

FREEDOM DATA PC PLATFORM

Spectral Analysis of Surface Waves (SASW)

System Reference Manual





Olson Instruments, Inc.

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1.0 INTRODUCTION

The structural version of the **Spectral Analysis of Surface Waves (SASW-S)** method is applied to structural elements to estimate surface-opening crack depths, fire damage and freeze-thaw damage depths, and to measure relative concrete quality. With optional WINSASW software, it can also be used for thickness profiling of pavements, including asphalt and layered systems. The **SASW-SA** system option includes the same SASW bar assembly as the basic SASW-S, but adds two accelerometers which can be mounted on nearly any surface at any desired spacing. The SA option allows the user to measure deeper into materials, and test in situations where the bar geometry might not be practical.

The SASW method uses the dispersive characteristics of surface waves to determine the variation of the shear wave velocity (stiffness) with depth. Surface opening cracks, honeycomb zones, fire damage, and other flaws create an effective "layer" of low velocity material with a depth which can be measured. Once the shear wave velocity profile is determined, shear and Young's moduli of the material can also be estimated through the use of simple mathematical equations. The shear wave velocity measurements can be used to compare concrete areas to locate zones of weak or degraded concrete. The SASW method can be performed on any material provided there is an accessible surface for receiver (accelerometer or transducer) attachments and source impacting. With optional WINSASW software, the shear wave velocity profiles (shear wave velocity versus depth) are determined from the experimental dispersion curves (surface wave velocity versus wavelength) obtained from SASW measurements through a process called forward modeling or through an inversion process.

NOTE: SASW measurements are accurate to within 5% for the determination of the thickness and stiffness of the top layer in a pavement system.

Applications of SASW-S include, but are not limited to, the following:

- Determination of surface opening crack depths
- Freeze-thaw damage depth measurement
- Fire damage depth measurement
- Determination of abutment depths of bridges
- Condition assessments of concrete liners in tunnels, and other structural concrete conditions
- Determination of pavement system profiles including the surface layer, base and subgrade materials, with optional WINSASW software.

Material Tested: Concrete, Asphalt, Soil, Rock, Masonry, and Wood



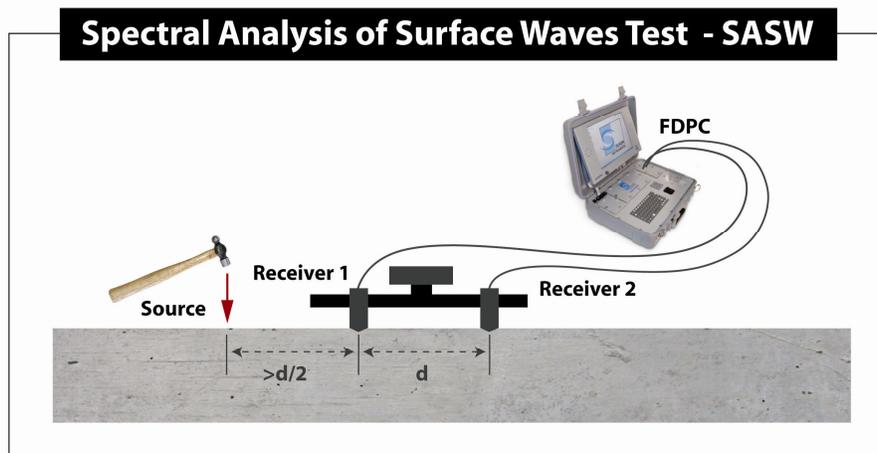
1.1 Organization and Scope of Manual

This operation manual for the SASW test with the Freedom Data PC system manufactured by Olson Instruments includes all required instruction for the use of the hardware and software included with the system. If any problems with the system appear that are not covered in this manual, please call Olson Instruments at the number included in the front of this manual. Note that training in the use of the system by Olson Instruments personnel is recommended for the most effective operation of this system.

1.2 Test Methodology

Spectral Analysis of Surface Waves (SASW) The SASW method uses the dispersive characteristics of surface waves to determine the variation of the surface wave velocity (stiffness) of layered systems with depth. The SASW testing is applied from the surface which makes the method nondestructive and nonintrusive. Experimental surface wave dispersion curves (velocity versus wavelength) can be produced with the basic WinTFS software, and are typically adequate for condition assessment of single-layered systems including cracked or damaged concrete. With optional WINSASW software, shear wave velocity profiles can be estimated from the experimental dispersion curves (surface wave velocity versus wavelength) obtained from SASW measurements through a process called forward modeling (an iterative inversion process to match experimental and theoretical results). The SASW method can be performed on any material provided an accessible surface is available for receiver mounting and impacting. Materials that can be tested with the SASW method include concrete, asphalt, soil, rock, masonry, and wood.

The SASW method requires an accessible surface for receiver attachments. The extent of the accessible surface limits the investigation depth. As a rule of thumb, if one is interested in material properties to a depth of D , then the accessible surface should extend in a line of receivers to a distance equal to $1.5D$, preferably $2D$. The figure below shows the general field arrangement used in SASW testing. Receiver spacings ranging from 0.25 to +300 ft have been used in the field by our firm to investigate depths from 0.1 ft up to +300 ft.





Typically the SASW-S system is used to check for concrete velocity profile within the concrete slab. The SASW method uses the dispersive characteristics of surface waves to evaluate concrete integrity with increasing wavelengths (depths). High frequency or short wavelength waves penetrate through shallow depths, and low frequency or long wavelength waves penetrate through deeper depths. Open, unfilled cracks will result in slower surface wave velocities. Weak, fire damaged and poor quality concrete also produces slower surface wave velocities.

It should be understood that if a crack is in tight grain-to-grain contact then the SASW dispersion curve will show minimal effect from the crack. This is because the surface wave energy will propagate across a tight crack that is under stress.

For geophysical applications and mass concrete (greater than 10 feet thick or so), the SASW-G system is typically used, with geophone receivers and sledge hammers or drop weights for sources. This system has been used out to depths of 300 feet or more for shear wave velocity profiling and modulus estimation.

Elastic Stress Wave Relationships. The following equations from elastic theory illustrate the relationships between shear moduli (G), mass density (ρ , total unit weight divided by gravitational acceleration), shear wave velocity (V_s), Young's modulus of elasticity (E), Poisson's ratio (ν), compression wave velocity (V_p), and constrained modulus (M):

$$\text{Direct P- or S- Wave Velocity: } V_p = D / t_p \text{ or } V_s = D/t_s \tag{1}$$

$$\text{Shear Modulus: } G = \rho V_s^{**2} \tag{2}$$

$$\text{Young's Modulus: } E = 2 (1+\nu) \rho V_s^{**2} = \rho V_p^{**2} [(1+\nu)(1-2\nu)/(1-\nu)] \tag{3}$$

$$\text{Constrained Modulus: } M = \rho V_p^{**2} \tag{4}$$

$$\text{Poisson's Ratio: } \nu = [0.5 (V_p/V_s)^{**2} - 1]/[(V_p/V_s)^{**2} - 1] \tag{5}$$

$$\text{P- and S-wave Velocities: } V_p = V_s [2(1-\nu)/(1-2\nu)]^{**0.5} \tag{6}$$

where D = Distance, t_p = P-wave travel time and t_s = S-wave travel time.

Values of these parameters determined from seismic measurements (SASW measurements) represent the material behavior at small shearing strains, i.e. strains less than 0.001 percent. Thus, moduli calculated from compression, shear or surface wave velocities represent the maximum moduli of materials because of their low strain levels. It should be noted that the measurement of the surface wave velocity, also called Rayleigh wave velocity, is actually performed in the SASW test. Surface wave velocity (V_R) in a homogeneous half-space is related to shear wave velocity by:

$$V_R \sim 0.9 V_s \tag{7}$$

(The exact equation is given in numerous geophysical textbooks)



Spectral Analysis of Surface Waves (SASW) Method. Surface wave (also termed Rayleigh; R-wave) velocity varies with frequency in a layered system with differing velocities. This variation in velocity with frequency is termed dispersion. A plot of surface wave velocity versus wavelength is called a dispersion curve.

The SASW tests and analyses are generally performed in three phases: (1) collection of data in situ; (2) construction of an experimental dispersion curve from the field data; and if desired (3) inversion (forward modeling) of the theoretical dispersion curve, where multi-layered systems exist, to match theoretical and experimental curves so that a shear wave velocity versus depth profile can be constructed. Wavelength (λ), frequency (f), and wave velocity (V_r), are related as follows:

$$V_r = f \cdot \lambda \quad (8)$$

When the velocity is uniform, the wavelength of the waves is the investigation depth. Forward modeling is most commonly performed on multi-layered systems to determine seismic velocity profiles for foundation design in earthquake zones or for vibrating machinery.

SASW Experimental Dispersion Curve Processing. The experimental dispersion curve is developed from the field phase data from a given site by knowing the phase (ϕ) at a given frequency (f) and then calculating the travel time (t) between receivers of that frequency/wavelength by:

$$t = \phi / 360 \cdot f \quad (9)$$

Surface wave velocity (V_r) is obtained by dividing the receiver spacing (X) by the travel time at a frequency:

$$V_r = X / t \quad (10)$$

The wavelength (λ) is related to the surface wave velocity and frequency as shown in equation 8.

By repeating the above procedure for any given frequency, the surface wave velocity corresponding to a given wavelength is evaluated, and the dispersion curve is determined. The raw phase data can be viewed on the Freedom Data PC platform in the field to ensure that acceptable data is being collected. The phase data is typically then returned to the office for processing using the WinTFS-SASW software. The phase of the cross power spectrum (transfer function) between the two receivers and the coherence function are used in creating the dispersion curves. Coherence is related to signal-to-noise ratio and system linearity; a value near 1.0 indicates good quality data. However, acceptable phase data may have comparatively low coherence.



After masking the phase data, an experimental field dispersion curve is developed that is the plot of surface wave velocity versus wavelength. The WinTFS-SASW software can be used to mask the phase data and generate the experimental field dispersion curves for report.

SASW Theoretical Modeling Processing with Optional WINSASW Software. To determine the shear wave velocity profile for the multi-layer system from the "apparent" velocities of the dispersion curve, analytical modeling is necessary. The analytical modeling typically used is a forward modeling process that is iterative and involves assuming a shear wave velocity profile and constructing a theoretical dispersion curve. The experimental (field) and theoretical curves are compared, and the assumed theoretical shear wave velocity profile is adjusted until the two curves match using optional WINSASW software from the Geotechnical Engineering Center of University of Texas at Austin. The interactive computer algorithm for both 2-dimensional and 3-dimensional analyses have been developed by Dr. Jose Roesset and his colleagues at the University of Texas at Austin to compute a theoretical dispersion curve based upon an assumed shear wave velocity and layer thickness profile. These algorithms have been in use for some time and have produced reasonable accuracy when comparing seismic soil and rock velocities determined with the SASW method with seismic velocities from boring based crosshole or downhole seismic methods.

SASW Method References.

1. "Nondestructive Test Methods for Evaluation of Concrete in Structures", reported by ACI Committee 228, ACI 228.2R-98 (Section 2.2.4).
2. M.F. Aouad, "Evaluation of Flexible Pavements and Subgrades Using the Spectral Analysis of Surface Waves Method", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, 1993.
3. S. Nazarian and K.H. Stokoe, II, In Situ Determination of Elastic Moduli of Pavement Systems by SASW Method (Practical Aspects), Report 368-1F, Center For Transportation Research, The University of Texas at Austin, 1985.
4. S. Nazarian and K.H. Stokoe, II, In Situ Determination of Elastic Moduli of Pavement Systems by SASW Method (Theoretical Aspects), Report 437-2, Center For Transportation Research, The University of Texas at Austin, 1986.
5. Roesset, J.M., D.W. Chang and K.H. Stokoe, "Comparison of 2-D and 3-D Models for Analysis of Surface Waves Tests", Proceedings, Fifth International Conference on Soil Dynamics and Earthquake Engineering, Karlsruhe, Germany, 1991, pp. 111-126
6. Andrus, R.D., K.H. Stokoe and J.A. Bay, "In Situ Vs of Gravelly Soils Which Liquefied", Proceedings, Tenth World Conference on Earthquake Engineering, Madrid, Spain, July 1992.
7. Seed, H.B. and Idriss, I.M., "Soil Moduli and Damping Factors for Dynamic Response Analysis", Report No. EERC 70-10, University of California, Berkeley, Sept., 25 p.



2.0 HARDWARE COMPONENTS

Spectral Analysis of Surface Waves-Structural (SASW-S) Equipment List

- (1) - 1 Olson Freedom Data PC
- (2) - 2 Channel SASW Input Module (High Pass Filter)
- (3) - 1 SASW-S Bar
- (4) - 1 SASW-S Extension Bar
- (5) - Ball Peen Hammer Set
- (6) - 1 6 Pin SASW-S Cable
- (7) - 2 Phone Jack to 4-Pin Conxall Adapter Cable



SASW-SA Option Additional Equipment List

- (1) - 2 Accelerometer Receivers
- (2) - 2 BNC Cables
- (3) - 2 4-Pin Conxall to BNC Adaptor Cables
- (4) - 2 Microdot to BNC Adaptor Cables



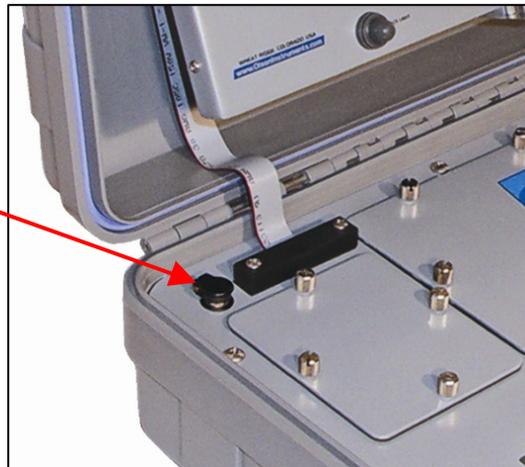
2.1 Freedom Data PC Hardware Setup

A step-by-step procedure for connecting the various system components is illustrated below. Please refer to these figures during connection of the components.

