Active Source Surface Wave
Field Testing Guidelines

QuakeCoRE Technology Platform 2

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Sensor installation and data acquisition

List of required items

- 4.5Hz Geophones (typically, 24 to 48)
  - Vertical geophones for Rayleigh waves (typical)
  - Horizontal geophones for Love waves (optional)
- Geophone spread (refraction) cables (one per 24 geophones, typically 2m spacing)
- Geode data logger (one per 24 geophones)
- 12v battery for Geode (one per Geode)
- Laptop with the Geometrics Seismodule Controller software
- Sledgehammer, hammer trigger, and trigger extension cable
  - Strike plate (steel and rubber)for Rayleigh waves
  - Steel-end-capped plank (with additional rubber mat) for Love waves
  - Alternatively, a dropweight system or a shaker can be used as a source of seismic energy
- Tape measures
- Personal protective equipment (steel-capped boots, gloves, hearing protection, etc.)

Active source surface wave testing considerations

The active surface wave testing method described herein is the multi-channel analysis of surface waves (MASW).

Rayleigh and Love Waves

Two types of surface waves are of interest for near-surface geotechnical and/or geophysical purposes: (1) Raleigh waves and (2) Love waves.

(1) Raleigh waves are generated by a vertical excitation at the ground surface (e.g., a downward sledgehammer strike, dropweight release, or a vertical shaker), exhibiting an elliptical particle motion in the vertical and in-line horizontal plane. Thus, Rayleigh waves are best observed using an array of vertical geophones and may be combined with P-wave refraction testing.

(2) Love waves are generated by a crossline horizontal excitation at the ground surface and exhibit a cross-line horizontal particle motion. A steel-capped shear/traction plank and an array of horizontal geophones oriented in the crossline direction are used for Love wave testing. This setup is also suited to S-wave refraction.

In order to develop/propagate Love waves, a strong impedance contrast is needed, such as a soft near-surface layer overlying a stiff layer, including shallow rock sites. Sites with a stiff surface (e.g., asphalt, concrete, compacted soil) are not suited to Love wave testing.

Most (if not all) active source surface wave testing includes the acquisition of Rayleigh wave data. When possible, the collection of Love wave data is encouraged to help provide an additional constraint during the inversion analysis.

Array design and geometry considerations

A rule of thumb for the active source surface wave testing is that the length of the array needs to be more than twice the depth of interest. The length of the array is constrained by (1) the number of geophones and (2) the spacing between the geophones.

Each Geode is a 24-channel digitiser, allowing the use of up to 24 geophones connected via a geophone spread (refraction) cable. Multiple geodes can be networked to extend the array. Typical active source surface wave testing (MASW) testing arrays use 24 or 48 geophones, requiring one or two geodes respectively.

The maximum spacing between the geophones is limited by the distance between geophone takeouts/connection points on the geophone spread (refraction) cable. Typically, cables with two-metre takeout spacing are used for sledgehammer and drop-weight MASW testing. If needed, the spacing can be decreased by bunching up the cable. Larger geophone spacings (5 to 10 metres) are suitable for testing with larger, low-frequency-rich active sources.

Also, the minimum spacing between the geophones limits the minimum resolvable thickness of the uppermost (i.e., near-surface) layer. Based on sampling theory in space (rather than time), the shortest wavelength (λ_{min}) resolvable by a pair geophones is two times the distance (spacing) between the geophones. This λ_{min} constrains the minimum resolved thickness of uppermost layer, typically 1/3 to 1/2 λ_{min} (Garofalo et al. 2016a, Cox and Teague 2016). Thus, the minimum resolvable thickness of the upper most layer is two-thirds to one times the minimum spacing of the geophones.

Based on the above, consider three example active source arrays:

(1) 24 geophones spaced 2 metres apart:
- (24 geophones – 1) * 2 metres/geophone = 46 metres
- 46 metres / 2 → The depth of interest must be 23 metres or less.
- 2 metre spacing → The minimum resolvable thickness of uppermost layer is 1.33 to 2.00 metres

(2) 48 geophones spaced 2 metres apart:
- (48 geophones – 1) * 2 metres/geophone = 94 metres
- 94 metres / 2 → The depth of interest must be 47 metres or less.
- 2 metre spacing → The minimum resolvable thickness of uppermost layer is 1.33 to 2.00 metres

(3) 48 geophones spaced 1 metre apart:
- (48 geophones – 1) * 2 metres/geophone = 47 metres
- 47 metres / 2 → The depth of interest must be 23.5 metres or less.
- 1 metre spacing → The minimum resolvable thickness of uppermost layer is 0.66 to 1.00 metres

Note that the above rule of thumb provides an estimation of the maximum depth of interest, which maybe further limited by the frequency content of the surface waves and the stiffness of the sub-surface.

