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Long Term Cyclic Axial Loading System for Shallow Anchors

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ABSTRACT

The response of offshore structures to cyclic wind and wave loading is likely to govern critical design elements and ultimately the cost of installation and the structure lifespan. This is especially true for offshore wind and tidal turbines, where the magnitude of cyclic load is in greater proportion to their relatively light weight. A variety of novel foundation types have been proposed for renewable energy developments, but few experimental studies have been conducted examining their response under long term cyclic loading. A system was developed and used to apply hundreds of thousands of load cycles to intermediate-scale model foundations. System details are described for a helical pile application and consideration is given to typical challenges encountered in long term cyclic axial loading, such as selecting hardware, managing simultaneous instrument measurement and control tasks, monitoring measurement accuracy, managing large data sets, and protecting equipment during unsupervised testing.

INTRODUCTION

The importance of understanding a foundation's response to cyclic loading, especially those of offshore structures subject to wind and wave loading, has been widely emphasized in literature (Byrne & Houlsby 2003; Lesny & Hinz 2009; Liu et al. 2019). However, relatively few experimental studies subjecting model-intermediate scale foundations to long term cyclic loading have been completed (Yu et al. 2015; Zhu et al. 2013; Cerato & Victor 2008; Newgard et al. 2015). The following paper describes a simple, low cost system capable of applying long term cyclic loading through an electric winch – which is easily routed through a block and pulley system to engage the foundation in vertical, horizontal, or combined loading.

As a point of contrast to the basic functionality of is system, other researchers have used an arrangement of rotating gears and masses to apply lateral cyclic loading to the pile head. By adjusting the loading weight attached to the gears, as well as their radius and angular velocity, the frequency dependent interactions between environmental (wind/wave) loads and the turbine rotor and blades, can be captured. Such a system is described in Zhu et al. (2013) as well as Nikitas et al. (2016). While the system described in this paper was designed to apply a singular cyclic loading pattern, simply duplicating the system and applying a second loading pattern could offer similar insights into these frequency dependent interactions. Additionally, the system described in this paper offers the advantage of applying combined vertical/horizontal/moment loading via pulley blocks to route the winch line in the desired direction of loading.

The system was used to apply hundreds of thousands of load cycles to helical anchors in a test trench as described in Newgard et al. (2015), and has been implemented in a laboratory setting in this study. Emphasis here is placed on explaining important features of the hardware and its control architecture as implemented in a LabVIEW program. Concerns specific to running long tests, such as managing a large amount of data and maintaining accurate instrument measurements, are addressed as well.

SYSTEM HARDWARE

The essential cyclic loading system hardware includes a winch motor, speed controller, data acquisition (DAQ) board, and relay switches. A clutchless electric winch (model SA12000AC from Dutton-Lainson Company of Hastings, Nebraska) is used to apply the upward axial loads . The clutchless version is recommended by the manufacturer for vertical lifting applications and indeed this version performed more reliably in long term cycling. The winch performed adequately through over 250,000 load cycles as part of the cyclic loading system. A counterbalance or pulley arrangement allows dead weight to be supported by the winch line for two-way cycling (cyclic axial loading of a pile in both compression and tension). To achieve compression loading, the winch pays out slack in the line and allows the dead weight to load the pile head. An annotated schematic and picture of the test setup is shown in Figure 1.

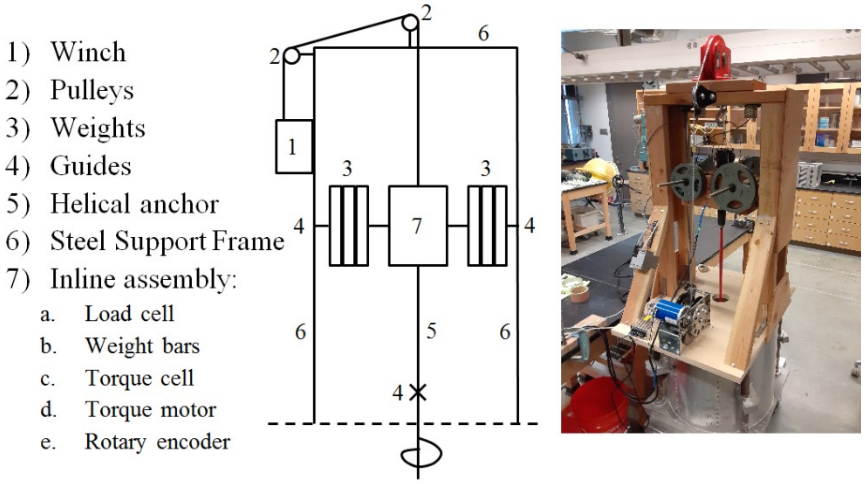


Figure 1. Cyclic loading system configured for a helical pile application.