1. Lay the instrument case and Freedom Data PC down on a flat, stable surface. Unlock the case if locked. Next, open the Freedom Data PC case. The location of the Freedom PC should be within 15 m (50 ft) of the subject/material to be tested.



2. Next, if desired, connect the Freedom Data PC to the external power supply with the 120/240 VAC Power Supply/Charger. The external power supply/charger automatically switches between 120/240 Volts AC.





The computer is designed to be resistant to light rain or other moisture but should not be exposed to heavy rain.

- 3. BATTERY INSTALLATION: If it is necessary to replace the batteries, remove the battery cover as shown. Insert both batteries with the (+) polarity to the right (photo below).



Fully charged batteries should power the IE system for 8 – 10 hours depending on the processor speed of the unit used. The Freedom Data PC can also be powered from a car cigarette lighter socket using a 12 VDC adapter. However, this may drain a weak car battery in a few hours if the engine is not running.



BATTERY CONDITION INDICATOR LIGHTS

Green Light – Batteries are fully charged

Yellow Light – Batteries are charging

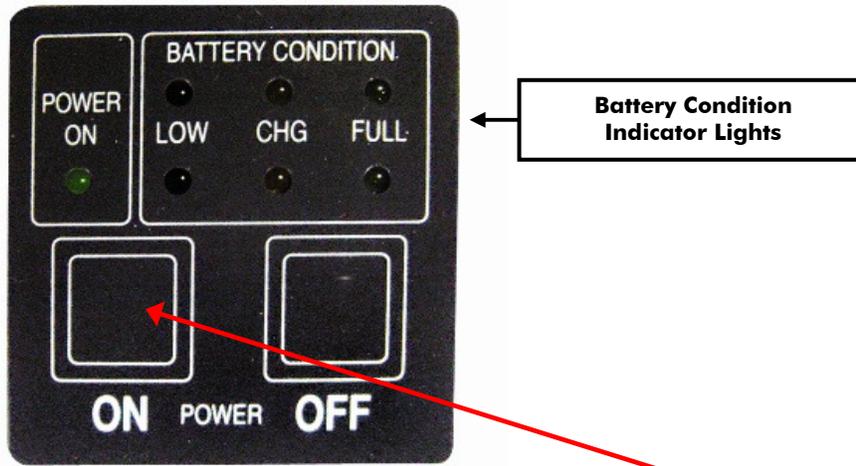
Red Light – Low Battery, ~ 15 minutes usage left, apply external power supply at this point



2.2 Freedom Data PC Hardware Operation

After the Freedom Data PC hardware is properly set up, operation is straightforward and primarily involves the use of the Freedom Data PC and the installed modules. The use of the Input Module and Pulser Module is described in this section.

1. Power



Power on Freedom Data PC by pressing the “ON” Button as shown.

If the battery LED is **red**, do not try to operate the computer, as the batteries are very low. In this case, the system should be run on external power rather than off the batteries. Charging of the batteries will begin once external power is attached. A running automobile outputs approximately 14.2 VDC, which will charge the batteries to around 85% of full charge. To achieve 100% charging power, use the 16 VDC AC powered external power supply that is shipped with your instrument.



When operating the computer on external power with partially or fully discharged batteries, a “Fault” light may appear after a period of time. This yellow flashing light is normal, and is due to the combined current drain of the computer operation and the battery charge current. The batteries will charge normally when the power supply is connected with the computer shut off (such as overnight). Totally drained batteries will require 12 – 13 hours for full charging.



2.2.1 Freedom Data PC Operation Notes

The Freedom Data PC is a self-contained data conditioning, collection, and processing platform usable for a number of types of NDT tasks as well as general data acquisition. The data acquisition tasks for which the Freedom Data PC is capable, depends on the modules installed (up to two at a time). The following section discusses the basics of the hardware operation of the Freedom Data PC, including module replacement, battery charging and replacement, external powering, and general maintenance.

2.2.1.1 General Maintenance and Usage

The Freedom Data PC is a rugged unit designed for field conditions. It is normally water and air tight when closed and latched, which will protect it in most storage and transportation conditions.

While the Freedom Data PC is watertight when closed, it is water resistant (not water tight) when open or operating. Thus, rain or other normal moisture should not bother the unit, but it should **NOT** be submerged or sprayed at high pressure. Also, water should not be allowed to collect on the face of the computer unit.



Never expose the external power supply/charger to rain or moisture.

When used in a field environment, the Freedom Data PC should be expected to get dirty. If this happens, wipe the unit with a damp (not wet), clean towel. Do not allow water to flow into any of the components, and do not wipe the screen with a dry or dirty towel.

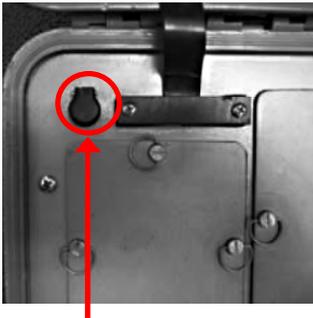


The screen is subject to damage if impacted or pressed on.



2.2.1.2 Battery Charging and Usage

The batteries inside the Freedom Data PC consist of 2 sealed units, each of which is 12 VDC, 11 Ampere-Hours. Depending on the usage, these batteries should last for 8-12 hours of continuous use. After this, the batteries should be recharged or switched out with a fully charged pair. The batteries used are Lithium Ion batteries with internal protection circuitry. There is no memory effect, so batteries can be used freely with only a partial charge.



External power supply jack



Opening battery cover



Cover removed, exposing 2 Lithium Ion batteries



Charging the Batteries

1. Turn off "POWER" to the Freedom Data PC.
2. Plug the external power supply/charger into the jack in the upper left-hand corner on the front panel of the unit (top left photo). The yellow "CHARGE" lights will come on for each battery for the bulk of the charge cycle. At 85% of capacity, the green "FULL" lights will light, with all lights out when the battery is completely charged. Always charge the batteries in a protected environment, at normal room temperatures. The batteries red "charge" light indicates that the batteries are nearly fully drained and need recharging.



To prolong battery life, always recharge the batteries immediately after use.



Do not disassemble, incinerate, short out, or otherwise abuse the batteries as there is a possible risk of fire or explosion.



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If power is available at the field site (110/220 VAC), the external power supply/charger can be used to power the Freedom Data PC with or without batteries installed. The external power supply/charger will run the unit and start to charge the batteries if installed. Note that the Freedom Data PC should be turned OFF before connecting or disconnecting the external power supply/charger. Disconnecting the power supply/charger during operation may cause the Freedom PC to reboot and lose data in memory, especially if the batteries are very low. If it does reboot, turn off power, then turn on again for normal operation. A 12VDC adaptor can also be used to power the unit off of a car battery.



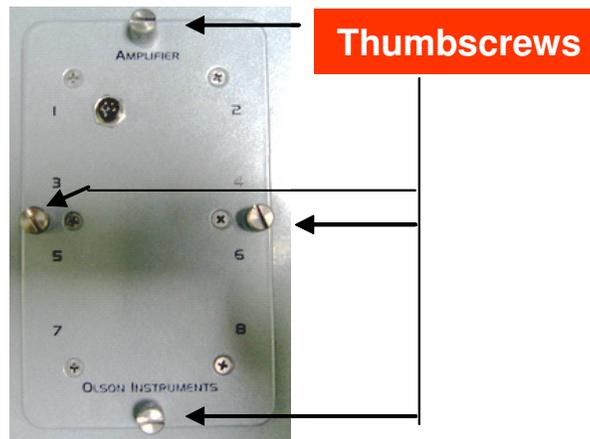
Notes on maximizing battery life. The following can help maximize the run-time of the batteries:

- Turn off the computer when not in use (when moving or setting up other equipment)
- Use external power when easily available
- Recharge the batteries immediately after each use to preserve capacity



2.2.1.3 Removing/Replacing Batteries and Modules

The batteries and Amplifier/Pulser Modules on the Freedom Data PC are field replaceable. They all use thumbscrew fasteners for securing. To remove the modules, turn off power to the Freedom Data PC, disconnect all cables from the module, and unscrew the thumbscrews counterclockwise. Then pull up firmly and evenly on the screws to remove the module. To replace, simply press the module fully into the slot and tighten the screws.



The amplifier module should be in the upper position and the pulser module, if required, in the lower position. No damage will occur by switching the locations, but no signal will be coupled from the amplifier module to the data acquisition card, and thus the modules must be placed in the right position.

Replacing the batteries in the Freedom Data PC is a similar operation. Unscrew the 8 thumbscrews then lift off the battery cover. The battery cover should lift up freely. Next, lift the batteries out by the lifting cord. Install new batteries by dropping them into the compartment (they are keyed for polarity and cannot be inserted wrong). Replace the cover. Finally, press and tighten each of the thumbscrews.





2.3 Step by Step Guide for SASW-S and SASW-SA Hardware Setup

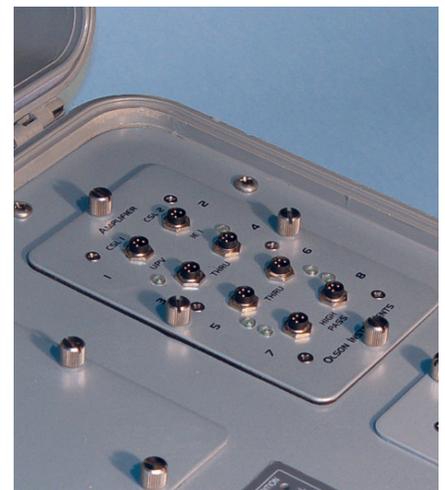
1. Insert the Input Module

After opening the Freedom Data PC, insert the input module into the top module pocket if not already present. This pocket is reserved for the input module.



2. Secure Module in Place

Be certain to align all of the screws with the holes in the Freedom Data PC while hand tightening the screws securely.

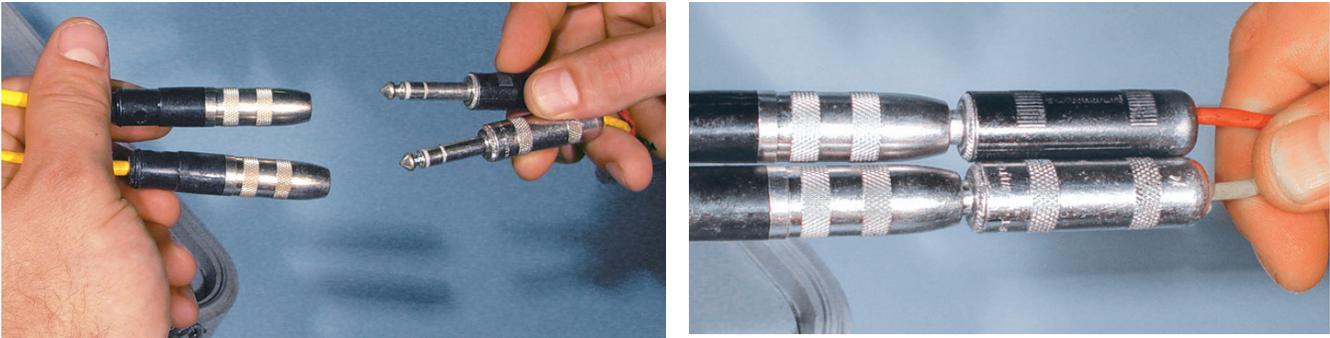




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3. SASW Bar: Connect the SASW-S cables to the Adaptor Cables

Connect the 4-pin adaptor cables to the phone plug connections on the SASW-S cable. This can be done by aligning the pins with the appropriate holes and gently pushing them in fully. It doesn't matter which phone plug connects to which adapter cable.



4. Connect the Adaptor Cables to the Input Module

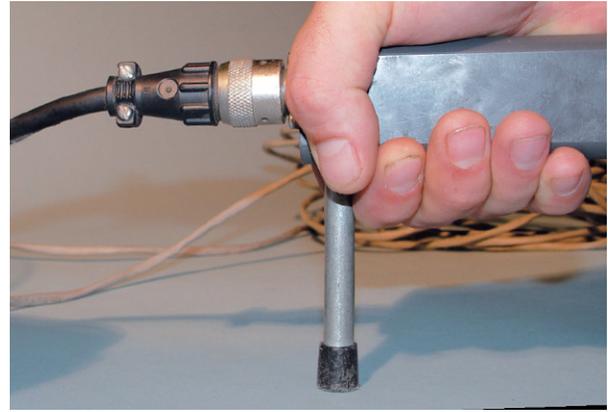
Next connect the two 4-pin adapter cables to the input module in channels with a high pass filter applied. This can be done by pulling back on the small black sleeve at the end of the cable and carefully lining up the four holes on the cable with the four pins on the input module. It doesn't matter which cable connects to which channel.





5. Connect the SASW-S Cable to the SASW Bar

Now secure the 6-pin SASW-S cable to the handle of the SASW bar. Note that the extension bar does not need to be added to the system unless spacings longer than 40 cm are needed.