Another important consideration is the shot location (e.g., source offset) of the source from the end(s) of the geophone array. Cox and Wood (2011) encourage the use of multiple shot locations to (1) identify potential near field effects (especially at short source offsets), (2) assist in the identification of the various modes of surface wave propagation (e.g. fundamental, first higher, etc.) and (3) provide a means to estimate uncertainty in the dispersion curves. The minimum source offset is constrained by near field effects (refer to Yoon and Rix 2009) and dependent of the wavelength of the surfaces waves. The maximum offset is limited by geometric spreading and anelastic damping of the surface waves traveling away the source, across the array. Thus, more energetic sources (e.g., drop weight releases or vibroseises) may be used at larger source offsets. Also, testing should include shot locations on both ends of the geophone array to aid in the assessment of lateral variability at the site (e.g., dipping layers).

Shot locations at 1 or 2 metres off the ends of the array are recommended for P-wave refraction testing. Shot locations at 5, 10, and 20 metres off the ends of the array are recommend when using a sledgehammer for surface wave testing. Again, the shot locations should be changed based on site conditions and discussed with colleagues.

An example 24 geophone MASW array is shown schematically below to visualise geophone placement, shot locations, and the recommend coordinate system. For this array, the geophones (red triangles) are spaced 2 metres apart and the shot (e.g., hammer strike locations) locations are indicated by yellow stars at ±1, ±5, ±10, ±20 metres off the ends of the array. Note that the first geophone is placed at the origin of the coordinate system, where tape measures.

Geophone (#)						1 2 3 4 ...		13...		24				
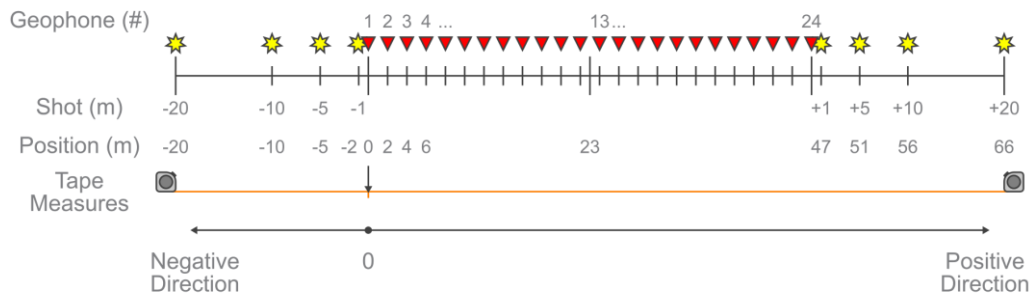
The MASW testing geometry (e.g., length of the array, spacing of geophones, shot locations) should be adapted to site conditions and discussed with research collaborators.

Equipment and Data Acquisition Setup

Setting up the geophone receiver array

1) Lay out the tape measures and geophone spread cable(s). Avoid power poles or trees nearby as they can create unwanted ground vibration (i.e. noise) under windy weather conditions.

2) Set out 4.5 Hz geophones at the designed spacing. For surveys on sealed/paved surfaces, geophone spikes can be removed and replaced with base plates.

   - Vertical geophones are used to measure Rayleigh waves.
   - Horizontal geophones are used to measure Love waves. The axis of the geophone needs to be perpendicular to the array and should be level as indicated by the bubble. Also, ensure the horizontal geophones are face the same direction (e.g., orient the top of the geophones along the tape measure/geophone spread cable).
   - If both vertical and horizontal geophone are being used, they may be placed together at each takeout; all vertical geophones on one side of the tape measure and all horizontal geophones on the other.

   A typical vertical geophone array is shown in the photograph below. In this case, a 1 metre geophone spacing used with geophone spread cable that has a 2 metre spacing between geophone takeouts.

3) Mark the planned shot locations at each end of the array. If space is limited, place the linear geophone array such that (1) most (if not all) shot locations may be used off at least one side of the array and (2) at least the one shot location off the other side of the array (typically, at 5 m) to assess the potential lateral variability at the site.

4) Ensure the trigger switch is securely fastened (e.g., taped) to the sledgehammer. Also, the trigger cable should taped along the length of the sledgehammer to limit the possibility that the cable pinched during testing.

Setting up the data-logging system

1) **Connect the 12v power** to the connector with the battery symbol (⊟).

