

SYSTEM REFERENCE MANUAL 2012



SPECTRAL ANALYSIS OF SURFACE WAVES TEST SASW-S/SASW-G NDE-360

NDE-360 Platform with WinTFS Software Version 2.6





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1.0 INTRODUCTION

The structural version of **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 the measure relative concrete quality. It can also be used for thickness profiling of pavements, including asphalt and layer systems. The method uses the dispersive characteristics of surface waves to determine the variation of the shear wave velocity (stiffness) of layered systems with depth. Surface opening cracks, honeycomb zones, fire damage, and other flaws with create an effective "layer" of low velocity material with a depth which can be measured. Once the shear wave velocity profiles are determined, shear and Young's moduli of the materials can also be estimated through the use of simple mathematical equations. 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. 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 attachments and source impacting.

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 pavement system profiles including the surface layer, base and subgrade materials
- 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

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

The geophysical version of **Spectral Analysis of Surface Waves (SASW-G)** method is applied to soil and rock to measure the shear wave velocity profile versus depth into the ground. This in turn allows the estimation of soil modulus values versus depth for foundation design and other soil profiling requirements. Note that this type of soil profiling can be done **WITHOUT** the use of a borehole or other probing device. The method uses the dispersive characteristics of surface waves to determine the variation of the shear wave velocity (stiffness) of layered systems with depth. Once the shear wave velocity profiles are determined, shear and Young's moduli of the materials can also be estimated through the use of simple mathematical equations. The shear wave velocity profiles (shear wave velocity versus depth) are determined from the experimental dispersion curves (surface wave velocity versus wavelength)



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obtained from SASW measurements through a process called forward modeling or through an inversion process. The SASW method can be performed on any relatively flat or constant slope profile, including through slabs, parking lot pavements, across roadways, etc.

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

- Determination of soil shear wave velocity profile versus depth
- Location of sub-surface soft zones and voids (such as at land fills or other fill sites)
- Thickness measurement of fill and rock layers
- Determination of abutment depths of bridges
- Condition assessments and characterization of mass concrete (dams, mat foundations, etc.)

Material Tested: Soil, Rock, Concrete, Asphalt

1.1 Organization and Scope of Manual

This operation manual for the SASW test with the NDE-360 system manufactured by Olson Instruments includes all required instruction for the use of the hardware and software included with the system. Also included at the end of the manual is a troubleshooting guide for the system to help overcome any problems experienced or answer any questions. 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

Introduction to the SASW Test Method. 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. Shear wave velocity profiles can be determined 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.

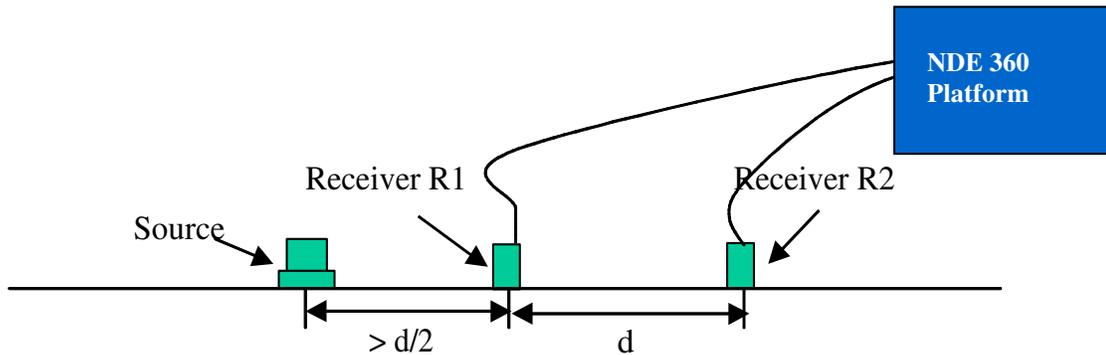
The SASW method requires an accessible surface for receiver attachments. The extent of the accessible surface limits the investigation depth. As a rule of thumb, if one is interested in material properties to a depth of D , then the accessible surface should extend in a line of receivers direction to a distance equal to $1.5D$, preferably $2D$. The figure below shows the general field arrangement used in SASW testing.



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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):

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

$$\text{Shear Modulus: } G = \rho V_s^2 \quad (2)$$

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

$$\text{Constrained Modulus: } M = \rho V_p^2 \quad (4)$$

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

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

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



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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:

$$V_R \sim 0.9 V_s \quad (7)$$

(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 (3) inversion (forward modeling) of the theoretical dispersion curve, if desired, 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:

$$V_R = f * \lambda \quad (8)$$

When the velocity is uniform, the wavelength of the waves is the investigation depth. Forward modeling is most commonly done to determine seismic velocity profiles for earthquake and vibrating machine foundation design purposes.

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:

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

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 NDE 360 platform in the field to ensure that acceptable data is being collected, although only a limited fixed window is applied. This means that final data quality of the phase plot will almost always be better after full office post-processing when compared to the field data. The phase data is typically then returned to the office for processing using the WinTFS 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 a value near 1.0 indicates good quality data. However, acceptable phase data may have comparatively low coherence.



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After masking of all forward and reverse phase record pairs from each receiver spacing, 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. 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 the WINSASW software of 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.



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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.
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2.0 HARDWARE

The SASW system with the NDE-360 platform consists of several basic components packaged into a padded carrying case. The padded case stores the NDE-360 data acquisition platform, power supply, battery charger, SASW bar and hammers (for SASW-S systems), geophones (for SASW-G systems) and cables. Note that for SASW-G systems with 1 Hz geophones, a separate case for the geophones may be required. A description of each of these components as well as their connection and operation is included in the following sections.



2.1 Hardware Component Listing

Component Name	QTY	Description
 1) Olson Instruments NDE-360 Platform	1	Platform for data acquisition, analysis and display of SASW time domain data
 2) SASW Bar (SASW-S only)	1	The SASW bar includes two displacement transducers connecting with a bar in a line.
 3) Cable (SASW-S only)	1	To connect the SASW bar and the NDE-360



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Component Name	QTY	Description
 <p>4) Hammer (SASW-S only)</p>	1	1 set of hammers (2 hammers)
 <p>5) 4.5 Hz Geophone (SASW-G only)</p>	2	A pair of 4.5 Hz geophones are used with an SASW-G system to measure surface waves at closer spacings (usually 20 feet and less)
 <p>6) 1.0 Hz Geophone (SASW-G only)</p>	2	A pair of 1.0 Hz geophones are used with an SASW-G system to measure surface waves at longer spacings (usually greater than 20 feet out to over 300 feet)
 <p>7) Phone Plug to 4 Pin Adaptor</p>	2	To connect the geophones to the NDE-360 input connectors



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	1	Power supply/battery charger to power the NDE360 and charge the battery
	1	To transfer the SASW data files to the analysis computer
9) Card Reader and Compact Flash Card		



2.2 Basic Components and Maintenance of NDE-360 Platform

Battery Charging: The power supply/charger (Item 8) must be plugged into the line voltage supply (110/220 VAC) using the correct plug adapter. The other end plugs into the NDE-360 next to the CF card slot. The battery is charged when the light on the charger unit blinks at a slow, steady rate.



Time required for a fully charge of battery is 8 hours. Fully charged battery will power the NDE-360 system for 8 – 10 hours.

Location of Battery: The panel housing the battery is located on the back of the NDE-360 system. Move the switch to remove the battery cover if battery needs to be replaced.



Do not expose the NDE-360 system or the battery to water.



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Channel Arrangement: The NDE-360 system is equipped with 4 channels. There are two 4 pin connectors per each channel. Channel 1 is located on the right hand side if facing the front screen of the NDE-360 system. In the case of the SASW-S, the system uses the IE/SASW Channel. Thus four 4 pins channel will not be used for the SASW-S system. The SASW-G will NOT use the IE/SASW connector, and will instead use the 4 pin connectors for Channels 1 and 2





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Data Storage: A compact flash card is used to store the SASW data files (in a subdirectory called NDE360/). In addition, the master program controlling the SASW test is stored in the compact flash card (in “tern_app.bin”). The system must start up with the compact flash secured in place. The card should be located on the left side of the NDE-360 system if looking at the front screen.



If the compact flash card is missing from the system, the system will not allow the test to continue. Do not remove the compact flash card while the system is turned on.

NDE-360 Operation Notes: The NDE-360 system is a self-contained data conditioning, collection, basic processing and data display platform usable for a number of types of NDT tests. The system was designed to make it user friendly and easy to handle and operate by a single operator. The main screen can be navigated using a touch screen feature.



Never impact the screen with any sharp object!