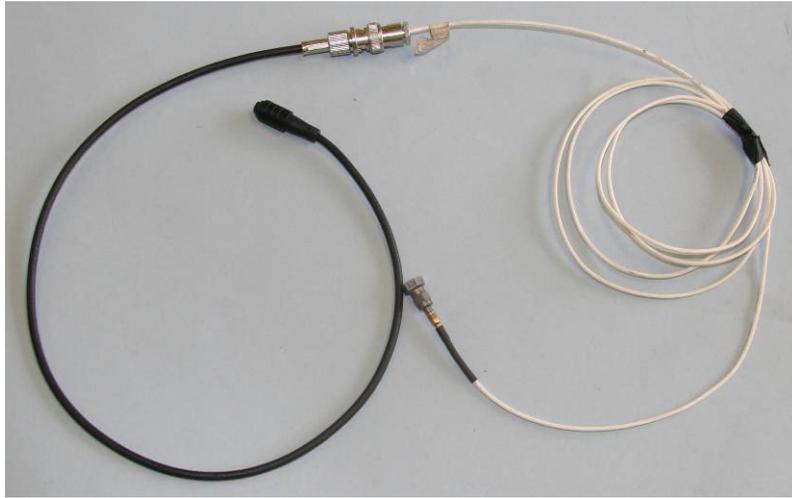


6. Accelerometer Use (SA Option): Connect the Accelerometers to the Cables

If using the SA option accelerometers, connect each of the two accelerometers to a white Microdot to BNC adaptor cable. These cables can then be connected to extension BNC cables, if needed, to allow enough cable length for the receiver locations desired.

7. Accelerometer Use (SA Option): Connect the Conxall Adaptor Cables

The Microdot or BNC cables are each then connected to one black BNC to 4-Pin Conxall adaptor. The other ends of the adaptor cables are connected to the Freedom Data PC input module. Be certain to use input channels that are wideband (not high pass). Note that the input channels used MUST have the green indicator lights present. These lights will turn on once the accelerometer is correctly connected. If the light does not turn on, check the connections and cables. Correct connection of an accelerometer to the white microdot cable and black adaptor (no extension BNC cable used in this example) is shown in the photo below.



8. Accelerometer Use (SA Option): Accelerometer Mounting

The accelerometers are typically mounted to the test surface with either wax or grease. If a magnetic base is used, the accelerometer can be directly mounted to a steel surface, nail head or small washer (which is then grease-mounted to the concrete or other surface). Using a magnetic base with a washer allows for a stronger connection to the surface. The accelerometers are mounted at the desired spacing (center to center), defining the test line. Make sure to measure and record this spacing for all tests.

Once all connections are made for either the SASW-S or SASW-SA system, and the receivers are mounted (or pressed on the surface for SASW Bar use), the hardware setup for the SASW-S acquisition system is complete and data collection can begin.



Before moving on to Data Acquisition, Section 4.0, it is critical to record the receiver spacing on the SASW bar. This will be used later in the analysis.

At this point, the system is ready for data collection. Details of data collection are presented in Section 4. Section 3, below, discusses the installation of the WINTFS software which is used for data collection. If this software is already installed and working, skip Section 3 and move on to Section 4.



3.0 WinTFS SOFTWARE SETUP

The WinTFS software for the SASW data collection is pre-installed and thoroughly tested at the manufacturer. If for any reason you need to reinstall/uninstall the software, or if you are installing software on a desktop/laptop computer, this section covers the steps required to install the WinTFS software from the supplied installation CD. **If your SASW system includes optional WINSASW software, please skip Section 3.1 and go directly to Section 3.2.**

3.1 Installation of WinTFS Software without Optional WINSASW

1. National Instruments Data Acquisition (NIDAQ) software is necessary to run the Olson Instruments WinTFS program. The NIDAQ drivers can be located on the supplied installation CD (run the NIDAQ SETUP file on the included CD and use the recommended defaults) or can be downloaded at: <http://www.ni.com/>

It is very important to uninstall any previous versions of NIDAQ before installing a new version.

NIDAQ Version 8.3 is required for Windows XP, Vista and 7 - 32 bit.

NiDAQ Version 8.9.5 can be used with 64 bit Windows on your personal computer.

If retrieving NIDAQ files from the web, download the necessary zip file. Unzip the file and install the NIDAQ program by running the SETUP file and using the **recommended defaults** (the minimum possible install options will run the WinTFS software). Note that an account with National Instruments (free of charge) may be required to proceed to the download page.



Failure to install the prerequisites will result in an error when running the WinTFS software.

2. Uninstall any previous version of WinTFS
3. Run "Setup.exe" from the Olson Instruments WinTFS installation CD
4. Follow the default setup
5. After finishing the installation, the "WinTFS.exe" file will be found on: drive C:\Program Files\Olson Instruments\WinTFS\. A shortcut to "WinTFS.exe" can be placed on the desktop



Failure to uninstall the previous version of the WinTFS software will prevent the installation of the new version.



3.2 Installation of WinTFS Software with Optional WINSASW

1. National Instruments Data Acquisition (NIDAQ) software is necessary to run the Olson Instruments WinTFS and WINSASW 3.2 software programs. The NIDAQ drivers can be downloaded at:

<http://www.ni.com/>

It is very important to uninstall any previous versions of NIDAQ before installing a new version.

NIDAQ Version 9.0.2 is **required** for WINSASW 3.2 and must be installed **before** the WINSASW software is installed. Other versions of NIDAQ will not work with WINSASW and must be removed.

When retrieving NIDAQ files from the web, download the necessary zip file. Unzip the file and install the NIDAQ program by running the SETUP file and using the **recommended defaults** (the minimum possible install options will run the software). Note that an account with National Instruments (free of charge) may be required to proceed to the download page.

2. Install WINSASW 3.2 from the provided CD
3. Uninstall any previous version of WinTFS
4. Run "Setup.exe" from the Olson Instruments WinTFS installation CD
5. Follow the default setup
6. After finishing the installation, the "WinTFS.exe" file will be found on: drive C:\Program Files\Olson Instruments\WinTFS\. A shortcut to "WinTFS.exe" can be placed on the desktop



3.3 Software Updates

To update the WinTFS software, the only file that is necessary is the new “WinTFS.exe” file. This file must be copied into the C:\Program Files\Olson Instruments\WinTFS directory. If not, the shortcut on the desktop references the old version of WinTFS. Replace the existing “WinTFS.exe” by copying and pasting the new version into the directory.

3.4 Software Uninstallation

The following steps are required to uninstall the WinTFS Software

1. Click on Start/Settings/Control Panel
2. Select “Add/Remove Programs”
3. Highlight WinTFS, select “Remove”
4. The uninstall process will begin automatically, removing all installed components including the shortcut.

3.5 First Time Executing WinTFS Software

To run the WinTFS-SASW software, execute “WinTFS.exe”. When the WinTFS software is executed for the first time, the program detects the missing software key (OlsonWinTFSKey.dat). The program will display a warning that the software key file is missing and will only enable two options on the main menu shown below (Software Key and Exit buttons).



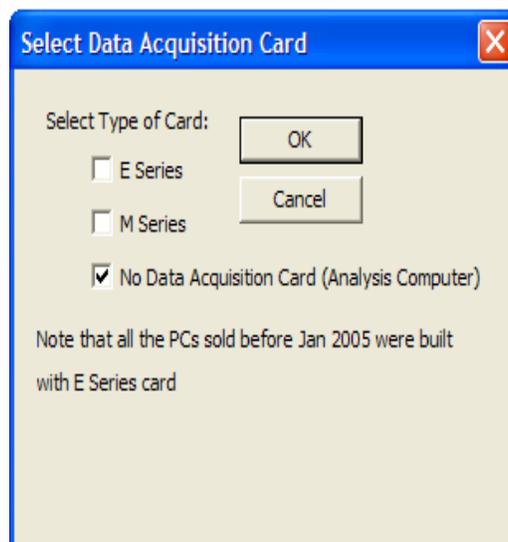


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Select the “Software Key” button and enter the software key printed on the installation disk. If a software key is not available or known, please contact Olson Instruments. Exit the software and restart the software. Then the new main menu with the SASW button (and any other modules purchased with the system) enabled will appear on the screen. Click on “SASW”.



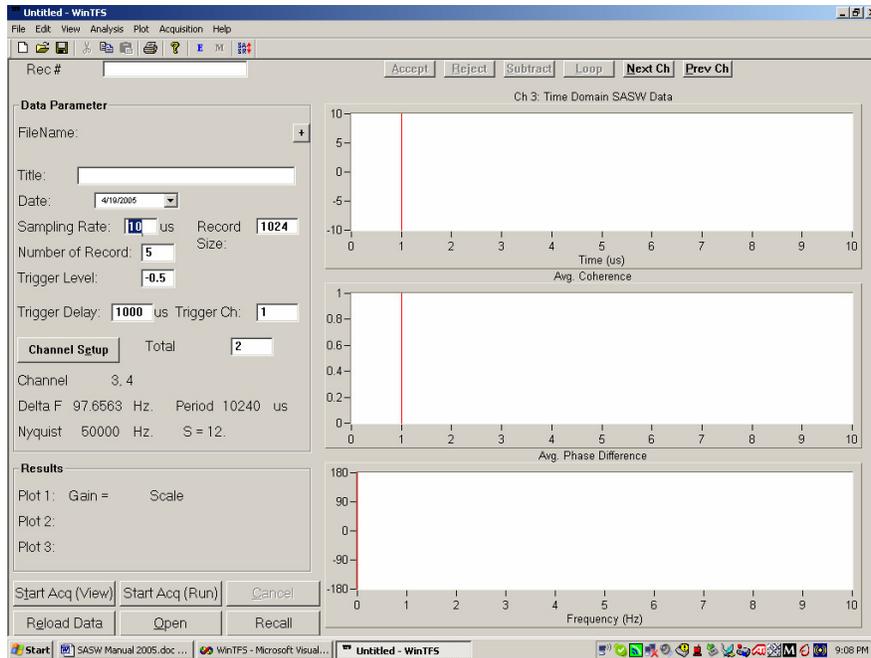
The software will detect the default missing parameter file and will automatically generate a new default file. The user will notice an applet as shown below. The user **MUST** select one type of National Instruments data acquisition card (either E or M or No Data Acquisition Card). In general, a Freedom Data PC with Transmetta CPU (running Windows 2000) comes with an “E Series” card. A Pentium M system (running Windows XP) or an Atom system (running Windows XP or 7) comes with an “M Series” card. A Desktop or Laptop computer requires “No Data Acquisition Card”.





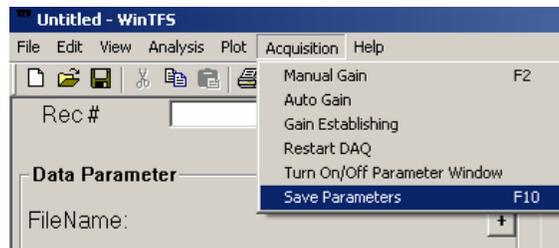
3.6 Start Program

The following image should next appear on your screen. The WinTFS-SASW program will be loaded with the data parameters saved in the "SASWdefault.prm" in your C:/Program Files/Olson Instruments/WINTFS directory.



Main Screen for SASW Software

You can change any of the data parameters through the various setup menus in the WinTFS program. If you want to keep these parameters for future use, you have to save the parameters by selecting "Acquisition/Save Parameter" as shown below or press 'F10'.



Saving Data Parameters



There are seven major parameters affecting the SASW data acquisition:

Sampling Rate: means how often (in the time domain) the system will acquire data points within a given data trace. In the case shown in the figure below, the Sample Rate was set at 10 microseconds. This means the system will acquire data at 10 microsecond intervals.

Record Size: is number of sampling points for each waveform. The higher this value, the more data is acquired in each waveform. The total time of a record is affected by both the Sample Rate and the Record Size. If the period is too low, the program will automatically increase the record size accordingly. For most SASW-S tests, this is set to 1024 or 2048 points.

Number of Records: is total number of SASW data records you want to save (for averaging) in a given test. For most SASW-S tests, this is set to 5-10 records.

Trigger Level: is the amplitude (in volts, from -10 to +10) that the input signal on the trigger channel must reach before a set of waveforms is collected. For the SASW bar, this is normally set to -0.5.

Trigger Channel: is the channel which is monitored by the system to determine when a signal from an impact is present. This MUST be set to one of the channels connected to a receiver – usually the one closest to the impact.

Trigger Delay: is pretrigger delay time in microseconds. This determines how far to the right the signals appear on the top plot (time plot) for each waveform collected. For most SASW-S tests, this is set to 3000 microseconds. Normally, this parameter is set to be about 5-10% of the period (which is visible on the screen).

Channel Setup: is the place to turn on and define the channels used in data acquisition. The settings shown in the figure below are for two geophones connected to channels 3 & 4.

Channel	Transducer	Gain	Calibration	Unit	Analysis
<input type="checkbox"/> Channel 1			1		
<input type="checkbox"/> Channel 2			1		
<input checked="" type="checkbox"/> Channel 3	Geophone	10	1		SREF
<input checked="" type="checkbox"/> Channel 4	Geophone	10	1		SA
<input type="checkbox"/> Channel 5			1		
<input type="checkbox"/> Channel 6			1		
<input type="checkbox"/> Channel 7			1		
<input type="checkbox"/> Channel 8			1		

Channel Setup



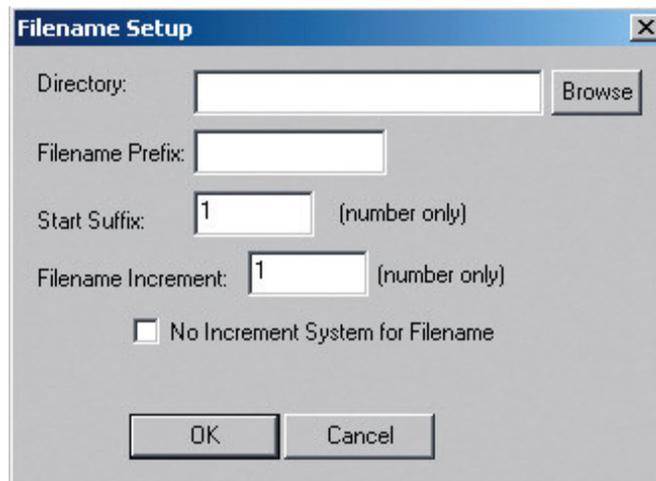
4.0 DATA ACQUISITION

After the Data Acquisition parameters are entered correctly, data collection can begin. The following steps outline the necessary procedures for proper data collection. Please note that data collection assumes that the hardware is properly set up and ready for testing. The hardware setup is discussed in Section 2.