2) **Connect the Geophone Spread Cables** to the connector with the geophone symbol (▽), and **the trigger cable** to the connector with the hammer symbol (⌐).
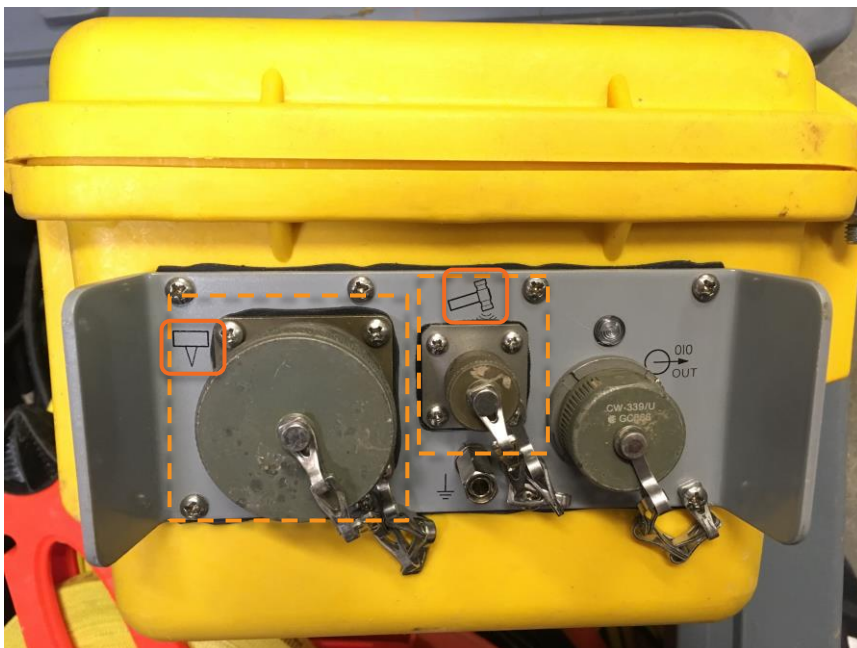
3) **Connect the Digital Interface Cable** to the Geode. The Digital Interface Cable has identical pinless connectors on either end. Geodes typically have two Digital Interface Cable connections. In this case, be sure to connect to the one labelled with the OUT symbol (⊖►), which indicates data is transmitted OUT of the Geode back towards laptop (storage and control device).

4) Connect the other end of the Digital Interface Cable to the connector on the small **Network Interface Box (NIB).** It is a small box, 5 cm square with a pinless connector on one side for the Geode interface cable and an RJ45 connector on the other. Connect the RJ45 connector to the network port or card of the computer.

5) **If you have other Geodes, connect them at this time as well**, with the OUT connector (⊖►) closest to the controller. Multiple Geodes are connected as shown below using additional Digital Interface cables.
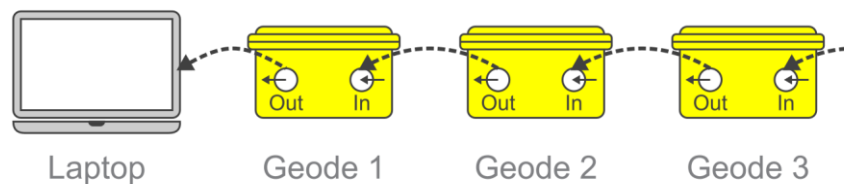
6) **Power on the Geodes**:
   - If the Geode NIB has a toggle switch, put the toggle switch in the **Enable Power Up** position.
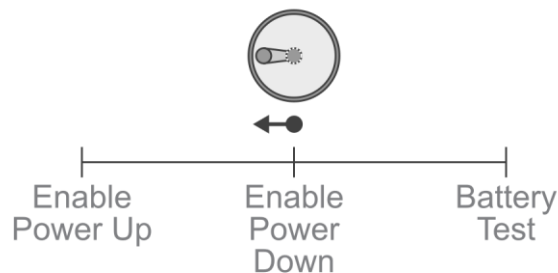

## Setting up the data acquisition software

After powering the Geode, start the Seismodule Controller software on the laptop. Prior to testing, several software settings should be verified or changed to reflect testing geometry, timing/trigger requirements, and file output.

1) Geometry and Channel Mapping Settings

    a) **Use the Noise Monitor Window to verify that all of the geophones are properly connected and appear in the proper order.** Walk/run along the geophone array and observe changes in the noise traces.
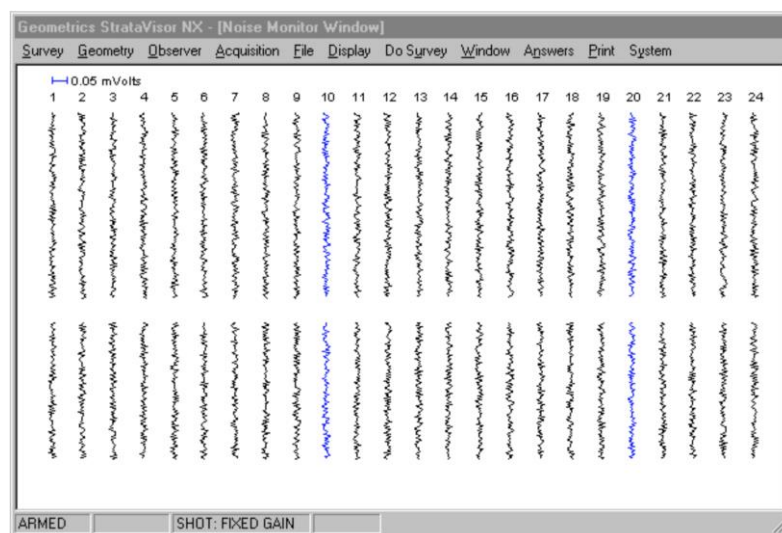
- Verify that all of the geophones are connected to the spread cable by observing the individual noise traces. If a geophone is not connected, the associated noise trace will not respond to vibrations, or will look different to other traces.

