rayleigh waves. Consequently it is important to have SH plates of limited dimensions that sit flat on the ground surface.

Another intuitive and fundamental SH source design requirement is to isolate the mast from the SH source plate. There are two reasons for this:

1) to reduce high bandwidth impact energy traveling through the drill rig and/or in-situ testing vehicle and down the SCPT rods.
   This high bandwidth measurement noise results in a low-signal-to-noise ratio recorded seismic trace due to the "ringing" effect.
2) to de-couple the mast from the plate in order to minimize the lateral resistance of the SH plate upon hammer impact.
   The objective is to maximize the shearing or particle velocity of the ground surface. BCE has been incorporating 2.5" to 3" thick rubber membranes between the mast and the SH source plate for over 15 years in order to address these two requirements.

Maximizing the shearing and/or peak particle velocity can be quantified by the Theorem of Maximum Shearing Traction for SH Source Design, which is introduced in this note.

Theorem of Maximum Traction for SH Source Design

The theorem is based on the following concepts:

<u>a. Momentum</u>

The momentum[1] *P* of a mass *m* travelling with velocity *V* is

$$P = m \bullet V \tag{1}$$

The change in momentum (the Impulse I of the Force) that a body undergoes is equal to the collision force F(t) times the duration of the collision (Impulse *I* of the force) or more accurately

$$I = \Delta\,(m \bullet V) = \int F(t)\,dt \tag{2}$$

If there are no external forces on the interacting masses then the sum of the momentums of the masses is constant.

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[1] Momentum is a vector unlike energy

b. Coefficient of Restitution

The coefficient of restitution for colliding objects[2] is defined as

$$C_R = \frac{relative\,speed\,of\;\;moving\,apart}{relative\,speed\,of\;\;moving\,together} \text{ where } 0 < C_R < 1 \qquad (3)$$

The modeling of the hammer impact on a stationary plate can then be described as follows:

$$V_{hammer} \bullet m_{hammer} = V_{hammer}^{/} \bullet m_{hammer} + V_{plate} \bullet m_{plate} \qquad (4)$$

where V_{hammer} is the hammer velocity prior to impact, V'_{hammer} the hammer velocity after impact, V_{plate} the SH plate velocity after impact, m_{hammer} the hammer mass and m_{plate} the effective SH plate mass (which accounts for the resistance against horizontal plate movement generated by the vertical mast load onto the plate).

Assuming that there is a perfectly elastic collision (i.e., $C_R = 1$) and that the plate is at rest prior to impact, (3) becomes

$$C_R = \frac{V_{plate} - V_{hammer}^{/}}{V_{hammer}} = 1 \qquad (5)$$

therefore

$$V_{hammer}^{/} = V_{plate} - V_{hammer} \qquad (6)$$

Substituting (6) into (4) gives the velocity of a suspended plate as a result of a hammer impact and a perfectly elastic collision:

$$V_{plate} = \left(\frac{2 \bullet m_{hammer}}{m_{hammer} + m_{plate}} \right) V_{hammer} \qquad (7)$$

The traction force ($F_{traction}$) applied by the SH plate to the ground surface is directly related to the impedance ($Z_{impedance}$) or interaction of the SH plate and ground surface, since the impedance that a given medium presents to a given motion is a measure of the amount of resistance to that particle motion. Specifically, impedance in elasticity is a ratio of stress to particle velocity, so that for a given applied stress the particle velocity ($V_{particle}$) is inversely proportional to impedance[3]. This relationship is mathematically expressed as:

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[2] In general energy is lost on an impact so that colliding particles move apart with a smaller relative speed than the speed in coming together.