4.1 Set Up Automatic File Naming System

Following the steps in Section 3.0 to set up the WinTFS Software for actual testing, this section explains the setup for optional **Automatic File Naming**.

The software allows the user to set up a filename system with a prefix and an increment for easy repetitive testing. To activate this option, go to “File/Setup Filename”. The dialog box, as shown below should appear on your screen. Once the prefix, first start suffix and increment are set, the data will be automatically named when the user clicks on “Start Acquisition” either in VIEW or RUN mode for the older systems. Newer systems have different acquisition modes. (i.e. “Save Current Data”).



Filename Setup Menu

If you do not set up the Automatic File Naming system, you will be able to name and save individual files after data collection.



4.2 Field Set Up for Test

In SASW tests, two receivers are placed on the surface, and a hammer or other source is used to generate the acoustic energy. Other sources used in SASW-S measurements include solenoid-operated impactors and V-meters (high frequency sources). Short receiver spacings with high-frequency impact sources (small hammers, allen wrenches, solenoid impactors, etc.) are used to sample the shallow layers while long receiver spacings with larger hammers (1 lb and heavier) are used in sampling deep materials. The two sets of receiver signals are recorded by a Freedom Data PC Platform with the SASW-S option and stored for further analysis. Two profiles, a forward profile and a reverse profile, are typically obtained in SASW measurements where the accessible surface is struck by a hammer on two opposite ends of the line of the receivers. Two functions in the frequency domain (spectra) are of great importance in SASW tests:

- (1) the cross power spectrum between the two receivers (used in the preparation of the experimental dispersion curve) and,
- (2) the coherence function (used to ensure that high signal-to-noise ratio data is being collected).

As noted previously, the hardware setup is detailed in Section 2.

4.3 Start the SASW Test

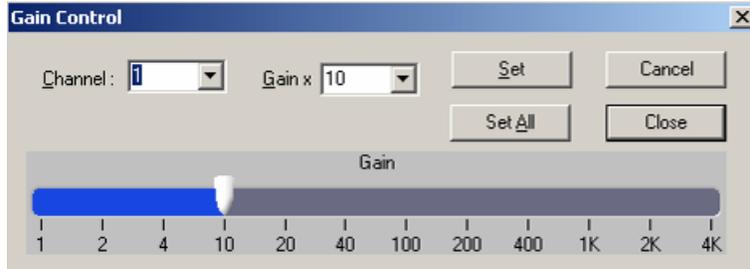
The SASW testing is started by setting the system to the “Run” or “View” mode, and then impacting the test surface with the selected hammer or other impact source. The impact location **MUST** be directly in-line with the two receivers and off one end of the bar. Typically, the impact location is selected to be between 0.5 and 1.5 times the spacing between the receivers on the bar. Note that all impacts in a given average (data set) should be collected with the same impact location and source. A photo of a typical SASW-S test in progress is shown below. Note the impact source being used off the end of the bar, in-line with the receivers.



In Run mode, all data traces are automatically accepted without user intervention required. This option is generally faster than the View mode, but can result in poor quality data if the gains are not set properly or if the data is noisy or of variable amplitude. Before starting data acquisition in this mode, the channel gains must be set properly. To set the gains, go to “Acquisition/Automatic Gain Setting” as described more in Section 4.4 below, or run the first test in the View mode. Gain will be set based on the signal amplitude. If no triggering occurs at all from the first impact, the user may have to manually set the gain level to a higher value than the default. In the auto-gain mode, if the maximum amplitude is less than 3 Volts (assuming enough signal is seen to trigger the system at all), gain will be increased. If the maximum amplitude is higher than 7.5 Volts, gain will be decreased. Gain is set when user accepts the data. After the gains have been set, click on “Start Acq (RUN)” to start recording data.

4.4 Gain Settings

The default value for gain is 10 for every channel. Gains can be saved in the default file and loaded when starting the program. In addition, gain can be manually set by going to “Acquisition/Manual Gain” or pressing ‘F2’. The gain applet as shown below should appear on the screen with the current gain setting. Simply select a channel and adjust the gain value by either clicking on the slider bar or changing the value in the gain entry box. If entered in the gain entry box, then press the “Set” button to complete the gain setting. However, if the slider bar is used to set the gain value, it is not necessary to click the “Set” button. To leave the gain applet, click on the “Close” button”.

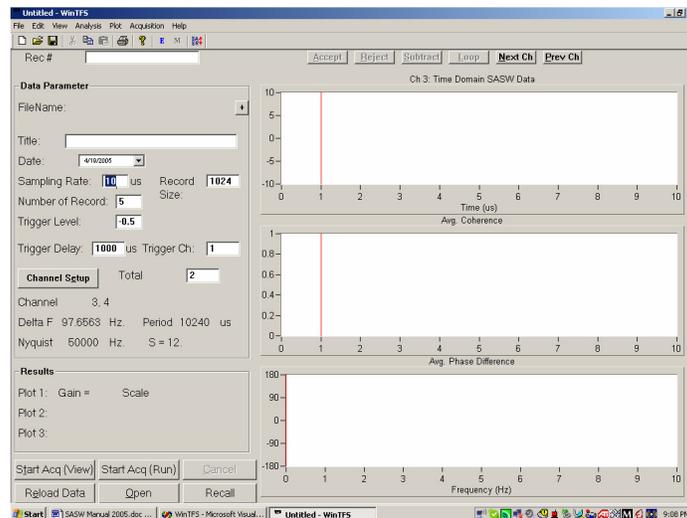


Gain Control Applet

For data acquisition in the RUN mode, it is strongly suggested to set the gains manually before starting the test, as noted in the paragraph above.

4.5 Turn On/Off Parameter Window

The parameter window can be turned on and off by going to “Acquisition/Turn On/Off Parameter Window”. This is a toggle function. The figure below shows the parameter window displayed.



SASW Window with Parameter Window Turned On

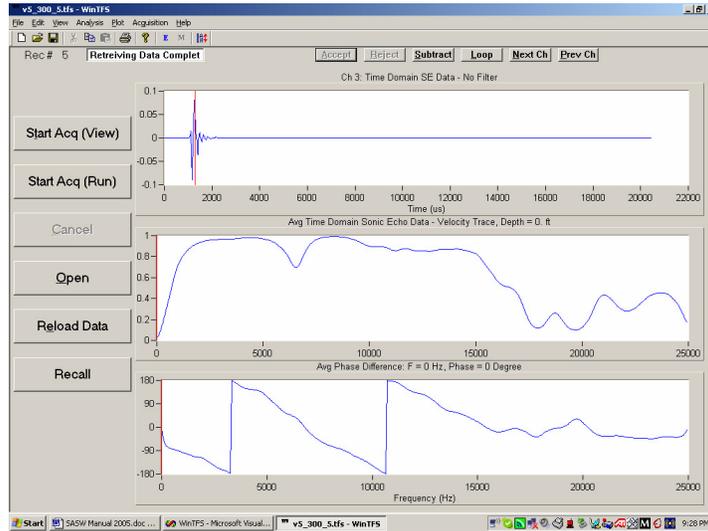
An example of the data with the parameter window turned off is shown in the figure below. This option can also be used during data analysis so that the signal window can be seen more clearly.



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SASW Data with Parameter Window Turned Off

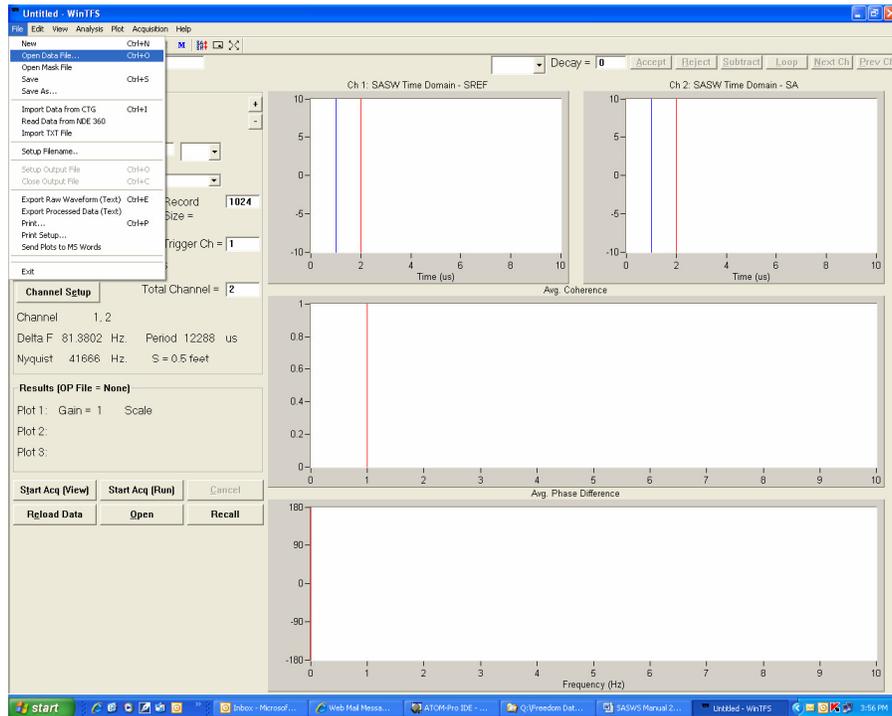


5.0 DATA ANALYSIS

This section includes instructions on how to reopen and analyze your files in WinTFS after data collection.

5.1 Open SASW Data File

For post-analysis (once all the planned waveforms have been collected and stored), use the WINTFS program analysis functions. If the WINTFS program is not currently running, start the program per the instructions in Section 3.6. Click on “Open” located on the bottom of the main screen to open the SASW file. You can also click on “File/Open Data File.” Select the file you want to analyze.



The software shows the time domain SASW traces in the top two side-by-side windows, with nothing in the lower two windows until the first pair of waveforms is accepted into the average.



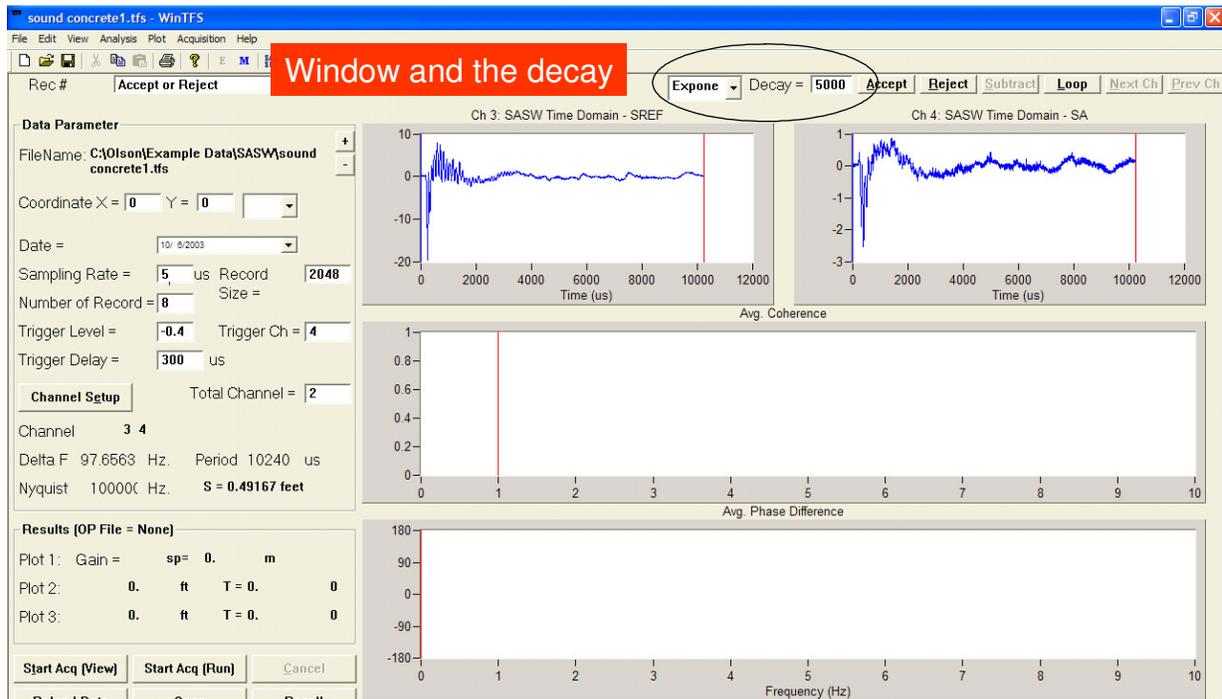
5.2 Open Next SASW Data File

If the files are sequentially numbered using the Automatic File Naming System described in Section 4.1, click on the +/- button to open the next SASW data file for speedy data recall once analysis is completed on the first record.