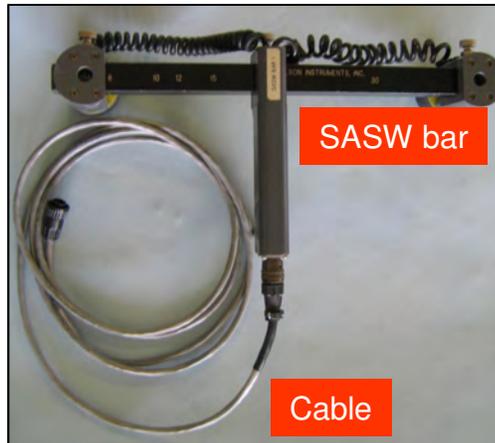


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2.3 Hardware Setup – SASW-S with Bar

1. Connect the cable (Item 3) to the SASW bar (Item 2) by aligning the pin on the cable with the corresponding hole in the end of the SASW bar



2. Connect the other end of the cable to the IE/SASW Channel on the NDE-360

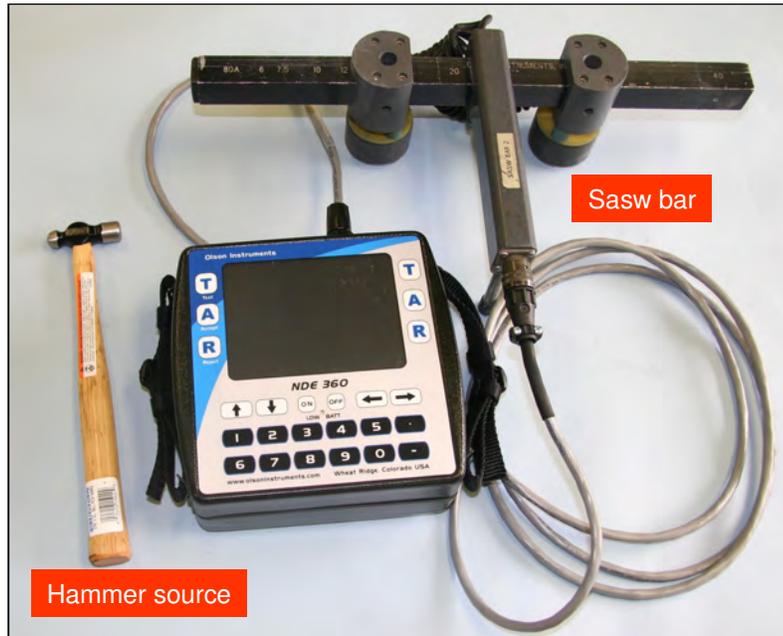




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- The picture below shows a complete hardware setup for the SASW test.



- The picture below shows the complete SASW system with the SASW bar on top of a concrete slab (ready to acquire data) and a small hammer being used as a source.





2.4 Hardware Setup – SASW-G with Geophones



IMPORTANT – NEVER MOVE THE 1 Hz GEOPHONES WITHOUT FIRST DISCONNECTING THEM FROM THE NDE-360. IF THE GEOPHONES ARE MOVED ABRUPTLY, DAMAGE TO THE NDE-360 COULD RESULT

1. First, identify the flat, open area where testing is to take place, and mark the centerline with a flag, paint, or other means. Ideally, the centerline should be centered over the area of interest but with enough room on either side to mount the geophones in a line with a spacing equal to 2 times the depth required.
2. Next, connect the 4-pin yellow adapter cables to the phone plug connections on each geophone cable. Push the phone plug into the jack fully, as shown below. It doesn't matter which phone plug connects to which adapter cable.



3. Next, position the geophones at the appropriate spacing for the test being conducted. Typically, 4.5 Hz geophones are used for soil tests at spacings of up to 20 feet, and 1 Hz geophones for any spacings longer than that.

IMPORTANT - Do NOT move the 1 Hz geophones with the cables connected to the Data PC input module. ALWAYS disconnect the cables before moving the geophones, or damage to the amplifiers could result. The 1 Hz geophones have built-in voltage limiter protection circuits, but could still produce a damaging voltage spike if moved very abruptly or dropped. The geophones are spaced out using a tape measure (or two tape measures measuring out from the center point). Use spikes for soil or grease/sandbags for pavement sites (as shown below)





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4. Next, connect the 4 pin adapter cables from each geophone being used to the “wide band” connection for the input channels set up for data collection. Normally, these will be channels 1 and 2. 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 connector. The geophone closest to the impact location should be connected as the trigger channel.
5. Make sure all connections are secure at this time. The hardware setup for the acquisition system is now complete. Surface wave energy is generated by a variety of sources, depending on the wavelengths (depths) required. For spacings out to 20-40 feet, various sized sledge hammers are used. For spacings of 40 to 100-120 feet, a 40-80 lb drop weight can be used, depending on soil surface type. A 6x6 inch wooden beam of 6 to 8 feet in length dropped on it’s end from 2 feet up has been used very successfully for this spacing range. For longer spacings, heavy equipment (cranes or bulldozers) is usually required for large drop weights or for driving back and forth to excite the ground surface.



Typical SASW-G test setup for a close-spacing test using 4.5 Hz geophones on pavement



Before moving on to Data Acquisition, Section 3, it is critical to record the geophone spacing for each test. This will be used later in the analysis

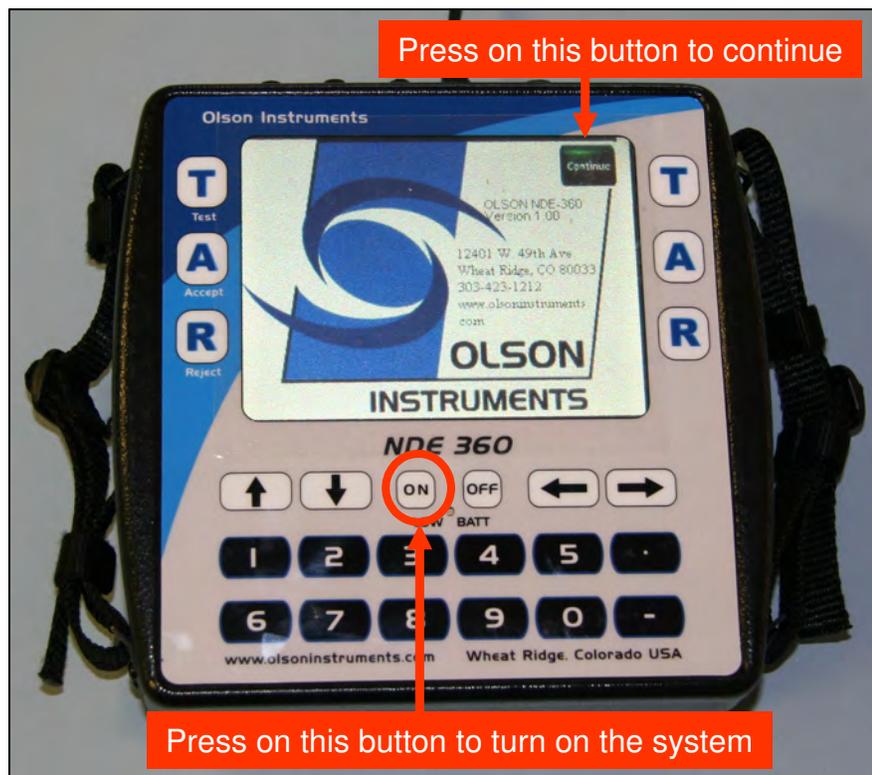


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3.0 SASW DATA ACQUISITION

1. Turn on the NDE-360 system (with the hardware in Section 2.0 connected). Make sure that the compact flash card is secured in place. The master software to run the system is located in the compact flash card. Press on the “Continue” button on the upper right corner of the screen. If the compact flash card is not in place, the “Continue” button will not appear on the screen.



If the continue button disappears from the screen, turn off the system and insert the compact flash card in place and turn the system on again.



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2. Press on the “SASW” option. The option included in the unit may be different depending on the order. The picture below shows the screen with SE (Sonic Echo), IE (Impact Echo), SASW, Slab IR (Slab Impulse Response), SE/IR (Sonic Echo/Impulse Response) and UPV (Ultra Sonic Pulse Velocity) options.

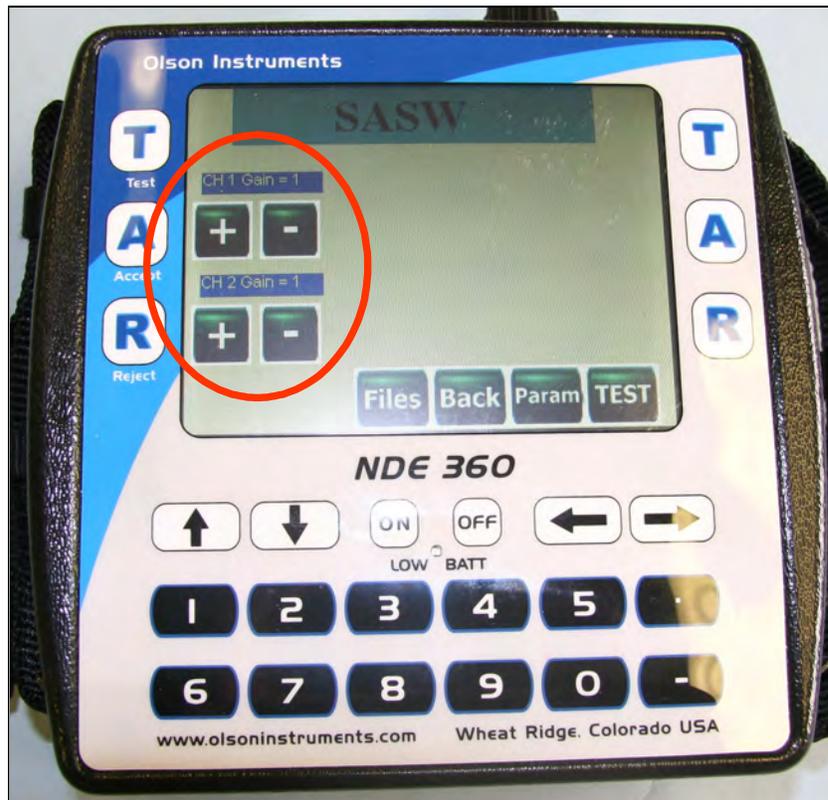




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- The system is ready to acquire data. In the SASW test, the initial gain will be automatically set to 1. If higher gain is required, simply press on the + button of the gain for Ch 1 and Ch 2 (or Ch 1 and Ch 4 for the SASW-S Bar). Typical starting gain for SASW-S tests on concrete or masonry is between 1 – 100. For SASW-G tests on soil, gains of 10-1000 are typically used (depending on the spacing and soil type).