[3] In seismology, the impedance encountered by a seismic wave traveling through a medium is defined as $Z_{impedance} = \rho \bullet V_{medium}$. The amplitude of the seismic wave varies inversely with the square root of the impedance (i.e., $Amplitude = \sqrt{1/(\rho \bullet V_{medium})}$). This implies that seismic amplitudes will increase as waves move into slower, less dense solids. This is an important factor in strong motion seismology where it is commonly observed that shaking from large earthquakes is more intense at sites on top of sediment compared with nearby sites on bedrock.

$$Z_{impedance} = \frac{Stress}{V_{particle}} \tag{8}$$

which implies[4]

$$V_{particle} = \frac{Stress}{Z_{impedance}} = \frac{F_{traction}}{A_{plate} \bullet Z_{impedance}} \tag{9}$$

where A_{plate} is the area of the plate.

Assuming that $m_{plate} >> m_{hammer}$ and $V_{plate} = V_{particle}$, (7) can then be revised to:

$$V_{particle} = \left(\frac{2 \bullet m_{hammer}}{m_{plate}} \right) V_{hammer} \tag{10}$$

Substituting (10) into (9) gives

$$F_{traction} = \left(\frac{2 \bullet m_{hammer}}{m_{plate}} \right) V_{hammer} \bullet A_{plate} \bullet Z_{impedance} \tag{11}$$

Alternatively, the stress imposed upon the ground surface due to an impact on the plate is given as

$$S_{traction} = \frac{F_{traction}}{A_{plate}} = \left(\frac{2 \bullet m_{hammer}}{m_{plate}} \right) V_{hammer} \bullet Z_{impedance} \tag{12}$$

where $S_{traction}$ is the traction stress.

From (12) it is evident that for a given hammer mass, hammer velocity and plate-ground surface interaction impedance the surface traction stress can be increased by decreasing m_{plate} (the effective SH plate mass, which accounts for the resistance against horizontal plate movement generated by the vertical mast load onto the plate). The most effective way to achieve this is de-coupling the plate from mast to allow increased movement in the horizontal direction, e.g. by inserting the 2.5” to 3” thick rubber membrane between the mast and SH source plate. BCE has been implementing this design for over 15 years, although more recently we have been advocating to place the plates underneath the tires of a vehicle, whereby the air filled rubber tires allow lateral displacement of the steel plates upon impact, while still maintaining a large vertical force to stop steel plate/ground slip. This approach also provides a larger radial offset, which further enhances the near-surface characterization of the soil (see http://www.bcengineers.com/images/BCE_Technical_Note_12.pdf).

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[4] $Stress \propto V_{particle}$

P- Wave Sources

In general terms, a P-wave source requires symmetric (with respect to volume change) displacement, such as an explosive source detonated within the medium near the surface. Some very good P-wave sources are an electrical sparker system (see Figure 5), buffalo guns (i.e., 12 gauge shot gun shell fired in the ground), air guns and vertical hammer impacts causing a symmetric displacement of a membrane placed within the medium near surface. As is evident from the data set shown in Figure 5, P-wave recordings can be obtained at significant depths (with high SNRs and repeatability) if a proper source is used, and at greater depths the P-wave source resides predominantly on the Z axis (as is expected for nearly vertical incidence).

It should be noted that the P-wave sources mentioned above may also generate SV waves, which are subsequently recorded by the downhole seismic sensors. Finally, some investigators apply simply a vertical impact on the ground surface to generate P-waves. The major disadvantages of this approach are three-fold:

1. Only one-third of the energy generated by a vertical source on a uniform half-space is transformed into body waves (compression and shear), while the other two-thirds of the energy generated is transformed into surface waves.
2. Source body waves generated at the surface have lower amplitudes than body waves generated in the half-space.
3. P-waves with low Signal to Noise Ratios (SNRs) and low repeatability are generated.

SV-Wave Sources

A typical SV wave source configuration consists of lowering a shear type source within a borehole and then clamping the SV wave source against the side of the borehole (using a pneumatic or mechanical clamp). This set-up allows for a vertical shearing impact to be applied to the side of the borehole so that a predominantly SV source wave is generated.