5.3 Data Analysis

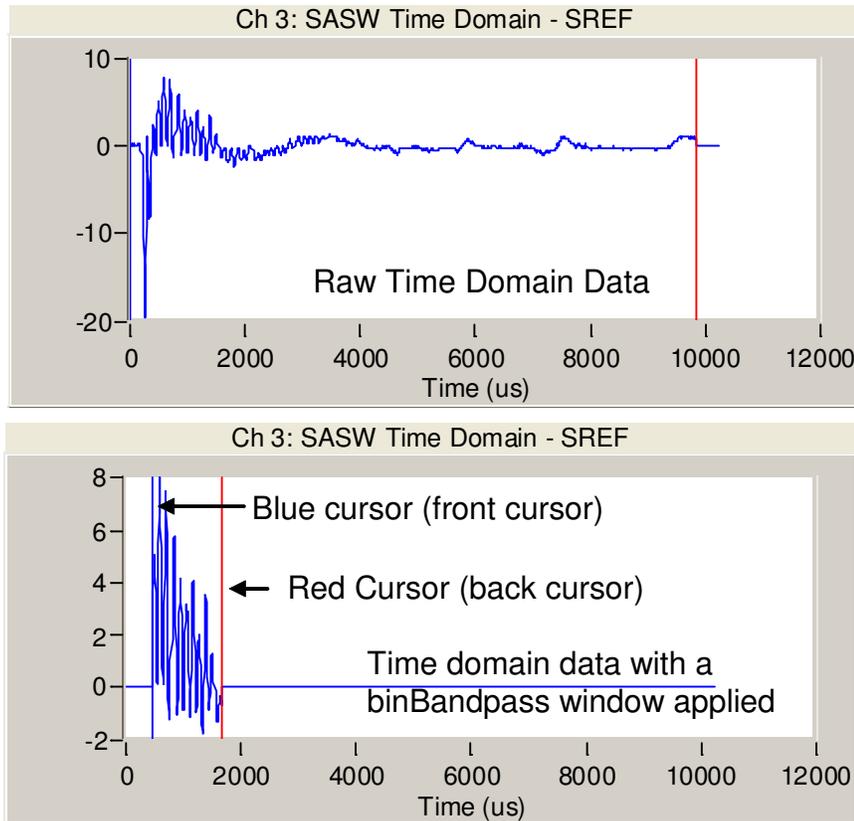
Some of the tools available for post processing of data include Windowing, Accept/Reject Data, Filtering, Masking, Transducer/Accelerometer Spacing, Velocity Plot, Data Export.

1. **Windowing Data:** The surface wave has the largest amplitude and is at the front end of the waveform acquired from the SASW tests. Time domain filtering is required to eliminate the back part of the waveform so that the non-surface wave is not included in the analysis. A typical window used in the analysis of SASW-S data is “Exponential” or “Hanning” with a decay of 1000 – 5000. The various window types are further explained below.





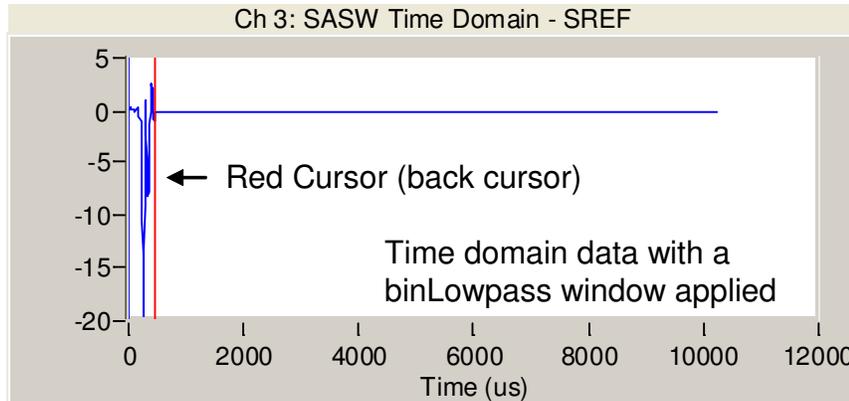
- a. BinBandPass. Allows time domain data between the front and back cursors in the analysis and eliminates the data before and after. This option is not recommended for SASW processing as the window applies sharp cuts to both ends of the waveform and will likely distort the frequency information.



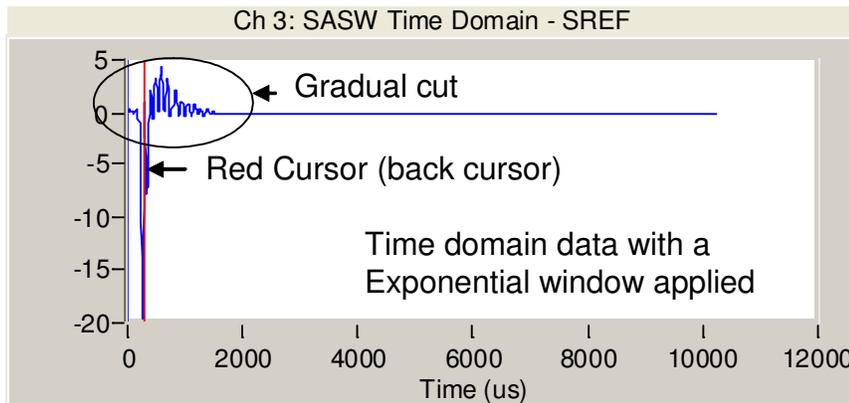
- b. BinHighpass Allows time domain data after the blue cursor (front cursor) in the analysis. This type of window is almost never used in the SASW data processing and is not recommended for SASW processing as the window applies a sharp cut to the waveform and will likely distort the frequency information.



- c. BinLowPass. Allows time domain data before the red cursor (back cursor) in the analysis. Note that the blue cursor (front cursor) is never used for the BinLowPass. This option is not recommended for SASW processing as the window applies a sharp cut to the waveform and will likely distort the frequency information.



- d. Exponential. Allows the data after the red cursor (back cursor) in the data analysis with a gradual cut (exponential cut) depending on the decay value. The higher the decay value, the sharper the cut of the signal. This option is typically used to process SASW data.



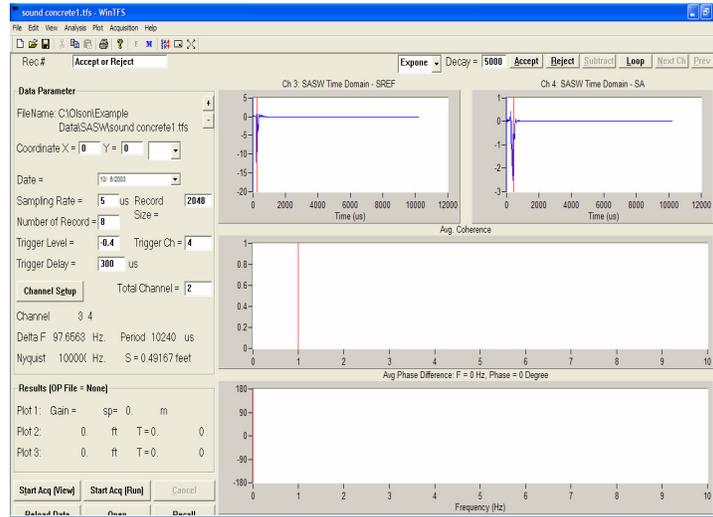
- e. Hanning. This window is similar to the binBandPass but with gradual cuts for both the front and back part of the data. This type of window is used when there is noise in the front part of the signal, or for continuous sources.



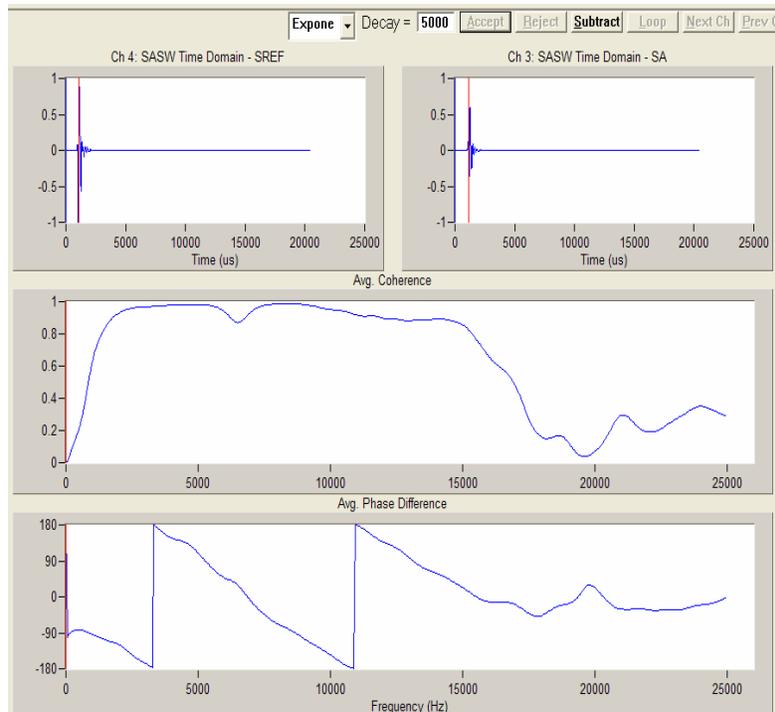
“Exponential and “Hanning” windows are the only two windows that allow a gradual cut in the time domain (with decay). Other types of windows (bandpass, lowpass and highpass) apply a sharp cut in the time domain and may alter the phase information.



After selecting the window (and decay for the Exponential and Hanning), move the cursor(s) to eliminate the non-surface waves. The picture below shows an exponential function being used to eliminate the back part of the waveform. In this case, the red cursors were positioned on the maximum negative peaks of both signals.



2. Accept or Reject Data: Accept or Reject the data on screen by clicking on the “Accept” or “Reject” buttons on the main screen. Note that all the data recorded must be either accepted or rejected before the phase data analysis can be performed. The SASW time domain raw/windowed data will appear on the top traces of the plot. The second trace shows the coherence of the data. The third trace shows the phase data.

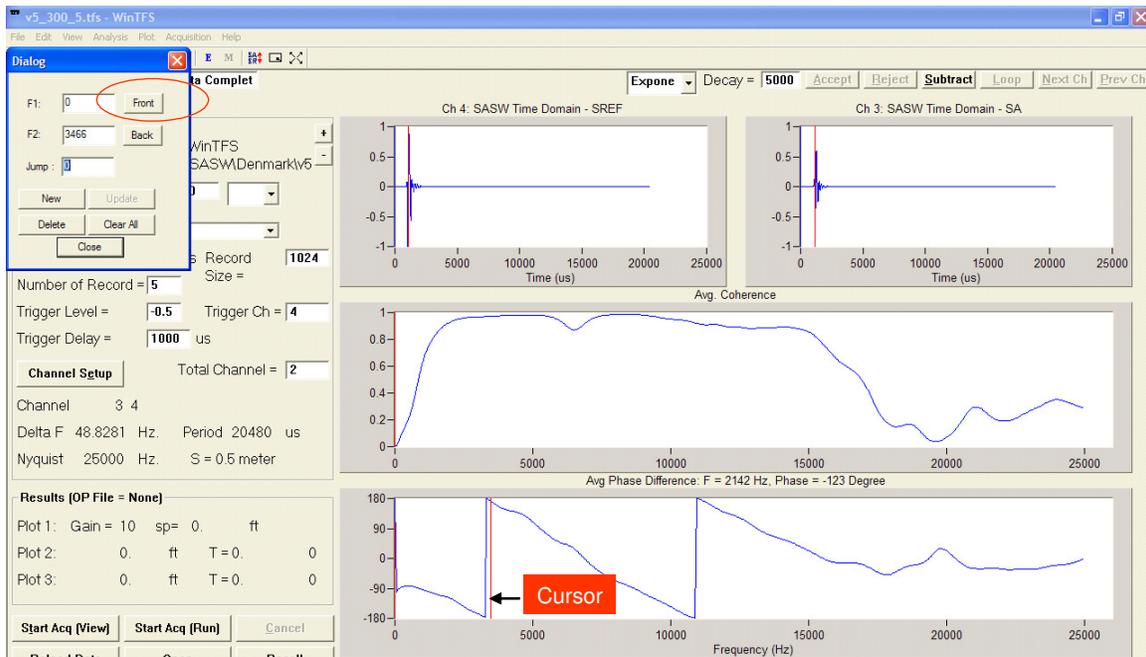




3. **Filter Function:** This feature is rarely used in the SASW data analysis.
4. **Masking:** To bring up the masking applet, simply right click on the bottom trace at the location that needs to be masked. In this case, it is the back part of Cycle 1. Then click on “Front” on the masking applet.



Typically Cycle 0 (or Jump 0) should be masked since this portion of data does not represent the actual velocity.



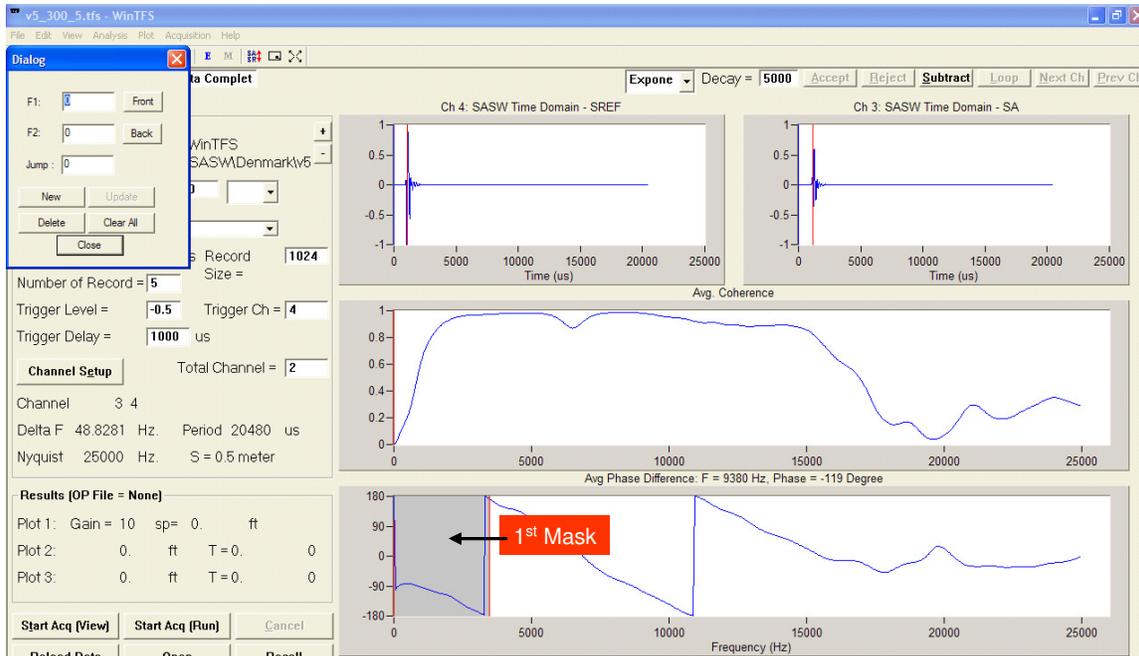
Then enter the Jump (Cycle) number. In this case the cursor is located on the first cycle so enter 1 on the Jump entry. The “Jumps” are easily visible in this phase plot example as the vertical lines on the lower trace. To the left of the first “Jump” is considered to be “Jump 0”. Between the first and second jumps is considered to be “Jump 1”, to the right of the second jump is “Jump 2”, etc. After setting the correct jump number, click on “New” on the masking applet. The mask will be created on the bottom trace and the masking applet will be cleared out for a new masking.