- The system is loaded with a default parameter set that is applicable for most SASW-S tests. However, if the parameters need to be adjusted, press the Param button. In the parameter setup screen, the user can change the following parameters by touching the button to toggle the value. Touch the “Back” button after the parameter setup is complete.
 - Change Units. The “M” or “E” button changes the current units (for spacing) from English to Metric and back.
 - Change Date/Time. This option allows the user to enter the correct date and time of testing
 - Time/Point or Sampling Rate means how often (in time domain) the system will acquire data points within a given data trace. In the case shown in the picture below, the Time/Point was set at 20 microseconds. This means the system will acquire data at 20 microsecond intervals. **This**



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parameter can not be changed after the data was taken. Note: For SASW-S, Usually 7 or 20 microseconds are used. For SASW-G testing, typical time/point settings will be 20 or 50 microseconds for closer spacings (less than 10 feet), 100 microseconds for 10-40 feet, and 200 or 500 for the longer spacings of greater than 40 feet. The ideal time/point will depend on the soil velocity as well as the spacing, but the exact setting is not critical for obtaining usable data.

- Points Per Record 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. **This parameter can not be changed after the data was taken.**
- Spacing. This is the distance between the two displacement transducers on the SASW bar or the two geophones for SASW-G tests. Entered in inches or mm.
- # Recs. Number of Records is the total number of SASW data records you want to average and save. **This parameter can not be changed after the data was taken.**
- Pre-Trigger is number of points before the triggering point that data collection starts. This parameter is typically set to be 1/10 – 1/4 of the record size. **This parameter can not be changed after the data was taken.**
- Trigger Level % is the minimum signal amplitude (in terms of percentage full scale) to trigger data acquisition. In this case, the trigger level was set at 6%. Therefore, the system will start acquiring data once the absolute amplitude of the signal exceeds 0.6 volt. **This parameter can not be changed after the data was taken.**
- Channel Setup. For the SASW test, two channels (connected to the SASW bar or the geophone pair) will be used. Ch 1 and Ch 4 MUST be turned on for the SASW-S test and this cannot be changed. For geophones, and combination of the 4 channels can be used, but channels 1 and 2 are recommended.

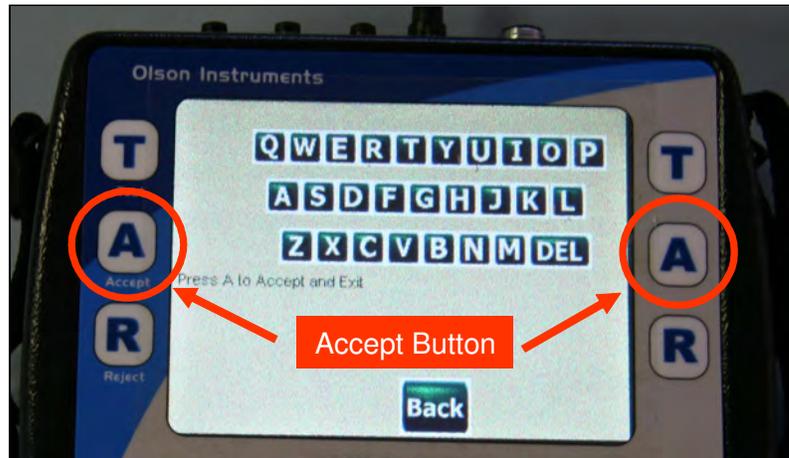




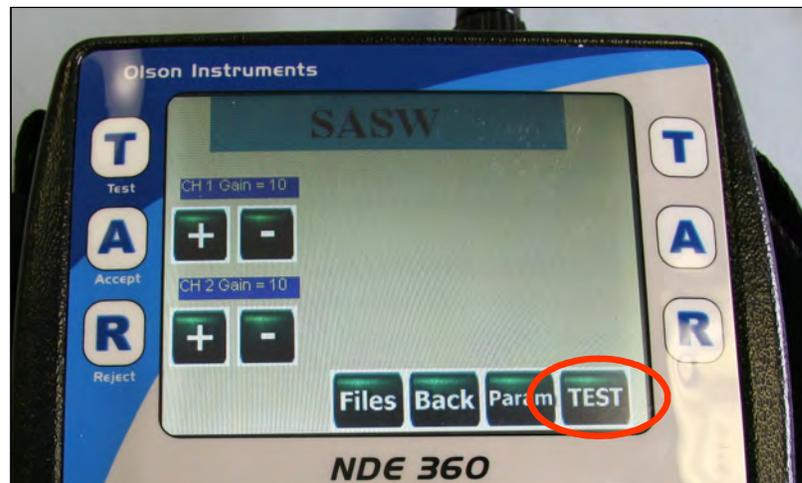
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- The filename arrangement of the NDE-360 uses a fixed prefix of letters and a suffix of number. The prefix can be set at the beginning of any test. If the prefix is not changed, a higher suffix number will be added to the current prefix for the new filename. To change the prefix, press on the “Files” button and press number 5 and then number 1. Then a virtual keyboard will appear on the screen and the user can change the prefix part of the filename. Press the “A” button on either side to accept the new prefix of the filename.



- After the parameter setup is complete press the “Back” button to return. Now the system is ready to take the SASW data. For SASW-S use, push the SASW bar on the tested member and press “Test” button to acquire the SASW data. For SASW-G use, simply press “Test” once the geophones are properly placed and connected to the NDE-360



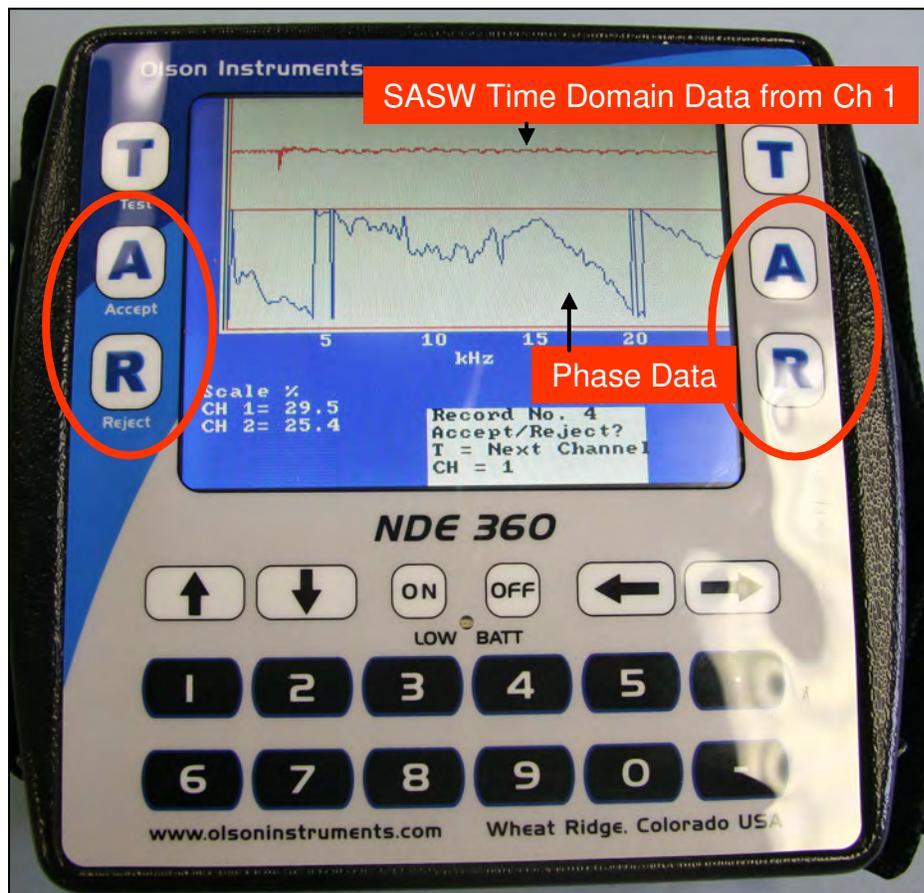


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7. For either type of SASW system, collect data by impacting the test surface with the impact source (hammer, drop weight, etc.) in the line of the SASW receivers. The location of the impact should be approximately $0.5d - d$ away from the transducer. Note that d = Spacing between the transducers.