- Verify that waves generated the ends of the array, correctly appear to travel down array in the software. If not, the order of the geophones may be corrected in the Channel Remapping Setup Window, which is accessed through the "*. System"* menu → *Channel Remapping* option. Check (or un-check) the box to the left of "REVERSE CHANNEL ORDER OF EACH GEOPHONE IN LINE X" to reverse the geophones. Then, re-verify the wave propagation direction in the Noise Monitor Window.
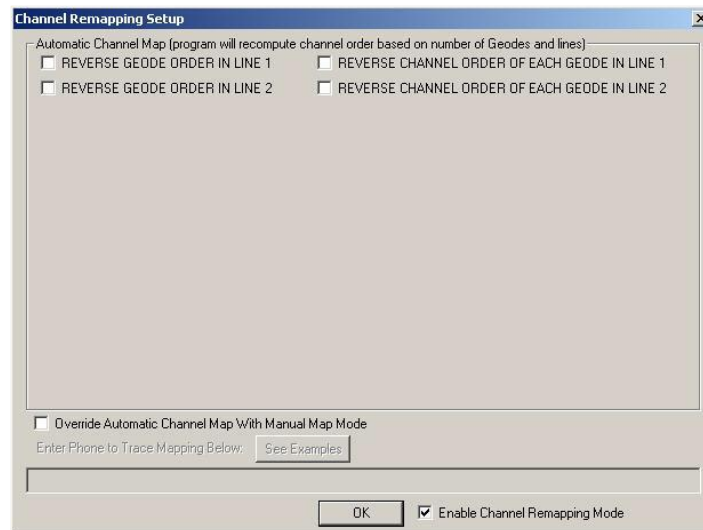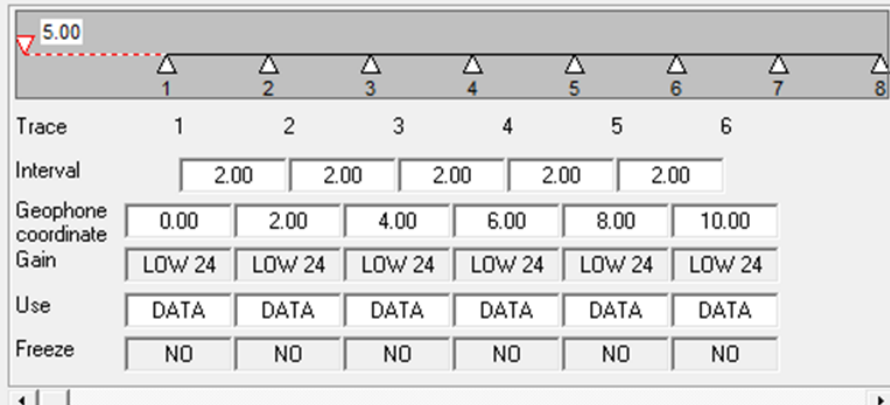