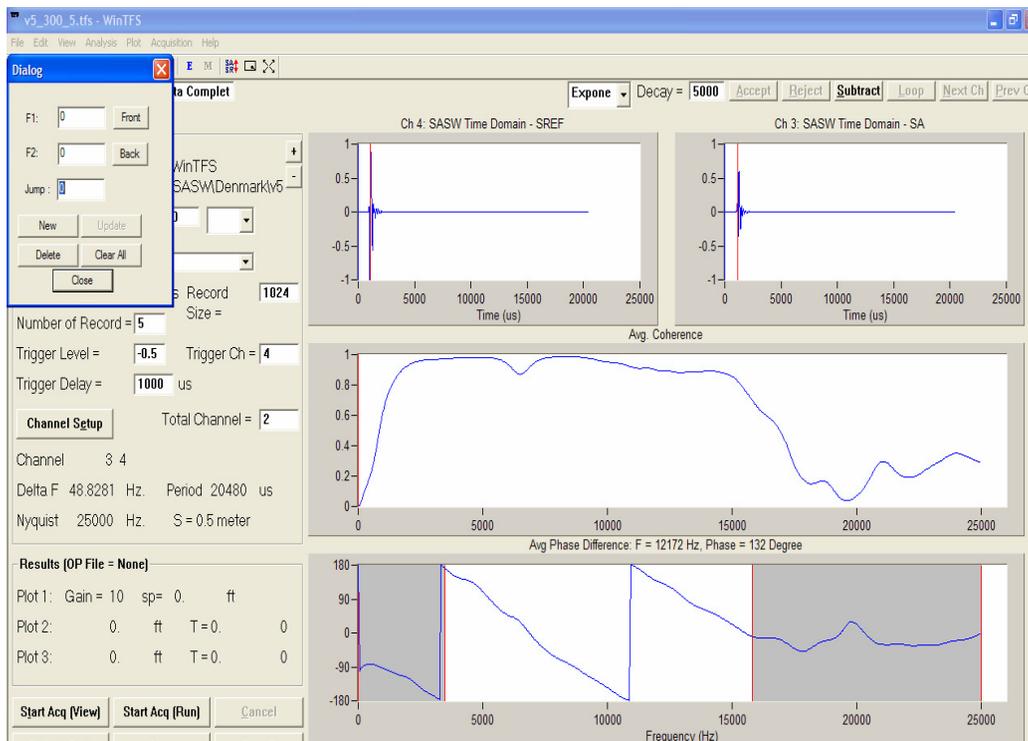
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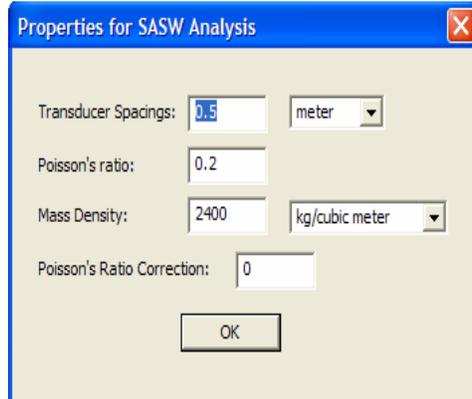


Typically the back part may also need to be masked. Repeat the same process by placing the cursor on the front location of the back part that need to be masked. Then click on “Back” on the masking applet. A new mask should be created. Note that jump number is not important for the “Back” mask.

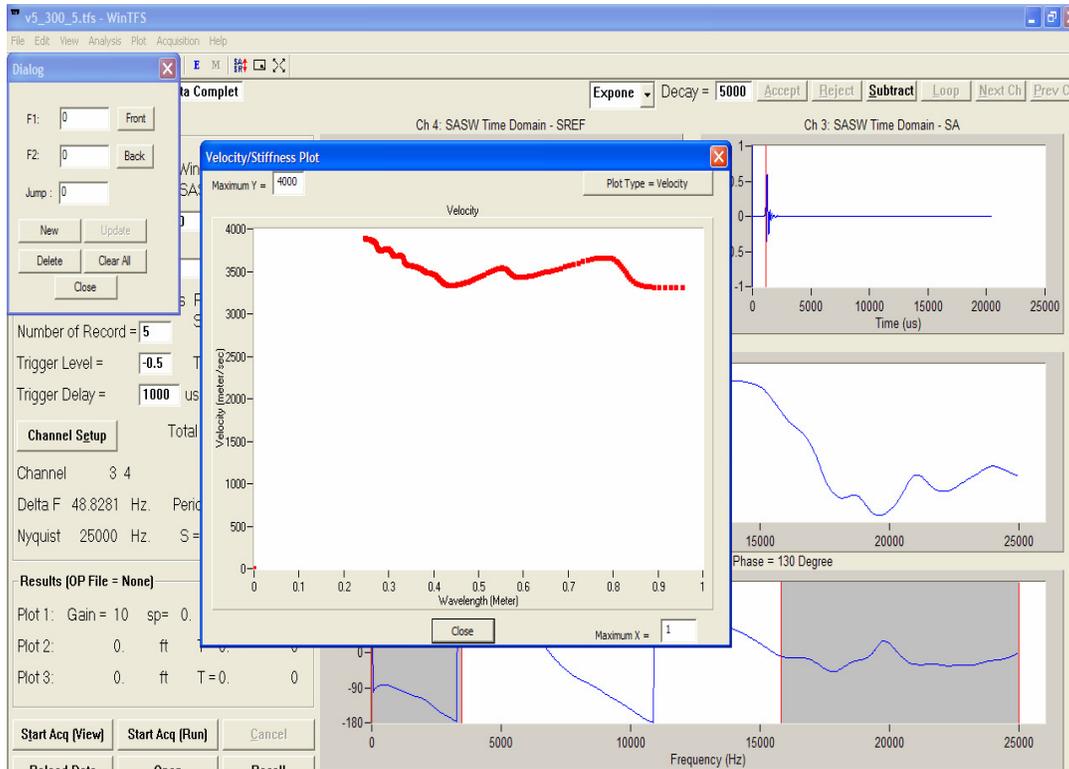




- 5. **Transducer/Accelerometer Spacing:** The spacing between the two transducers or accelerometers must be entered correctly to create a velocity plot. To change the spacing, go to “Analysis/Change SASW Properties”. Enter the correct spacing, Poisson’s ratio and density.



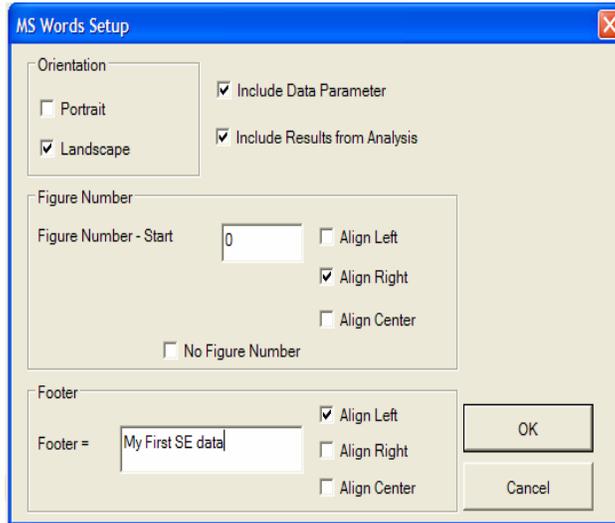
- 6. **Velocity Plot:** To view the dispersion curve (surface wave velocity versus wavelength), go to “Analysis/Velocity Plot”.



If the velocity plot shows an excessively high velocity, or is unrealistic, be sure to verify that the spacing data has been set correctly, and the masking is accurate.



- Data Export:** The plots can be sent to MS Word for printing. Go to “File/Send Plots to MS Word”. Then set up the orientation and figure number and click the “OK” button.



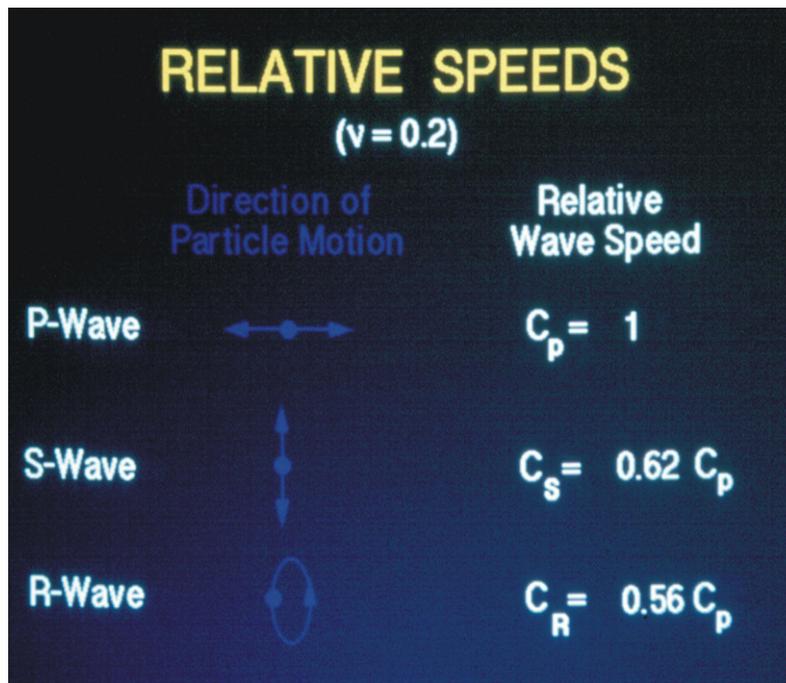
5.4 Output Files

While processing the TFS data, the software automatically generates the output files for WinSASW 124 and WinSASW 2.0 (or higher). The files' extension are *.coh, *.tf (for WinSASW 123) and *.hyx (for WinSASW 2.0 or higher).



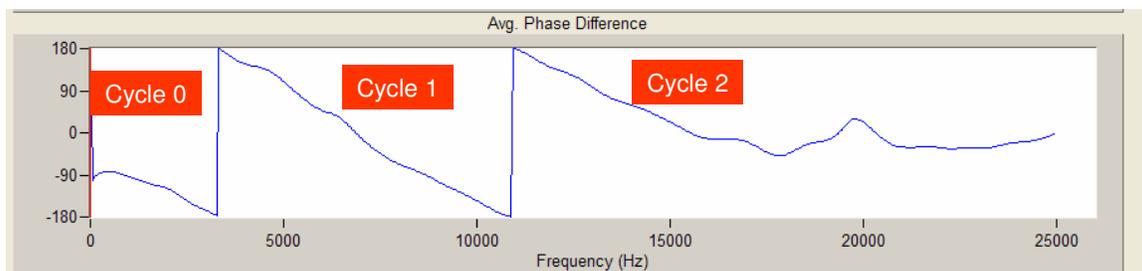
5.5 Additional Information for Data Analysis

Wave Speed: The SASW test is probably one of the most complicated of NDE tests. The test involves acquiring surface wave velocities. This is typically referred as the experimental data. For a single layer system, the shear (C_S) or compressional (C_p) wave velocities can be calculated from the surface wave velocity (C_R) obtained from the WinTFS software using the following relationships for concrete material.



However, a theoretical modeling software is required when working with a system that involves more than two layers (e.g. asphalt on top of concrete) to obtain the most accurate value of the shear and compressional wave velocities of each layer.

Phase Counting: Counting the Cycle or Jump is very important to obtain the correct dispersion curve (velocity versus wavelength). This section illustrates the assigned cycle for phase data.





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Non-Destructive Evaluation Scanning Techniques for Structural Components of Concrete Bridges

Yajai Tinkey, Ph.D., Olson Engineering, Wheat Ridge, CO
Larry Olson, P.E., Olson Engineering, Wheat Ridge, CO
Pat Miller, Olson Engineering, Wheat Ridge, CO

ABSTRACTS

This paper describes the state of the art of several Non-Destructive Evaluation (NDE) techniques used for quality control/assurance of structural components focusing on bridge decks, girders and columns in concrete bridges. The main objective of the NDE tests is to locate internal anomalies that cannot be observed by visual inspection of the bridge components. The paper summarizes the general background of the NDE techniques. The NDE techniques include Impact-Echo Scanning (IES), Spectral Analysis of Surface Waves (SASW), and Ultrasonic Pulse Velocity (UPV) tests. In addition, the paper includes the findings from a research project funded by the NCHRP – IDEA Program discussing the experimental results from studies using an Impact-Echo Scanner (IES) to detect and image grout discontinuities in post-tensioned ducts of a mockup full scale bridge girder. Comparisons of the IE defect interpretation and the actual design conditions of the ducts inside the bridge girder are presented. The IE test results are presented in a three-dimensional fashion using thickness surface plots to provide improved visualization and interpretation of the internal grout to void defect conditions inside the ducts of the girder.