Once the data is collected, a time domain SASW data from Ch1 will be displayed on the top trace and the calculated phase data between the data from the two channels will be displayed on the second trace. Accept or Reject the data on the screen. Note that the SASW test typically is done with multiple waveforms collected and averaged at each test location – typically 4-7 records. (This is set up in the parameter setup).



Automatic fixed, simple time domain windowing is applied to the time domain data

8. Repeat Step 7 until all the records are collected.
9. After all the records are collected. Press “2” to save the data or “1” to exit without saving.



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10. To perform more SASW tests, repeat Steps 7 – 9.
11. The data can be recalled in the NDE-360 system by pressing the “File” button on the main screen and then select Option 2.
12. The data files on the compact flash card must be moved to the analysis computer for post-data analysis.

3.1 Additional Information on the Data Collection

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). Sources for SASW-G tests include sledge hammers, wooden beam drop weights, concrete or rock drop weights, and heavy equipment moving back and forth. Short receiver spacings (SASW bar) are used to sample the shallow layers while long receiver spacings (typically geophones) are used in sampling the deep materials (soils). The source and receiver signals are recorded by an NDE 360 Platform with the SASW-S or SASW-G options 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 sides 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).



4.0 WinTFS Software

This section covers step-by-step instructions for post data analysis and output generation for the Windows WinTFS software.

4.1 WinTFS Software Installation

1. Prerequisite software (NIDAQ version 7.4 or higher) prior to installing the WinTFS software is required. The NIDAQ drivers can be located in the enclosed CD or downloaded at:

<http://joule.ni.com/nidu/cds/view/p/id/319/lang/en>

If retrieving files from the web, download the file named NIDAQmx8.1.ZIP. Unzip the file and install the NIDAQ program. Note that an account (free of charge) may be required to proceed to the download page.



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

2. Uninstall the previous version of WINTFS (if installed) or delete “c:\program files\olsoninstruments\WinTFS\WinTFS.exe” if the older file exists
3. Run “Setup.exe” from the Olson Instruments install 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\ . The shortcut to the WinTFS.exe can be located on the desktop.



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

4.2 Software Updates

For updates to software, the only file that is necessary is the 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. Simply replace the existing WinTFS.exe by copying and pasting the new version into the directory.

4.3 Software Uninstallation

The followings are steps to uninstall the WinTFS Software



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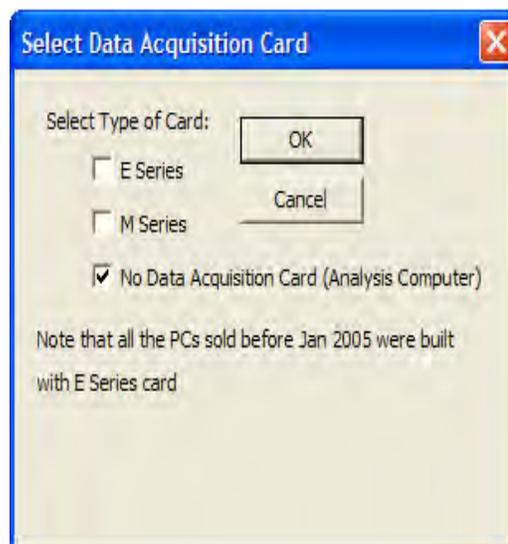
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1. Click on Start/Settings/Control Panel
2. Select "Add/Remove Programs"
3. Highlight WinTFS, select "Remove"
4. The uninstall process will begin automatically, removing all installed components including the shortcut.

4.4 First Time Executing the WinTFS Software

If the WinTFS software is executed for the first time, the program detects 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. Select the "Software Key" button and then enter the software key attached to the case of the installation disk. Exit the software and restart the software.

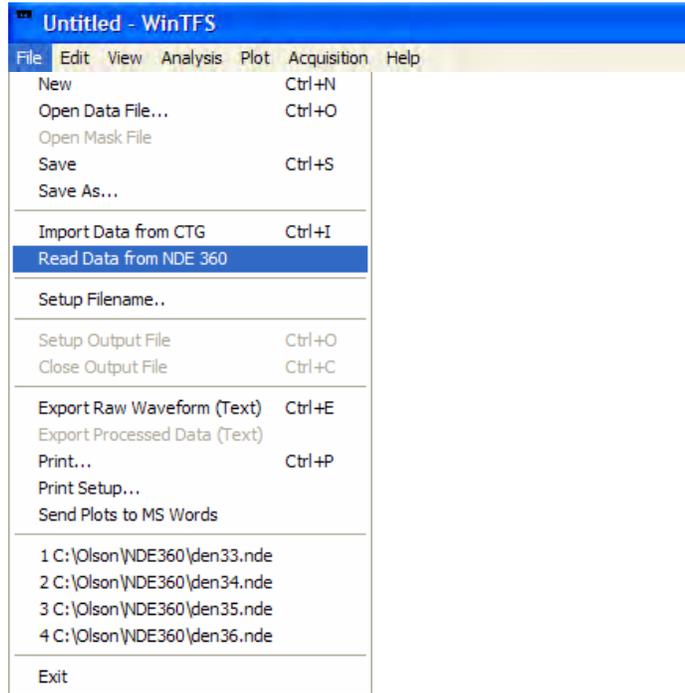
Now the software will detect missing parameter file (SASWdefault.prm file) and then will automatically generate a default file. The user will notice an applet shown below for the type of acquisition card. Select "No data Acquisition Card" option to continue.





4.5 Data Analysis with WINTFS

1. **Read the Data file:** To read the data file, go to File/Read Data from NDE-360 and select the filename to analyze.

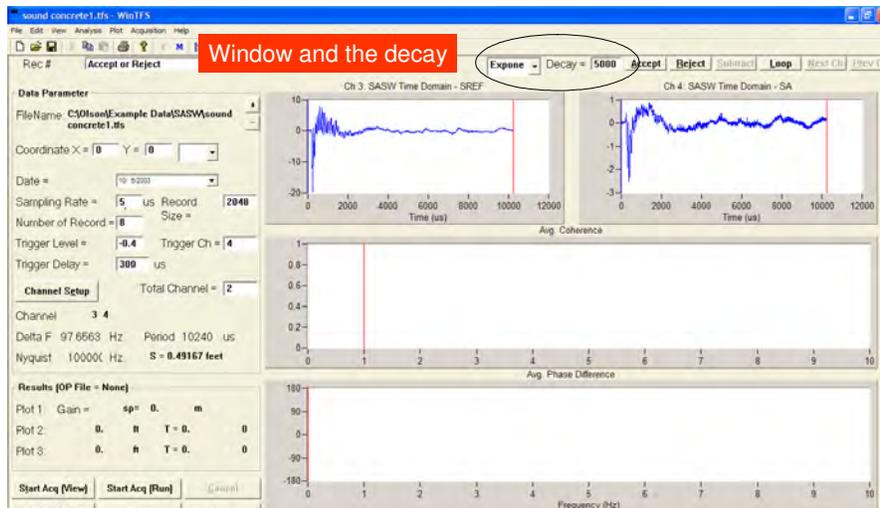


2. **Windowing Data:** The surface wave has the largest amplitude and is the front of the waveform package acquired from the SASW tests. Time domain filtering is required to eliminate the back part of the waveform so that the non-surface wave is not included in the analysis. A typical window used in the analysis of SASW-S data is “Exponential” or “Hanning” with a decay of 1000 – 5000. For SASW-G data, often no windowing is required, or an exponential window with a decay of 200-500 may be used. For data collected with a continuous source (such as a bulldozer driving back and forth) a Hanning window is normally used. The following is a summary of each window.