b) **Specify the geophone array setup within the software.** If the geophone spacing is uniform, it can be set using the Geophone Interval window, which is accessed through the *2 Geom* menu → *2 Geophone Interval* option.
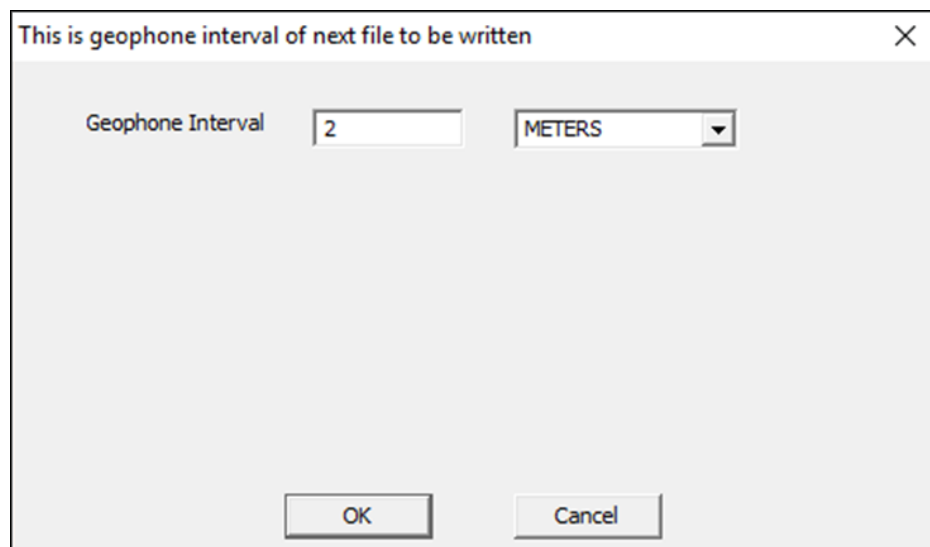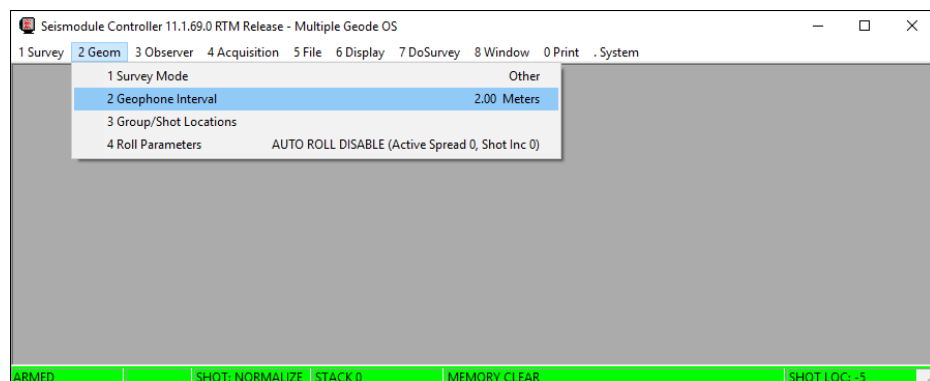
c) **Specify the shot coordinate and any irrgular geophone spacing** in the Group/Shot Locations window (*2 Geometry* Menu → *3 Group/Shot Locations* option).
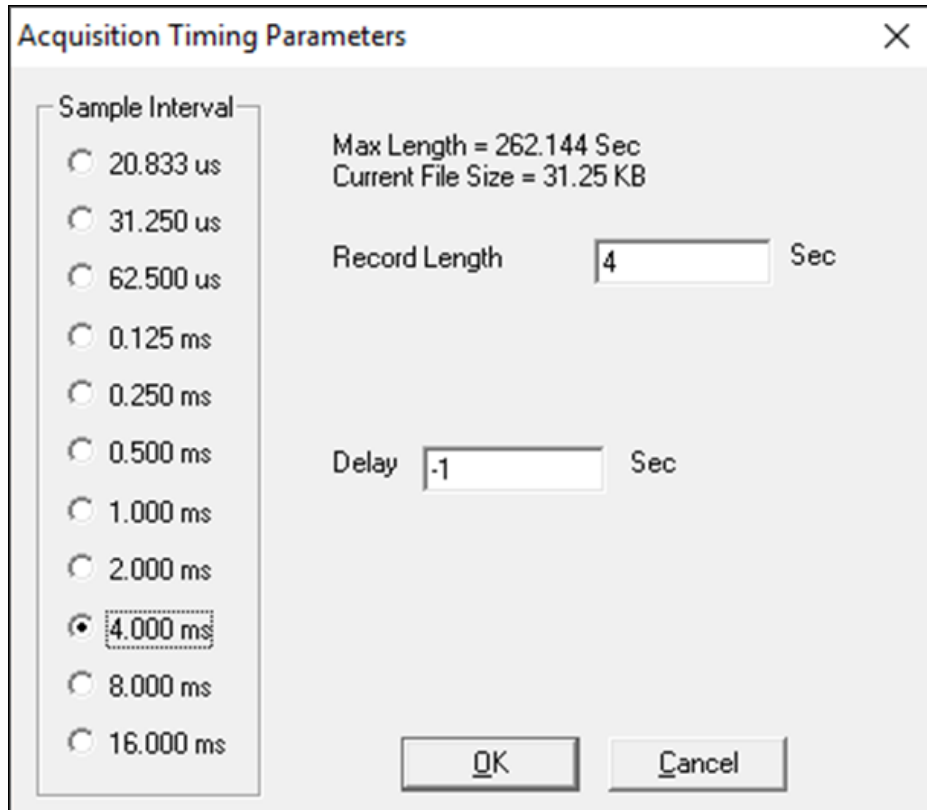
2) Acquisition Timing and Triggering Settings