Keywords: Condition Assessment, Bridges, Concrete, Post-Tensioned Bridges, Non-Destructive Evaluation, Internal Condition, Impact Echo, Ultrasonic Pulse Velocity,

INTRODUCTION

Several stress wave methods used for condition assessment of the superstructure of concrete bridges are discussed in this paper. The background, capabilities, and an example case history of selected nondestructive evaluation (NDE) methods applicable for the superstructures are presented herein. NDE methods for superstructures include Ultrasonic Pulse Velocity (UPV), Impact Echo (IE), and Spectral Analysis of Surface Waves (SASW) for quality assurance and integrity evaluations of decks, girders and exposed substructure. Recent innovations in Impact Echo Scanning (IES) technologies for evaluation of internal grout conditions in post-tensioned bridge ducts are also discussed. Most of the NDE methods discussed herein are also discussed in the two ACI 228 Nondestructive Testing Committee reports (ACI 228.1R-03 and ACI 228.2R-98).

Stress wave NDE methods can be used for quality assurance of new bridge decks and girders, or condition assessment of existing, aging bridge superstructure. The methods can provide data on the following concrete conditions: corrosion induced delaminations of deck and girder elements; thicknesses of concrete decks; fire and frost damage, internal void, cracking and honeycomb; concrete strength; and, void in post-tensioned ducts in girders. The following sections discuss the UPV, IE and SASW methods along with example results.

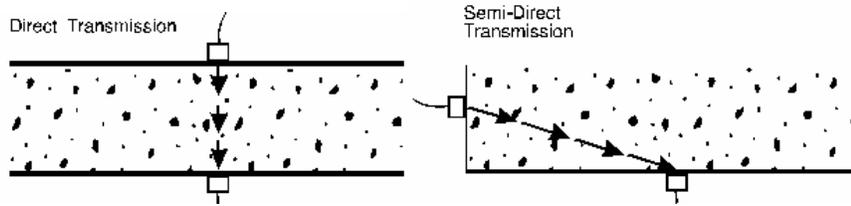
BACKGROUND AND APPLICATION OF NDE METHODS

This section outlines the background of the selected NDE methods applicable for the superstructure of concrete bridges and its applications. The NDE methods include UPV, IE, and SASW.

ULTRASONIC PULSE VELOCITY AND ULTRASONIC TOMOGRAPHIC IMAGING

The UPV method involves measuring compression wave velocity and amplitude in concrete by measuring the direct travel times and amplitude of compression waves (ASTM C597-02). In general, if couplings between the

transducers and concrete are good, low velocities and amplitudes indicate poorer concrete quality (or void or cracks). This method requires 2-sided access to the structure. Typically, two 54 kiloHertz UPV transducers used as a source and a receiver are greased-coupled to the concrete and placed at two locations on a structure with a known distance between them. A schematic of the UPV method is presented in Fig. 1



Applications of the UPV methods include condition assessment of concrete members with 2 accessible surfaces (such as girders and columns), internal flaw imaging and concrete strength prediction. For internal concrete condition assessment, the UPV method is based on the speed and amplitude of a compressional wave pulse and is used for determining material velocity and integrity conditions. Ultrasonic source and receiver transducers are placed on opposite ends of a given test path, and a signal is sent between them (see Figure 2). The signal travel time and attenuation provide information as to the concrete integrity along that signal path. Since this method uses a source and receiver to pass wave energy through a test member, it requires access to two sides of a member for evaluation of interior material conditions. A faster measured velocity in a given material generally correlates with greater strength and better integrity. The velocity (V) is calculated as the travel path distance (d) divided by time (t) and it is normally the compressional wave velocity, but shear transducers are available if the shear wave velocity is to be measured in the UPV test.

$$V = d/t \tag{1}$$

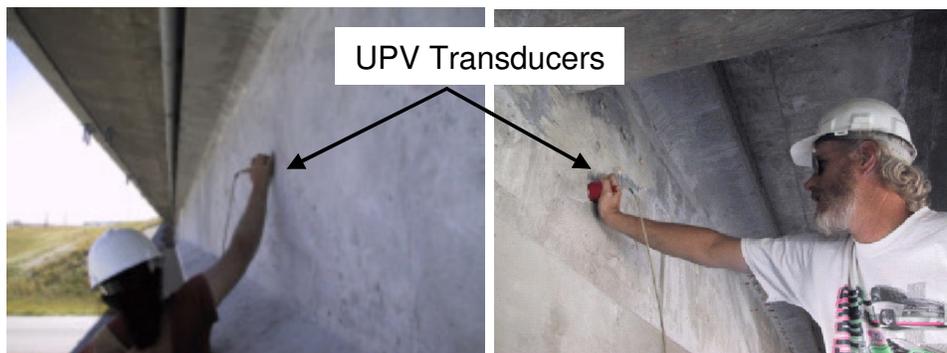


Fig. 2 UPV Tests on Concrete Girder of a Bridge

If anomalies are detected inside the concrete member, Ultrasonic Tomography (UT) can be performed for more information about the shape, size, location and severity of the suspected anomalies. UT is an imaging method analogous to CAT-scanning in the medical industry but uses acoustic waves rather than X-rays. UT data collection is intense and the procedure is relatively slow compared with UPV. In UT, many test paths are used to produce precise, detailed images of internal concrete conditions. The spatial resolution of UT is much higher than that of UPV and actual 2-D and even 3-D images of the internal concrete structure can be produced. Because of the higher resolution of the UT test, often more anomalies and smaller anomalies are identified in addition to those found with UPV tests.

For a concrete strength prediction application, the UPV tests measures the compressional wave velocity in concrete. This compressional wave velocity is related to Young's Modulus (E) and compressive strength for concrete ($f'c$) by the approximate relationship of (ACI 228.2R-98):

$$V^4 \text{ is proportional to } E^2 \text{ is proportional to } f'c$$

The exact relationship is best determined with multiple regression analyses of velocity measurements with compressive strength test results on cylinders (new concrete) or cores (existing concrete).

Strength predictions with UPV and other stress wave measurements have been performed on concrete, grout samples and foamed concrete materials and the authors have developed similar high quality correlations with multiple regression analyses for correlation of UPV and strength. An example linear regression correlation of UPV predicted strength is presented in Figure 3 below from tests on low density foamed concrete cylinders sampled from a bridge approach embankment for a DOT highway project.

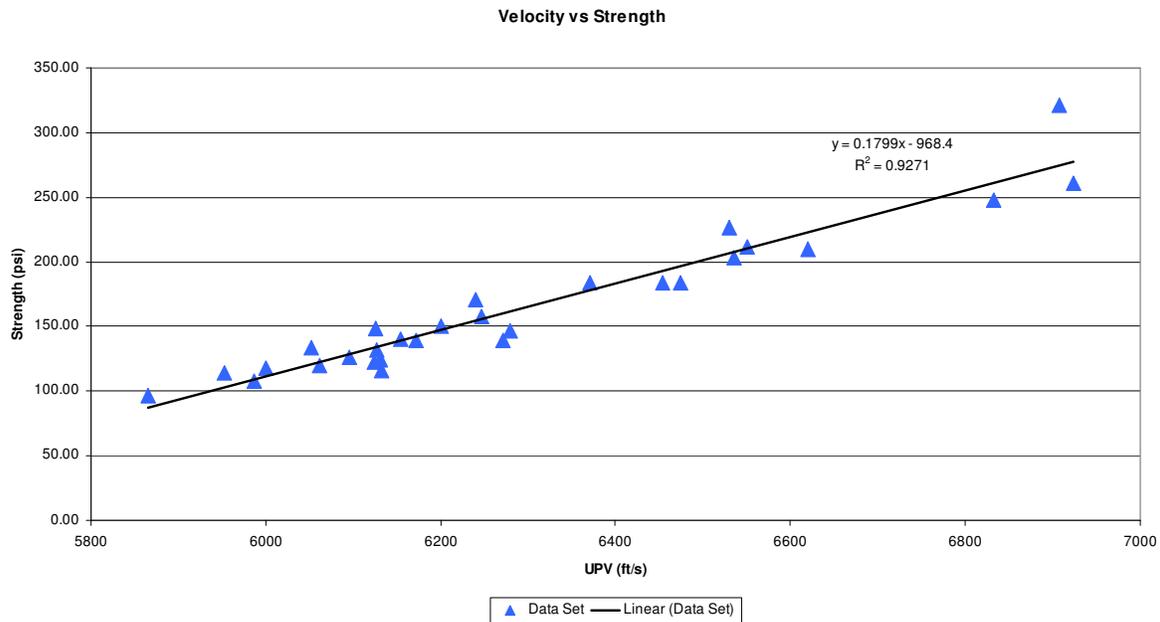


Fig. 3 Correlation of Ultrasonic Pulse velocity and Compressive Strength for Foamed Concrete Embankment 3x6 inch test cylinders

IMPACT ECHO

The Impact-Echo test involves dynamically exciting a concrete structure with a small mechanical impactor and measuring the resonantly reflected wave energy with a displacement transducer. The resonant echoes in the displacement transducer responses are usually not so apparent in the time domain, but are more easily identified in the frequency domain. Consequently, linear amplitude spectra of the displacement responses are calculated by performing a Fast Fourier Transform (FFT) analysis to determine the resonant echo peak frequencies in the frequency domain from the displacement transducer signals in the time domain. The relationship among the echo frequency peak f , the compression wave velocity V_p , and the echo depth D is expressed in the following equation:

$$D = \beta V_p / (2 * f) \quad (2)$$

where β is a shape factor which varies based on geometry. The value of β was found by theoretical modeling to be equal to ~ 0.96 for a slab/wall shape (Sansalone and Streett, 1997).

Impact-Echo Scanner

The Impact-Echo rolling Scanner was first conceived by the second author of this paper and subsequently researched and developed as a part of a US Bureau of Reclamation prestressed concrete cylinder pipe integrity research project (Sack and Olson 1995). This technique is based on the Impact-Echo method (Sansalone and Streett,

1997). In general, the purpose of the Impact-Echo test is usually to either locate delaminations, honeycombing or cracks parallel to the surface or to measure the thickness of concrete structures with typically one-sided access for testing (bridge deck thickness, pavements, floors, retaining walls, tunnel linings, buried pipes, etc.). To expedite the Impact-Echo testing process, an Impact-Echo scanning device has been developed with a rolling transducer assembly incorporating multiple sensors, attached underneath the test unit. When the test unit is rolled across the testing surface, an opto-coupler on the central wheel keeps track of the distance. This unit is calibrated to impact and record data at intervals of nominally 25 mm (1 inch). If the concrete surface is smooth, a coupling agent between the rolling transducer and test specimen is not required. However, if the concrete surface is somewhat rough, water can be used as a couplant to attempt to improve displacement transducer contact conditions. The maximum frequency of excitation of the impactor in the scanner used in research is 25 kHz. The impactor in the scanner can be replaced by a smaller impactor that generates higher frequency, if needed for applications with thickness less than 4 inches.

A comparison of the Impact-Echo Scanner and the point by point Impact-Echo Scanner unit is shown in Figure 4. Typical scanning time for a line of 4 m (13 ft), approximately 160 test points, is 60 seconds. In an Impact-Echo scanning line, the resolution of the scanning is about 25 mm (1 inch) between IE test points. Data analysis and visualization was achieved using Impact-Echo scanning software developed by the first author for this research project. Raw data in the frequency domain were first digitally filtered using a Butterworth filter with a band-pass range of 2 kHz to 20 kHz. Due to some rolling noise generated by the Impact-Echo Scanner, a band-stop filter was also used to remove undesired rolling noise frequency energy. Automatic and manual picks of dominant frequency were performed on each spectrum and an Impact-Echo thickness was calculated based on the selected dominant frequency. A three-dimensional plot of the condition of the tested specimens was generated by combining the calculated Impact-Echo thicknesses from each scanning line. The three-dimensional results can be presented in either color or grayscale.

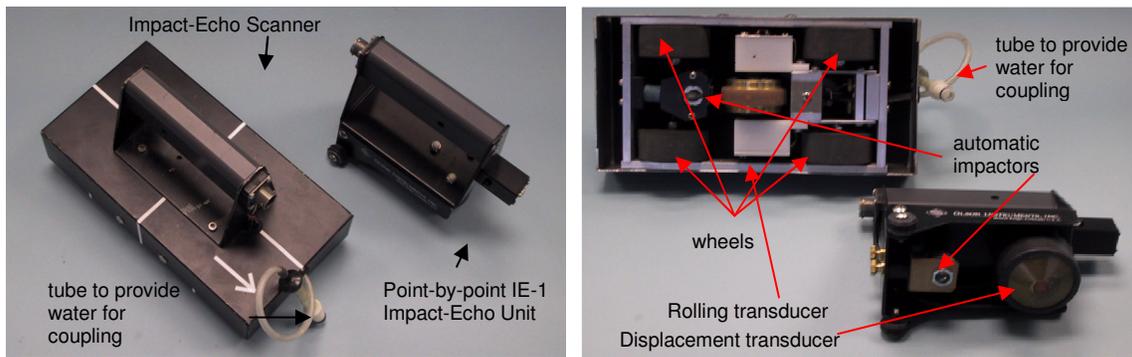


Fig. 4 Impact-Echo Scanner Unit and Point-by-Point Impact-Echo Unit

Impact Echo Application

Typical applications of IE tests include measurement of concrete thickness and its integrity where only one side access is available. In addition, recent research and consulting experience have shown that the IE tests can be used to determine the internal grout conditions of post-tensioned bridge duct in order to detect voids that could lead to corrosion (Tinkey et al, 2008).

The results from the NCHRP – IDEA research showed that localization of grouting discontinuities through Impact-Echo in the mockup girder as based on an analysis of variations in the Impact-Echo thickness echo depth/frequency. A direct echo from the void or duct wall, measured as an Impact-Echo frequency corresponding to the depth of the discontinuity (given by the formula in equation (2) above) has not yet been observed with the IE Scanner. However, as previously found by others, the IE results indicate the presence of well-grouted, filled tendon ducts by a nil to minor increase in apparent wall thickness over a grouted duct. Grouting defects (in this case, Styrofoam voids) inside the ducts cause a more significant increase of the apparent wall thickness in IE results as presented herein vs. well-grouted ducts). This is in accordance with the interpretation of the Impact-Echo signal as a resonance effect, rather than a reflection of a localized acoustical wave, i.e., the void may be simply thought of as a hole in the web

wall that due to decreased section stiffness causes a reduction in the resonant IE echo frequency and a corresponding increase in thickness. An example result from the research project and its description are included herein.