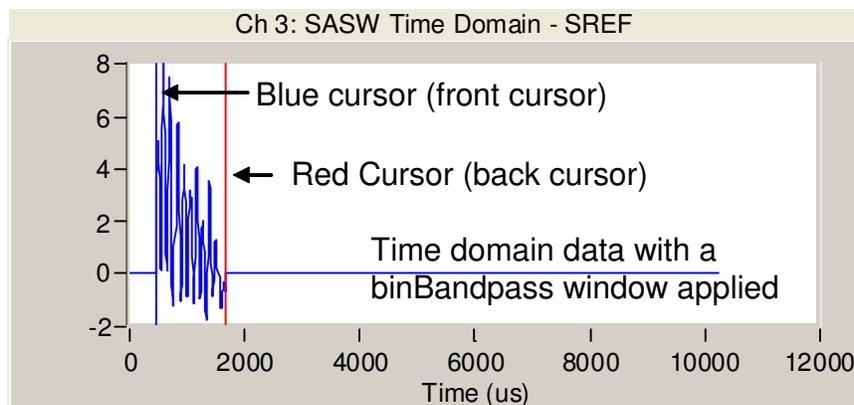
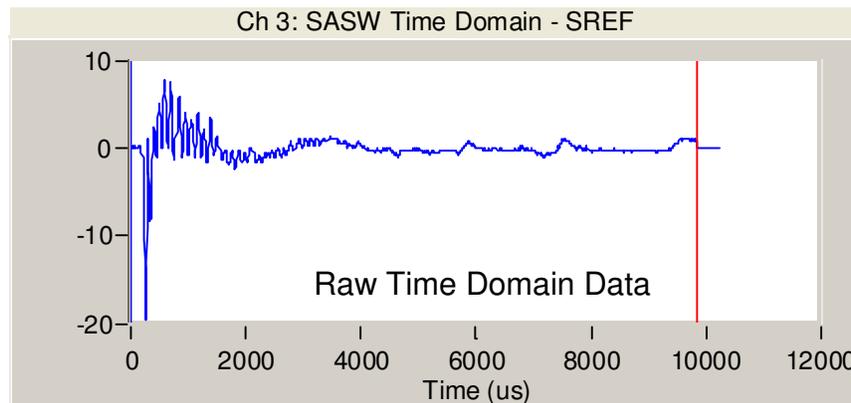


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- BinBandPass. Allow time domain data between the front and back cursors in the analysis and eliminate the data before and after.

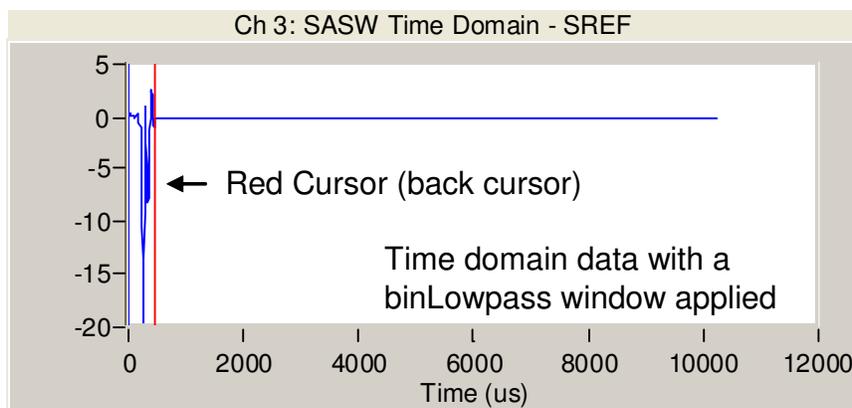




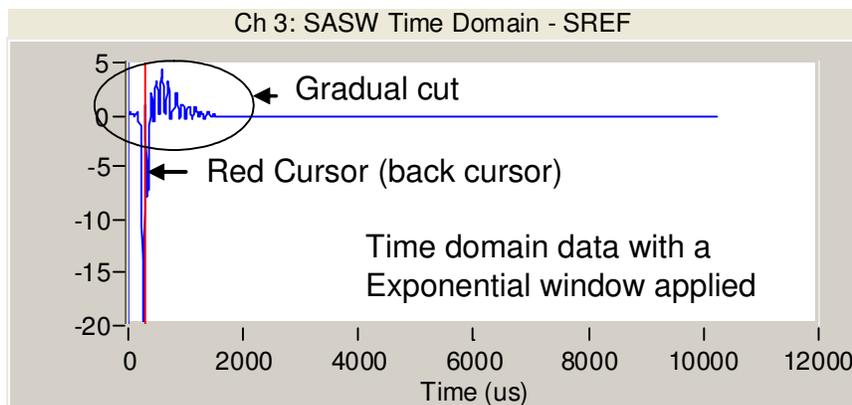
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- **BinHighpass** Allow time domain data after the blue cursor (front cursor) in the analysis. This type of window is almost never used in the SASW data processing.
- **BinLowPass**. Allow time domain data before the red cursor (back cursor) in the analysis. Note that the blue cursor (front cursor) is never used for the BinLowPass.



- **Exponential**. Allow 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.



- **Hanning**. This window is similar to the binBandPass but with gradual cuts for both 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.



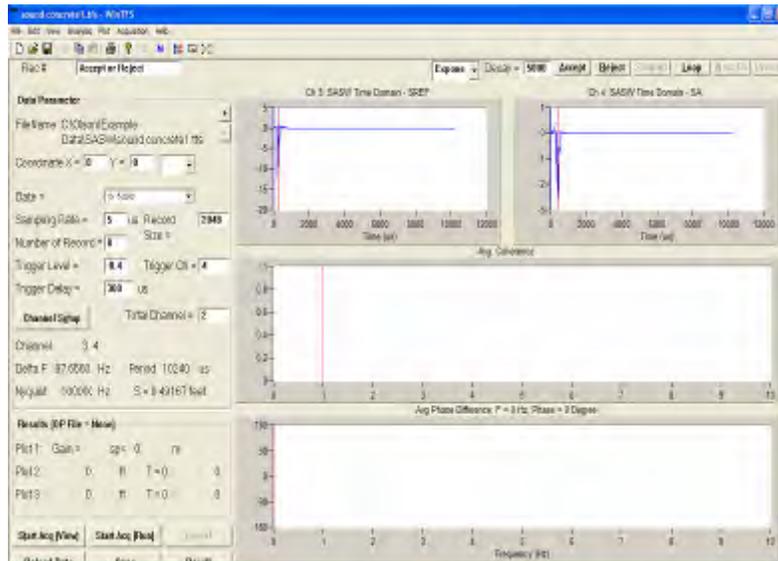
“Exponential” and “Hanning” windows are the only two windows that allows a gradual cut in the time domain (with decay). Other types of windows (bandpass, lowpass and highpass) apply a sharp cut in the time domain, thus may alter the phase information.



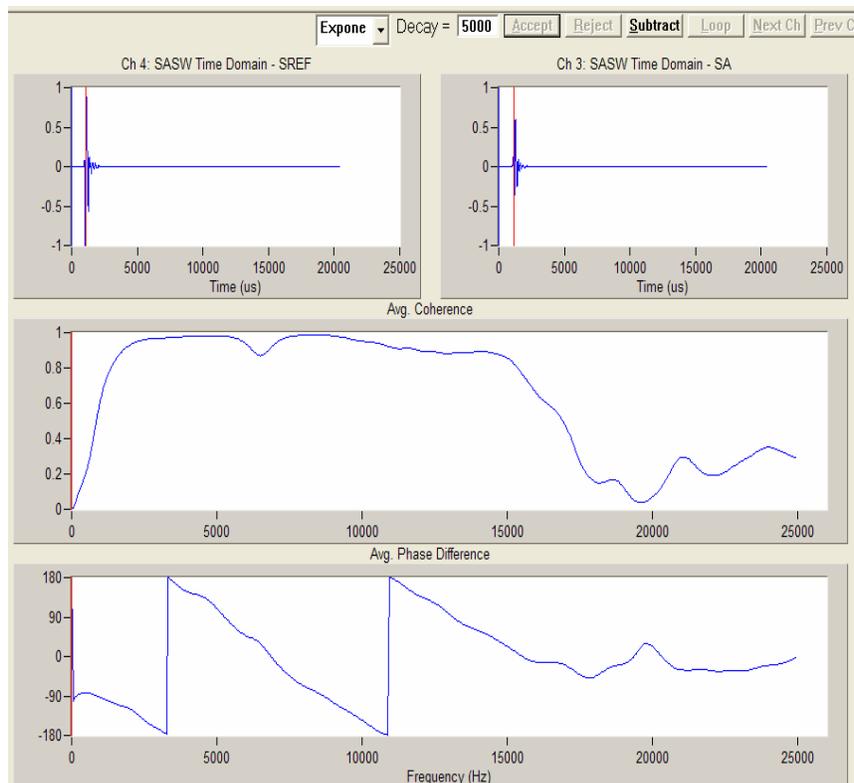
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After selecting the window (and decay for the Exponential and Hanning), move the cursor(s) to eliminate the non-surface waves. The picture below shows an exponential function being used to eliminate the back part of the waveform. In this case, the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



3. **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 a coherence of the data. The third trace shows a phase data.