a) **Set the sample interval, record length, pre-trigger delay** in the Acquisition Timing Parameters window (*4 Acquisition* menu → *1 Sample Interval/Record Length* option).

Please note that each of these parameter values should be carefully considered and discussed with your research colleagues. However, the following are reasonable starting values for surface wave testing with a typical 2 m geophone spacing:

- Sample Interval: 4.000 ms (a sampling frequency of 250 Hz)
- Record Length: 4 Sec (a long time record to capture the full surface wave train at the furthest receiver
- Delay: -1 Sec (a negative pre-trigger delay "captures" the ambient noise before the source excitation and can be used for a signal-to-noise ratio calculation)

If additional shots/data will be collected for P-wave refraction analysis, the sample interval should be decreased to 0.125 ms or less (i.e., a higher sampling frequency) to better capture the high frequency P-wave arrivals and the record length should be decreased to 1 or 2 seconds to reduce the output file size.

b) **Ensure automatic stacking is disabled.** This is verified/set in the Acquisition Stack Parameters window (*4 Acquisition* menu → *4 Stack Options*), by selecting the "Replace" radio button. Instead of stacking automatically in the Seismodule Controller software, the
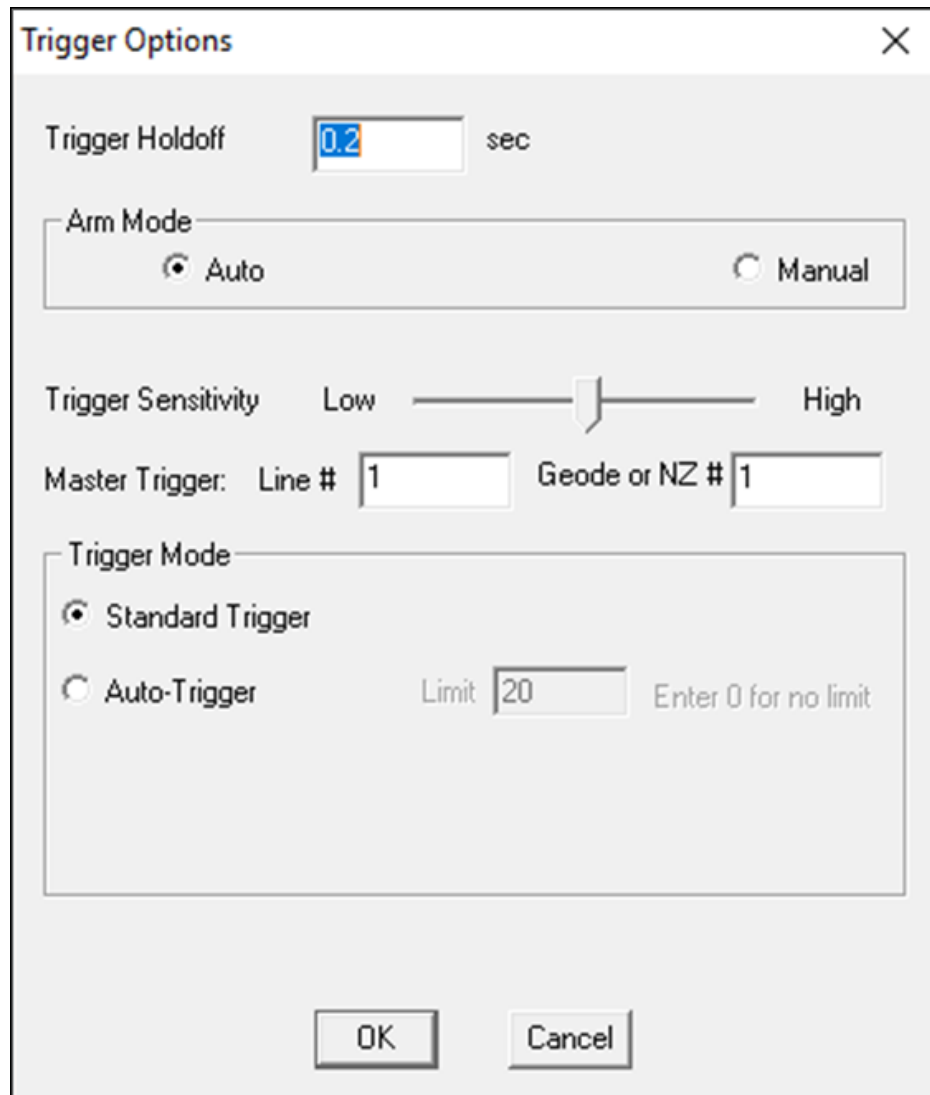
individual waveform recordings are stacked during post-processing.
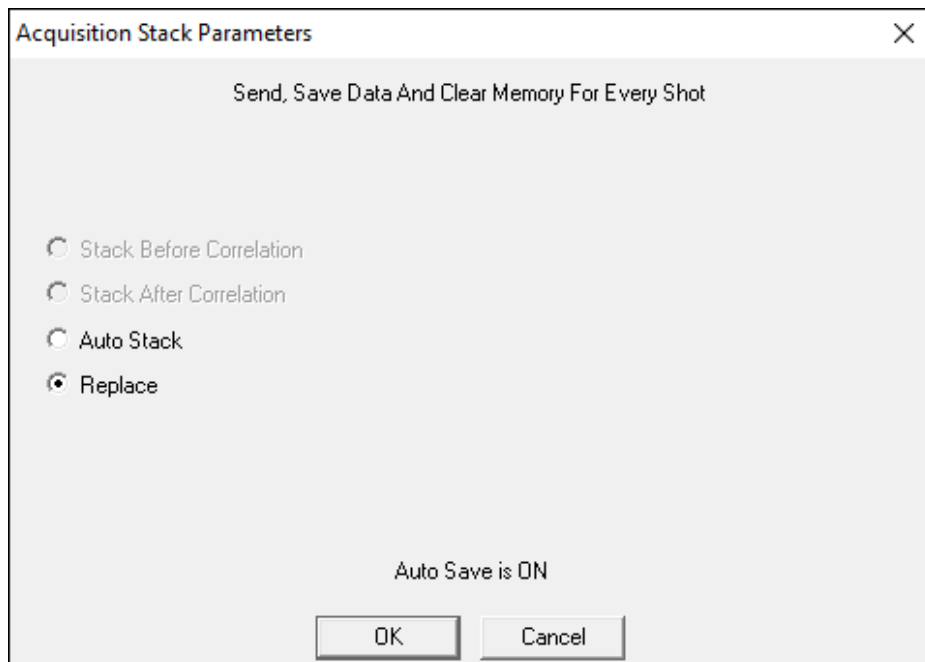
c) **Triggering settings may be verified/changed in the Trigger Options window** (*4 Acquisition* menu → *8 Trigger* Options).