Erick Baziw
Gerald Verbeek

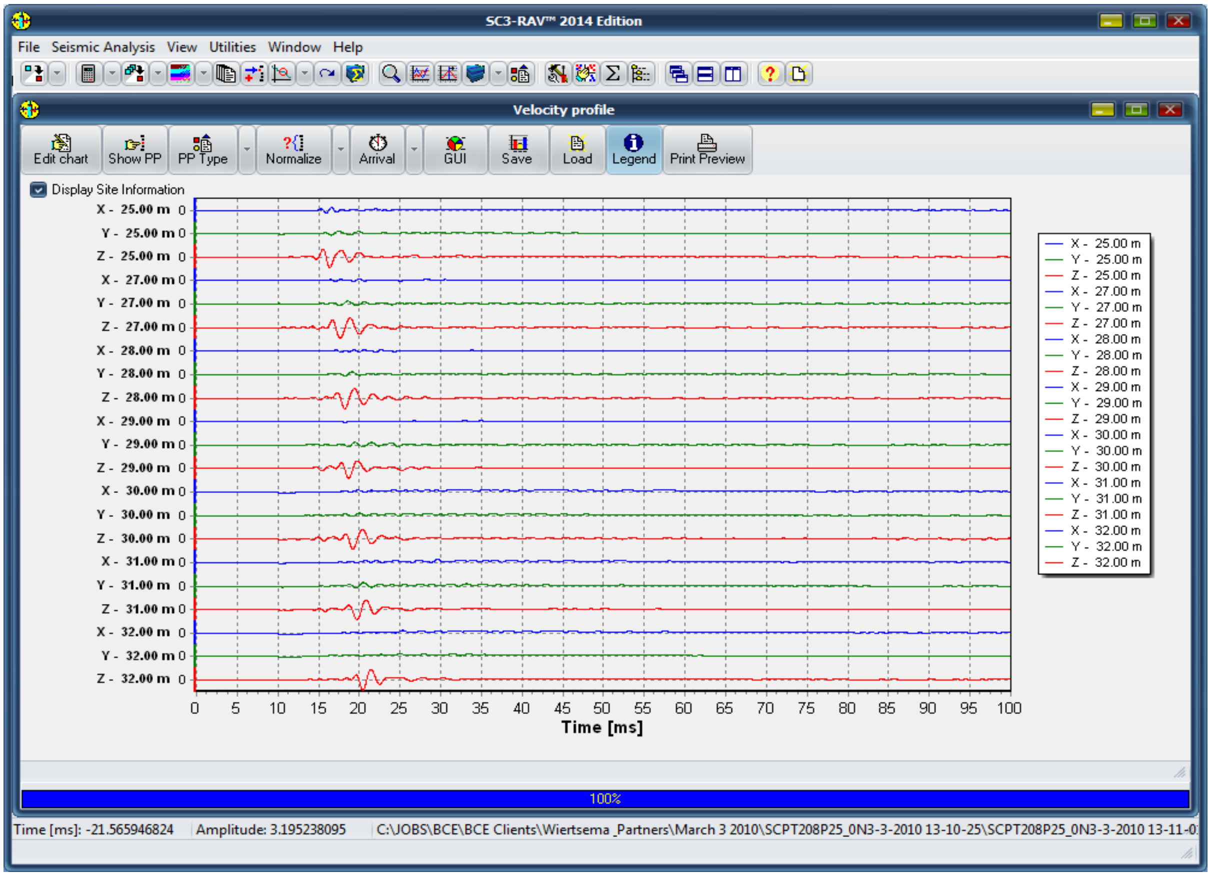

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Figure 5. P-wave data acquired with a BCE triaxial system and utilizing an electrical sparker system. The data is unfiltered and SC3-RAV option *Localize Normally* is enabled.

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e-mail: info@bcengineers.com

phone: Canada: (604) 733 4995 – USA: (903) 216 5372