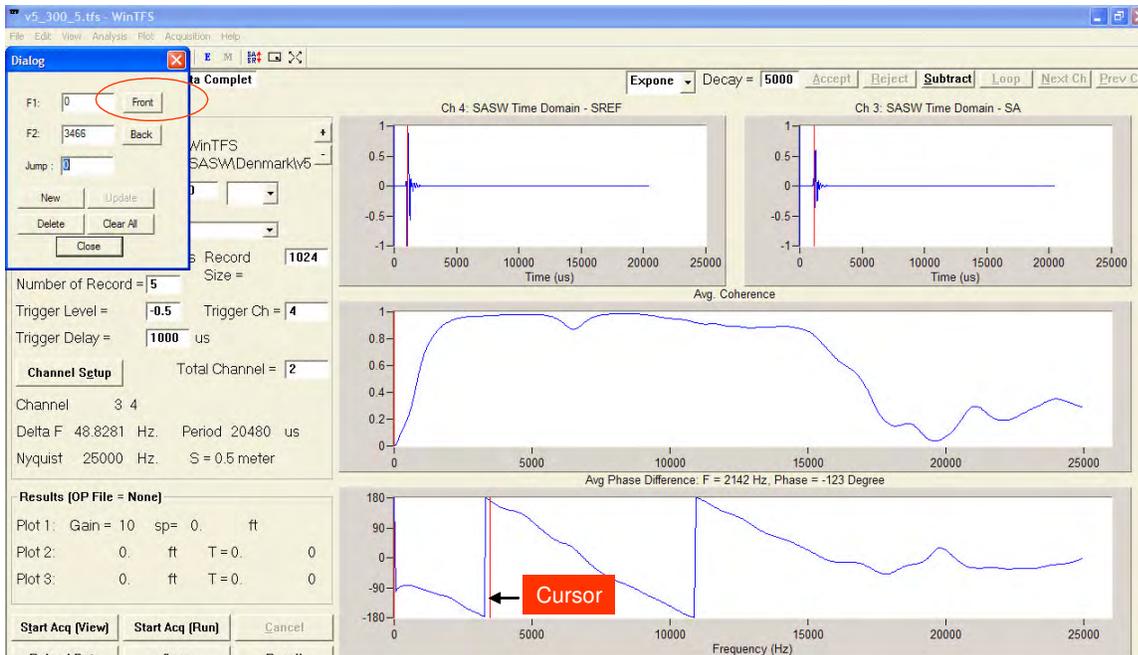
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4. **Filter Function:** This feature is rarely used in the SASW data analysis.
5. **Masking:** To bring up the masking applet to the screen, simply right click on the bottom trace at the location that needs to be masked. In this case, it is the back 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

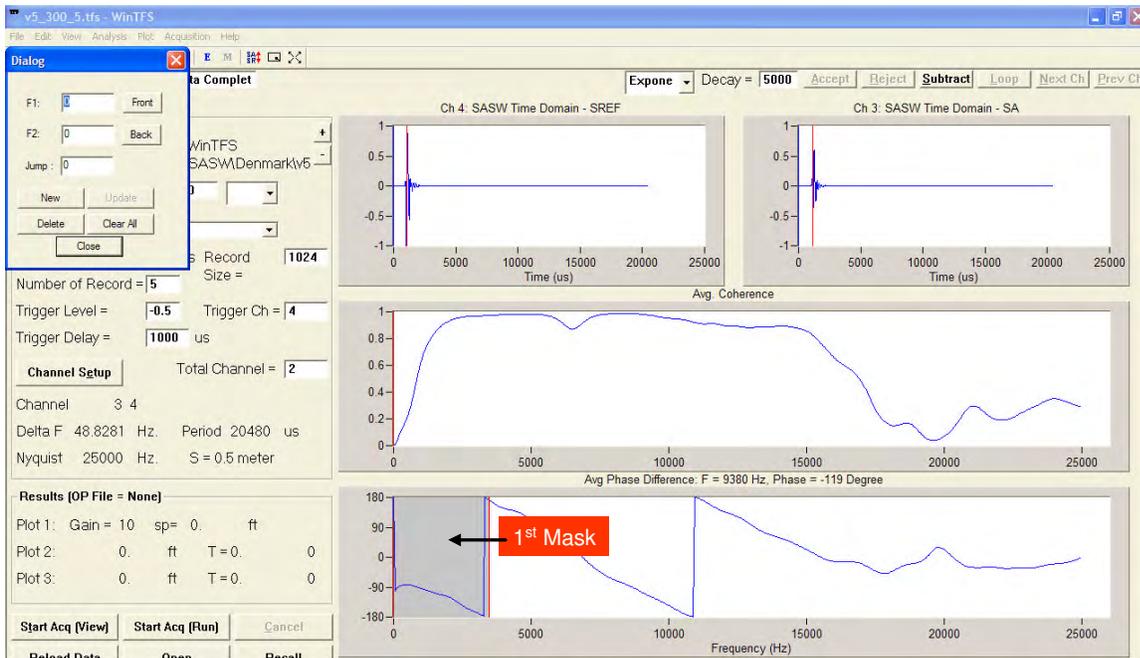


Then enter the jump (cycle) number. In this case the cursor is located on the first cycle so enter 1 on the Jump entry. Then click on “New” on the masking applet. The mask will be created on the bottom trace and the masking applet will be cleared out for a new masking.

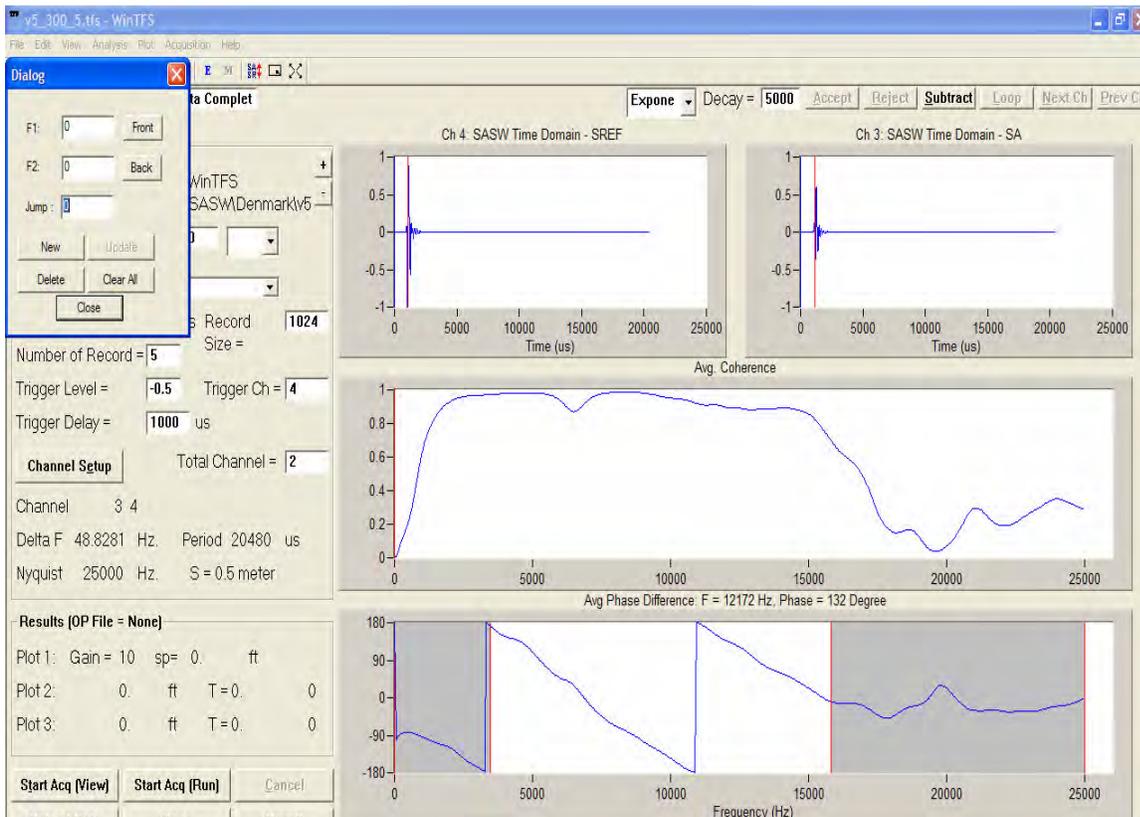


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Typically the back part may need to be masked. Repeat the same process by placing the cursor on the front location of the back part that need to be masked. Then click on “Back” on the masking applet. A new mask should be created.