The Trigger Holdoff time is used to guard against false triggers by specifying the minimum time between recognised trigger signals. The system will ignore any trigger signals arriving within the trigger holdoff time of the last trigger signal.

If the trigger, is not connected to the primary Geode (i.e., the Geode directly connected to the computer via the NIB), another Geode may be specified.
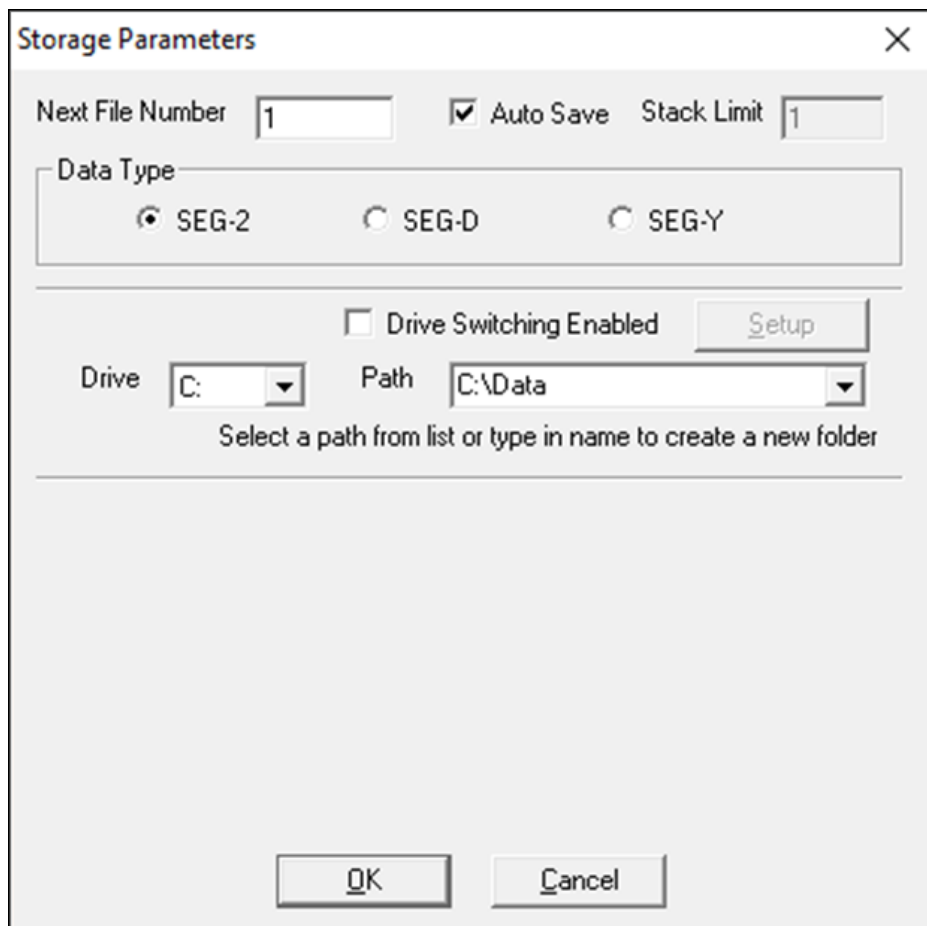
3) File Storage Settings

The file storage settings are specified in the Storage Parameters window (*5 File* menu → *1 Storage Parameters* option).

a) The output files are automatically, incrementally increased. The Next File Number should be set to 1 for the first data file. In cases where an output file is bad (e.g., a false trigger), the data file may be deleted and the "Next File Number" can be decreased to replace the file and ensure numbering continuity.

b) The box next to Auto Save should be checked (i.e., turned on), such that after each shot (trigger, hammer strike) a file is saved.

c) The Stack Limit should be greyed out. If not, change the triggering settings as described above.

d) The data type should be the SEG-2 file type.

e) The Drive (typically, C: for the main hard drive) and the Path are specified here. Note that the Seismodule Controller requires a folder in the root directory of the drive. It is a good idea to move and separately store the data files for an individual MASW array for subsequent analysis and data archival.

Testing and Data Acquisition Procedure

Once the geophone array is placed, the geode(s) connected, and software settings specified, the MASW test may be performed as follows:

1) **Begin filling out the Field Data Sheet (and notes) for the site/array**, noting details such as the project name, site/array name, date and time; personnel, source/geophone/digitizer information (e.g., physical descriptions, serial numbers), and array geometry information. A simple sketch of the site (e.g., the array and any distinct site features) should also be included.

Additional testing information (e.g., test type, source location, sample rate, record length, trigger delay, and raw file names) should be added as the shot (source) location is moved and the testing progresses.

2) Disarm the system (e.g., geode and laptop) to prevent false triggers while moving source equipment to a shot location.