In this research project, a full scale pre-cast bridge girder (U-shaped) was donated to the research team for use in grout defect sensitivity studies. The length of the girder is 30.48 m (100 ft) with a typical wall thickness of 254 mm (10 in). There were four empty metal ducts (101.6 mm or 4 inches in diameter) inside each wall. The west end of the girder (6.1 m or 20 ft long) was selected for this study. Stepped and tapered Styrofoam rods (101.6 mm or 4 inches in diameter) were inserted into the ducts before grouting to form internal voids with sizes ranging from small to almost full diameter voids.

The IE Scanner results from the one of the web wall with the actual defect design of the top duct placed above the IE results of the top duct are shown in Figure 5 (presented in a thickness tomogram fashion). The results are interpreted to indicate that the grout defect started to appear at a length of 1.93 m (76 in) and becomes clearly evident at length of 2.92 m (115 in) from the west end of the duct. The location that the defect starts to appear corresponds to void with 11% depth lost or 20% circumferential perimeter lost. The location that the grout defect become more evident corresponds to void with 59% depth lost or 57% circumferential contact diameter lost. The dominant frequency of the fully grouted duct is approximately 6.4 kHz, resulting in an apparent Impact-Echo thickness of 28.37 mm (11.17 in.). The dominant frequency shifted downward to approximately 5.37 kHz for an empty duct, which corresponds to an apparent Impact-Echo thickness of 340 mm (13.4 in). This is a relatively large thickness shift of over 30% compared to the nominal thickness of the wall. The interpretation of the Impact-Echo Scanner results, however, shows a downshift in frequencies from lengths of 5.49 to 6.1 m (216 to 240 in), indicating voids at duct locations where no discontinuities were intentionally placed. It is likely that grout did not flow into the higher east duct end due to the big voids in front of it.

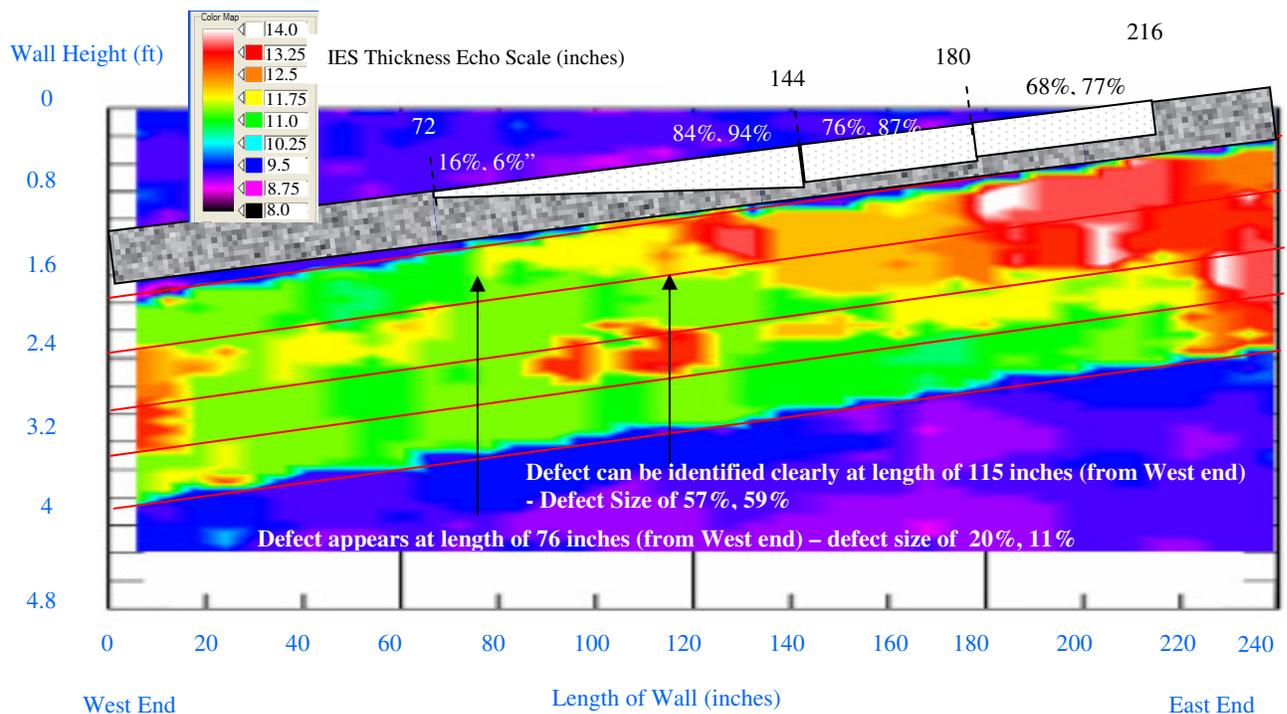


Fig. 5 – IE Results from the South Wall with Actual Design Defects of Top Duct

SPECTRAL ANALYSIS OF SURFACE WAVES

One stress-wave based NDE method, which has recently been applied to structural and geotechnical testing, is the SASW method (Bay and Stokoe, 1990). This is based on a similar procedure used for the determination of shear moduli profiles at soil sites (Stokoe et al, 1988) and Young's moduli profiles at pavement sites (Nazarian and Stokoe, 1985). The method relies on the dispersion characteristics of surface waves.

In SASW tests, two receivers (or more) are placed on the surface of the structural member surface to monitor the passage of surface waves due to an impact from a source placed at distance from Receiver 1 equal to the distance between the two receivers. Figure 6 shows a SASW test setup on a bridge deck. A digital analyzer is used to record the receiver outputs for spectral (frequency) analyses. The result of the analysis is a plot of the phase difference between the two receivers versus frequency. A dispersion curve (surface wave velocity versus wavelength) is calculated from the phase plot using the following equations:

$$t = N/360 \quad (3)$$

$$V_R = X/t \quad (4)$$

$$\delta_R = V_R/f \quad (5)$$

where t = Time, V_R = Surface Wave Velocity, X = distance between receivers, δ_R = Wavelength, N = phase shift of the cross power spectrum in degree and f = Frequency.



Fig. 6 SASW investigation on concrete bridge deck with hand-held IE/SASW gauge

The final process in SASW testing is the forward modeling process to determine the shear wave velocity profile. The forward modeling process is an iterative process, and involves comparing the actual dispersion curve with a theoretical dispersion curve calculated from an assumed shear wave velocity profile.

To illustrate the use of the SASW test method, concrete SASW results from the aforementioned bridge deck are presented in Fig. 7. The SASW method is a more complicated method for analysis, but field data acquisition can be straightforward for concrete pavement/bridge deck thickness evaluation when SASW tests are combined with IE tests by using the gauge shown in Fig. 6. The SASW method can uniquely evaluate fire damage, frost damage, perpendicular cracks and concrete quality/strength with 1-sided access (ACI 228.2R-98).

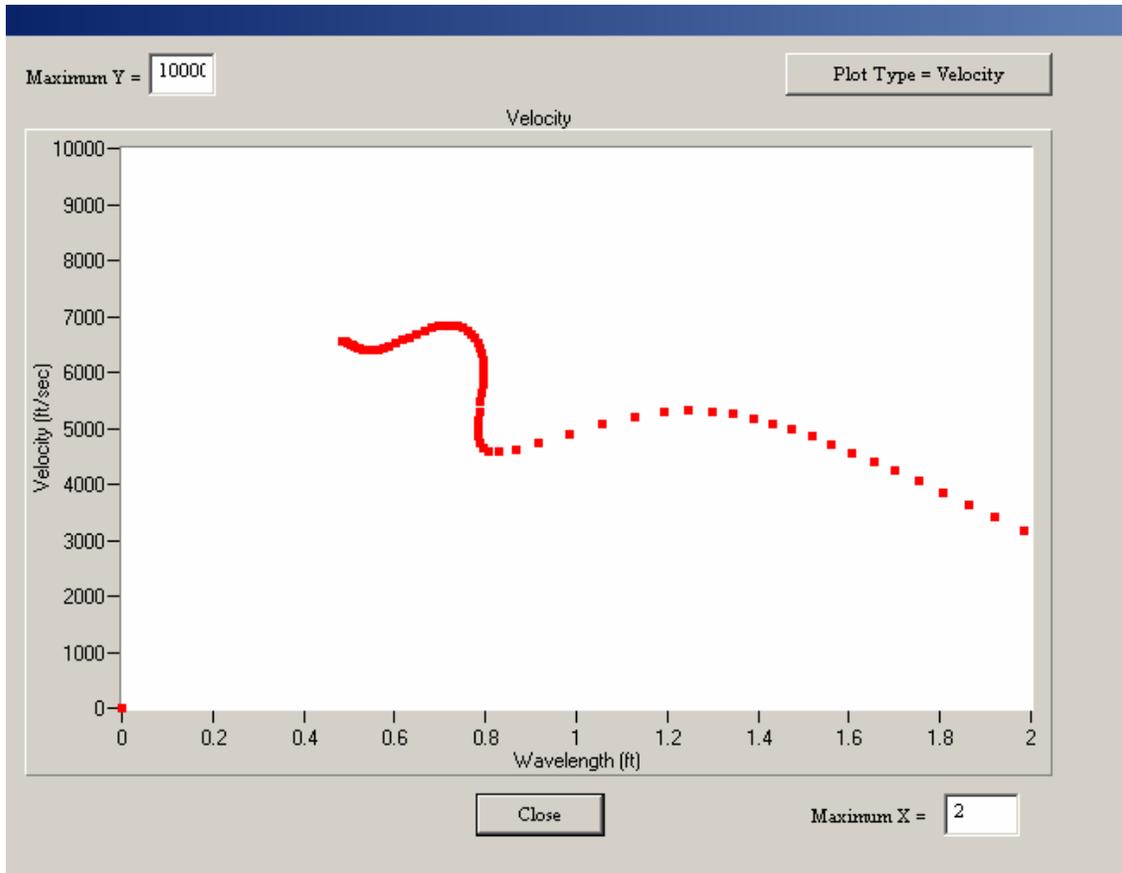


Fig. 7 SASW velocity plot showing approximate thickness = 0.8 ft, surface wave velocity = 6,500 ft/s.

SUMMARY

Non-destructive Evaluation (NDE) techniques have a distinct advantage of leaving the tested concrete member intact while acquiring the information on its internal integrity. As well as the obvious benefit of no damage from NDE, the use of multiple NDE methods also allows for testing of multiple possible problem causes and increased confidence in the results. Finally, a non-destructive test facilitates the investigation of potentially damaged concrete when there is no visible surface evidence that a problem exists. Each NDE method is applicable overlapping and different types of application and each method therefore has its limitations. Combining the findings from different NDE techniques can help to provide a better interpretation of the results and a more accurate condition of the tested member. Interpretation of the results from the NDE tests can be subjective and depends significantly on the experience of the interpreter. NDE results are often used to target cores or other destructive investigation methods to better characterize areas identified as having sound, questionable or poor/damaged concrete conditions. Proper use of NDE methods will help identify the internal conditions of concrete bridge components which results in improved diagnosis of damage/flaws for planning of repairs and improved bridge safety. The IE Scanning technique allows for more complete NDE of concrete bridge decks and girders. The authors are currently conducting an NCHRP – IDEA research study on bridge deck scanning using both contacting and non-contacting transducers to take another step towards scanning based imaging of internal bridge deck conditions in terms of concrete problems such as delamination due to reinforcing corrosion and internal cracking.

REFERENCES

ACI 228.1R-03, "In-Place Methods to Estimate Concrete Strength," American Concrete Institute Manual of Concrete Practice, Part 2.

ACI 228.1R-98, "Nondestructive Test Methods for Evaluation of Concrete in Structures," American Concrete Institute Manual of Concrete Practice, Part 2.

ASTM C 597-02, "Standard Test Method for Pulse Velocity through the Concrete," Annual Book of ASTM Standards, Vol. 04.02, ASTM, pp. 317-320.

Bay, J.A. and K.H. Stokoe, II, Field Determination of Stiffness and Integrity of PCC Members Using the SASW Method. Proceedings of Nondestructive Evaluation of Civil Structures and Materials Conference, University of Colorado at Boulder, 1990.

Nazarian, S. and K.H. Stokoe, II, In Situ Determination of Elastic Moduli of Pavement Systems by Spectral-Analysis-of-Surface Waves Method (Practical Aspects). Research Report 368-1F, Center for Transportation Research, The University of Texas at Austin, 1985.

Sack, D.A. and L. D. Olson, "Impact Echo Scanning of Concrete Slabs and Pipes," CANMET/ACI International Conference on Advances in Concrete Technology, Las Vegas, Nevada, June 11-14, 1995.

Sansalone, M. J. and Streett, W. B., "Impact-Echo Nondestructive Evaluation of Concrete and Masonry", ISBN: 0-9612610-6-4, Bullbrier Press, Ithaca, N. Y, 1997 339 pp.

Stokoe, K. H., II, S. Nazarian, G.J. Rix, I. Sanchez-Salinero, J.C. Sheu and Y.J. Mok, In Situ Seismic Testing of Hard-to-Sample Soils By Surface Wave Method. Proceedings, American Society of Civil Engineers, Specialty Conference on Earthquake Engineering and Soil Dynamics II- Recent Advances in Ground Motion Evaluation, Park City, Utah, 1988, 264-278.

Tinkey, Y. and Olson, L.D., Sensitivity Studies of Grout Defects in Post-Tensioned Bridge Ducts using Impact-Echo Scanning Method", Journal of Transportation Research Board, to be published in 2008