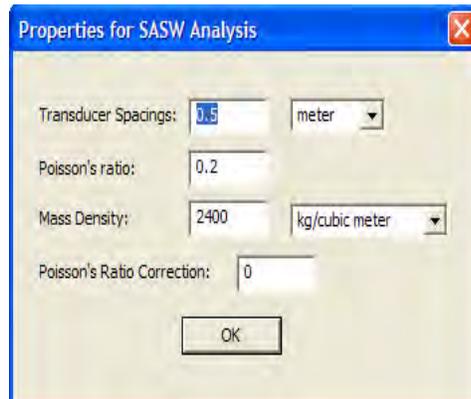




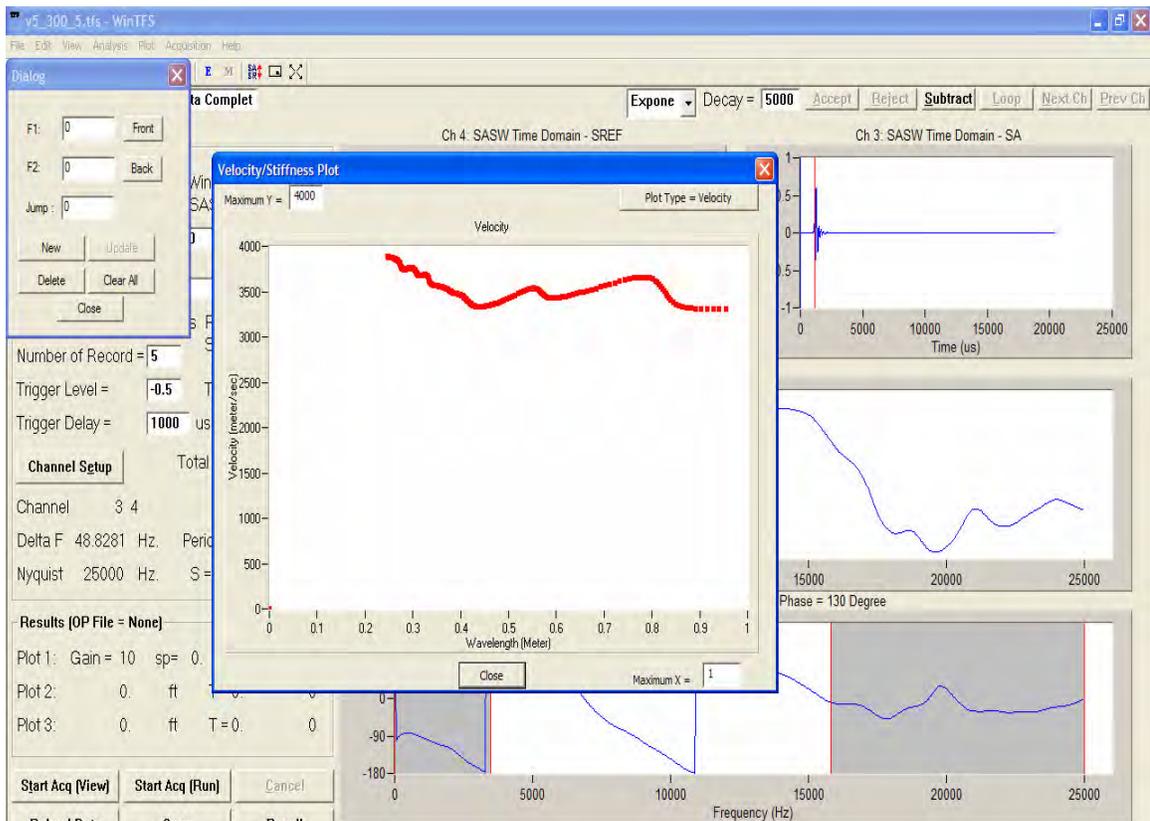
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6. **Transducer Spacing:** The spacing between the two transducers must be entered correctly. To change the spacing, go to Analysis/Change SASW Properties. Enter the correct spacing, Poisson's ratio and density.



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

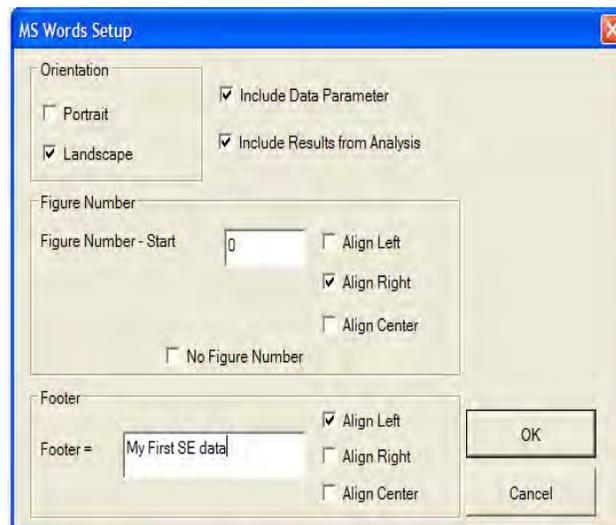




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8. **Open the next SASW data File:** For speedy data recall, simply click on the +/- button to open the next data file if all the files have the same suffix.
9. **Data Export:** The plots can be sent to MS Word for print out. Go to File/Send Plots to MS Word. Then setup the orientation and figure number and click the OK button.





4.6 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).

4.7 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 1 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 relations for concrete material.

	Direction of Particle Motion	Relative Wave Speed
P-Wave	↔	$C_p = 1$
S-Wave	↑↓	$C_s = 0.62 C_p$
R-Wave	↻	$C_R = 0.56 C_p$

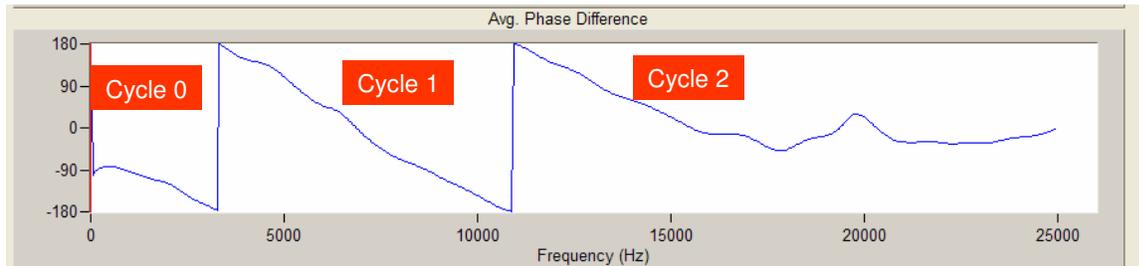
However, a theoretical modeling software is required when working with more than 2 layer system (asphalt on top of concrete) to obtain the most accurate value of the shear and compressional wave velocities of each layer.



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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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(Published in the Proceeding of National Concrete Conference 2008)**



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.

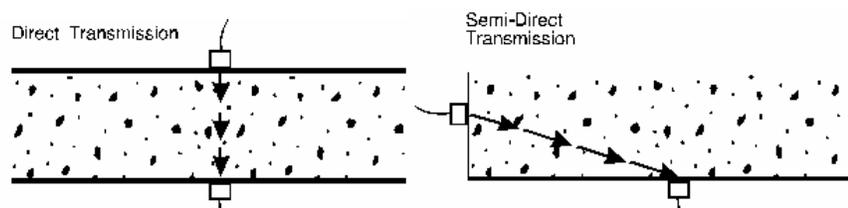
BACKGROUND AND APPLICATION OF NDE METHODS

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.

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

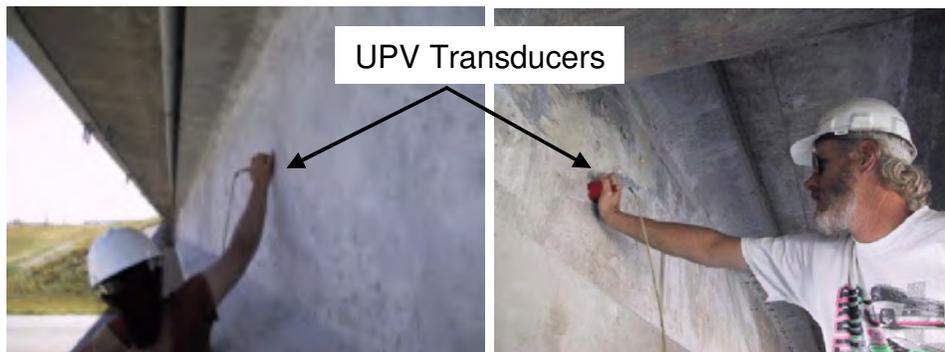


Fig. 2 UPV Tests on Concrete Girder of a Bridge

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



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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.

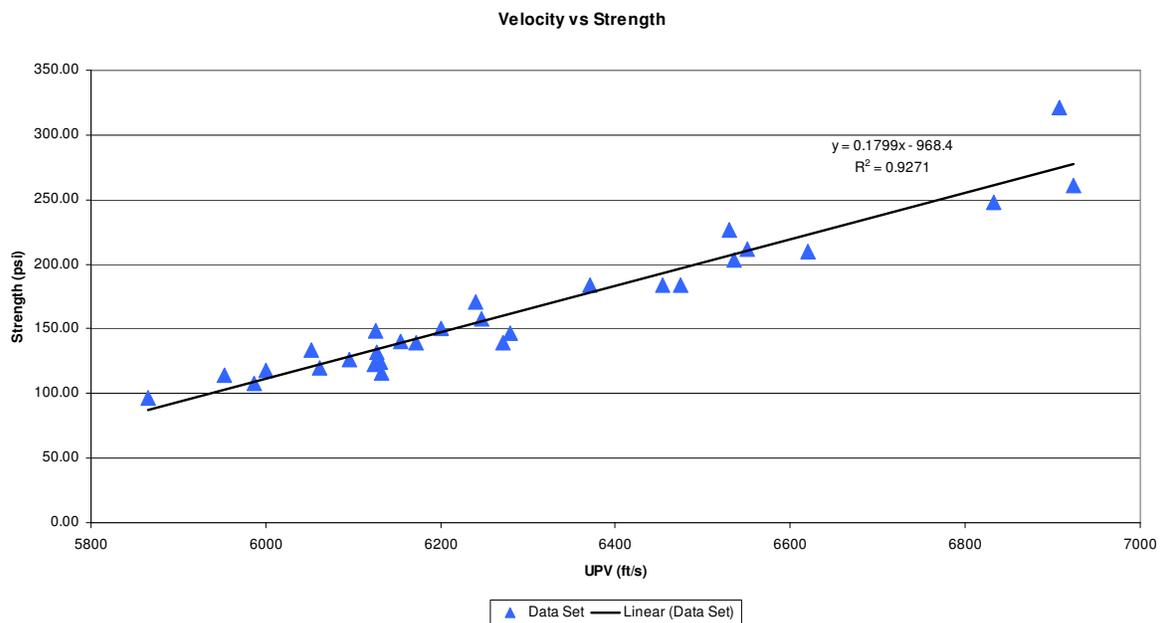


Fig. 3 Correlation of Ultrasonic Pulse velocity and Compressive Strength for Foamed Concrete Embankment 3x6 inch test cylinders



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.