As needed, the system can be armed (indicated by a green status bar) or disarmed (indicated by a red status bar) by pressing the "1" key on the laptop keyboard or using the *7 DoSurvey menu → 1 Arm/Disarm* option.

| ARMED | | SHOT: NORMALIZE | STACK 0 | | MEMORY CLEAR | | | SHOT LOC: -5 | |

| DISARMED | | SHOT: NORMALIZE | STACK 0 | | MEMORY CLEAR | | | SHOT LOC: -5 | |
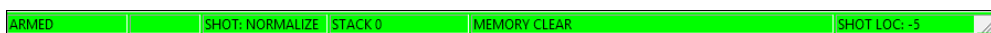
3) **Place the strike plate (or shear plank) at the first shot location.**

Ensure that the shot location is logged correctly in the software (*2 Geometry* Menu → *3 Group/Shot Locations* option). In cases, where MASW and refraction testing are conducted together using the same array, ensure the timing parameters (*4 Acquisition* menu → *1 Sample Interval/Record Length* option) are correctly set for each test type, as described above.

Record the shot location, timing parameters, and test type (e.g., Rayleigh wave MASW, Love wave, MASW, P-wave refraction, or S-wave refraction) on the field data sheet. Also, note the file numbers associated with the first and last shot at each shot location.

The most recent file stored may be checked on the status bar (or directly in the file directory) and the next file is always indicated (and may be changed) in the Storage Parameters window (*5 File* menu → *1 Storage Parameters* option).

4) **Hit the strike plate (or shear plank) to excite the surface wave (Be sure the system is armed).** The hammer strike should be "clean" and not bounce on the strike plate. It is recommended that the sledgehammer user wear gloves allow better motion of the sledgehammer and protect hand from abrasions.

Upon hammer strike, the data acquisition system should be triggered and temporarily disarmed, as indicated by the yellow status bar at the bottom of the screen. Once the data has been acquired the geode,

transferred to the laptop, and stored in a file, the system should automatically "armed" ready for another shot, as indicated by the green status bar.

If the laptop audio is turned on, the software will play series of sounds ending with a sharp "Beep", indicating the data has been stored and system is armed and ready for another shot.

The status bar will also indicate the current shot location and the most recent file number stored after trigger.

5) **Examine the recorded times series displayed after each shot.** Ensure that the recorded signals are clear (Note: the signals furthest away from the source will be smaller in amplitude and longer in duration as the P, S, and surface waves separate).

If the signals are inadequate, look bad, or system is false triggered, the "bad" data file may be deleted in the directory (e.g., Windows Explorer). In this case, change the "Next File Number" in the Storage Parameters window (*5 File* menu → *1 Storage Parameters* option).

6) **At each shot location, typically 10 shots (i.e., hammer strikes or source excitations) should be generated, acquired, and stored.** The number of shots at each location may be varied depending on nearby noise sources and other conditions. Again, consult with your research colleagues. When collecting Love wave data, 10 shots should be generated and collected for each polarity (i.e., striking on both ends shear plank), resulting in a total of 20 shots.

Extra shots maybe needed in cases where data acquisition is falsely triggered or the shot is too early (i.e., the system is not armed or "busy").

7) **After collecting the appropriate number of shots at the shot location, disarm the system (press the "1" key), move the strike plate (or shear plank) and the sledgehammer/source to the next shot location.** Ensure the shot location field datasheet entry is complete and correct, including the file number associated with the first and last shot (e.g., hammer strike) at the shot location. Also, note any issues with the testing and potential sources of noise. Change and ensure the shot location (and timing parameters) are correct in Seismodule Controller software, as described above. Repeat steps 4 – 6 for each shot location.

End of Testing/Equipment Clean-up

1) **Before disassembling the array and equipment, properly shut down the Geode system.** Move the toggle switch on the NIB to the Enable Power Down position. Close the Seismodule controller software to terminate the survey and fully shut down the array. Wait until all communication windows have closed before disconnecting the geodes.
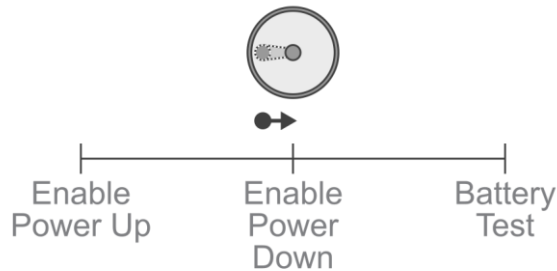
2) Disconnect the various cables and disassemble the geode network system.

3) **Pull the geophones out of the ground.** *Pull out the geophones themselves, and do not pull out using the cables.* Remove any soil, vegetation, debris, and moisture from the geophone spikes to prevent corrosion of the metal.

   If further testing is planned and the geophones do not need to be swapped, it is often helpful to temporarily leave the geophones connected to the geophone spread cable. This facilitates faster equipment setup. For long term storage, it is recommended that the geophones disconnected from the geophone spread cable and stored in bundles of 24 geophones.

4) **Carefully wrap/coil the geophone spread cable (with or without the geophone attached)!** These cables are easy to tangle. It may be helpful slowly place and coil the cable directly into the appropriate storage box.

5) **Ensure the field datasheet is complete**. Make appropriate notes such as the weather/surface/soil conditions, potential sources of noise, and issues with the equipment.

6) Move the raw data SEG-2 (.data) files to another folder for processing and back up as needed.

References

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