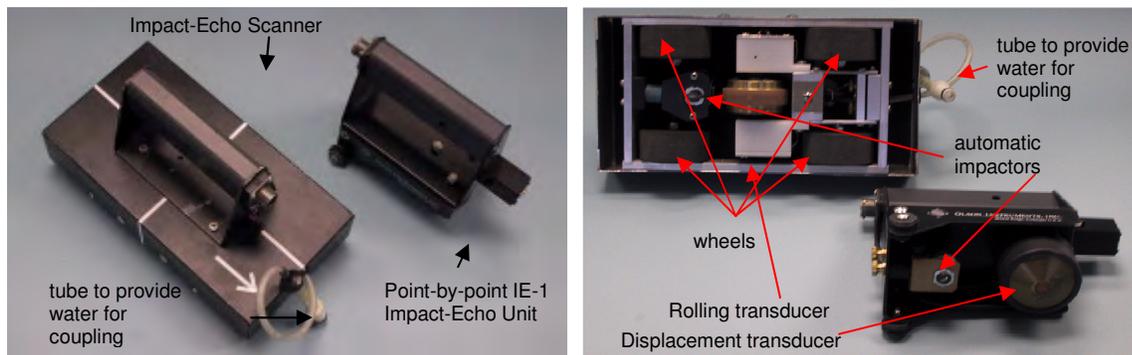


Fig. 4 Impact-Echo Scanner Unit and Point-by-Point Impact-Echo Unit

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



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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.

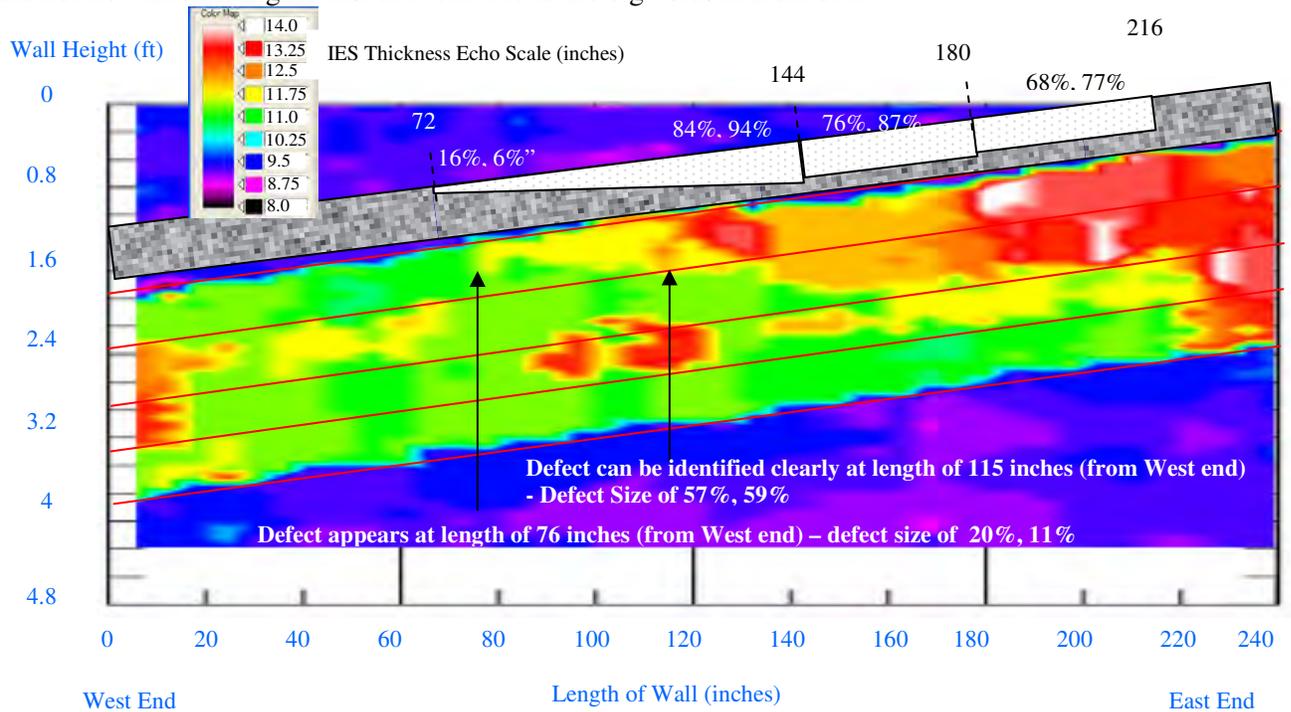


Fig. 5 – IE Results from the South Wall with Actual Design Defects of Top Duct

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:

$$t = \phi/360 \tag{3}$$

$$V_R = X/t \tag{4}$$

$$\lambda_R = V_R/f \tag{5}$$



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where t = Time, V_R = Surface Wave Velocity, X = distance between receivers, λ_R = Wavelength, ϕ = 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).



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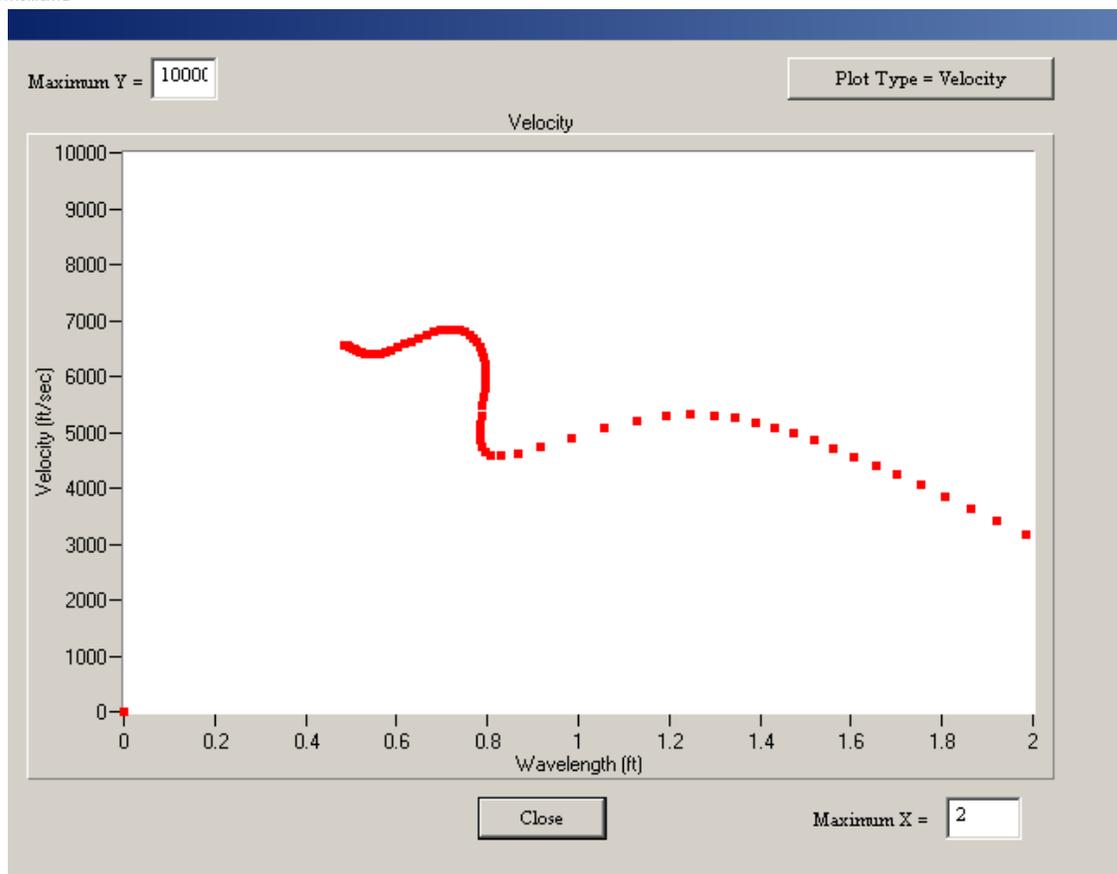


Fig. 7 SASW velocity plot showing approximate thickness = 0.8 ft, surface wave velocity = 6,500 ft/s.

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



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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.

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