A motor speed controller (model 130HC100 from Dart Controls of Zionsville, IN) is used to change the winch speed and direction. A dial potentiometer on the controller changes the DC voltage output to the winch motor, thereby adjusting the winch speed. The dial can be reliably adjusted to the nearest 0.2 increment on a scale of 0 to 10. This adjustment could be made more precise by replacing the dial potentiometer with a programmable potentiometer. This study used a programmable potentiometer (model VSI2 Signal Follower Option from Dart Controls) which accepts a DC voltage direct from a data board. The controller provides a Form C contact which consists of one normally open and one normally closed contact to common. When the normally open contact is connected to common, the winch runs up; when the normally closed contact is connected to common, the winch runs down. The winch may be stopped via an additional switch which disconnects both contacts from common. The controller is compatible with any electric motor that has a 90V DC armature – and in this sense, scales very easily from load magnitudes ranging from a few Newton to thousands of Newtons depending on the motor size selected.

The input signals and control signals during cyclic axial loading are controlled using a USB-6212 M Series multifunction data acquisition device from National Instruments (NI) from Austin, Texas. The device has 16 analog input channels that are capable of sampling a total of 400 kS/s, as well as two analog output channels capable of generating signals ranging between +10 V at a current level of 2 mA each. A variety of multifunction input/output (I/O) devices may be substituted into the cyclic loading system if they include analog output capability for sending the speed control signal to the motor controller.

A relay (924 Sensitive Relay from Elk Products of Hildebran, North Carolina) was used to switch the Form C contacts on the motor controller based on the analog output signal from the USB-6212 device. The sensitive relay requires either a 12 V or 24 V DC baseline excitation and, most importantly, can be triggered at a current of only 1.2 mA. The 912 Standard Relay (also from Elk Products), draws a current of 30 mA, and would therefore require a stronger signal than that provided by most NI devices to successfully switch the winch direction through the motor controller. For an even lower cost option, these relays may be replaced by a Sun Founder 2-channel 5V relay module (model SRD-05VDC-SL-C) controlled by an Arduino board, which itself can interface with LabVIEW via LINX.

SYSTEM OPERATION

This section provides an overview of how to configure the various hardware and corresponding controls in the LabVIEW program to perform cyclic loading tests. The basic method by which the system applies cyclic loads is described to help introduce the program. Then hardware connections and their virtual counterparts in the LabVIEW program, which includes a front panel user interface and block diagram code, are presented.

Two versions options were developed to apply: 1) a simple "sawtooth" version, where the winch speed is manually operated by the dial potentiometer and remains essentially constant, and 2) a "sinusoidal" version, where the winch speed follows a sinewave signal generated in LabVIEW (Simulate Signal Express VI) and automatically calibrates itself with each successive direction change. Both control systems accept either position or load limits, and the system simply changes the winch direction when either upper/lower bound of position or load is reached. The automatic calibration feature in the enhanced version is critical to maintaining accurate position/load cycle changes, because the controller only interprets speed – *not* position or load directly. Typical pile loading curves for each of these systems are shown in Figure 2.

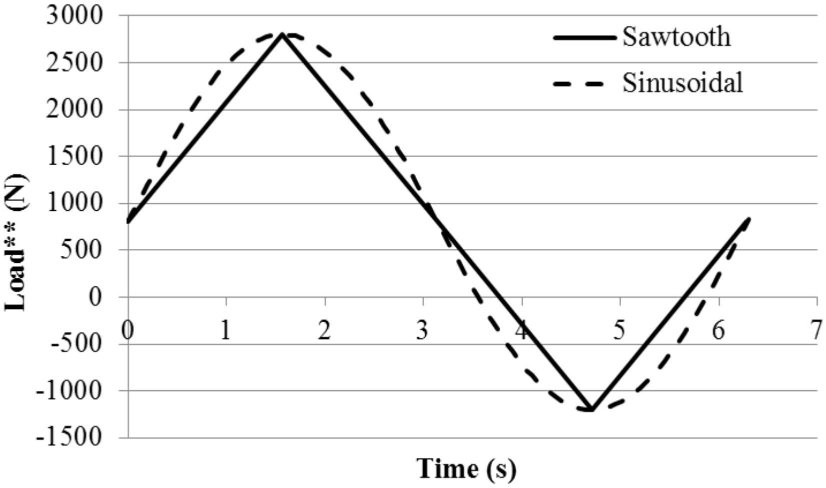


Figure 2. Pile loading curves for simple and enhanced versions of the control system. Note that the system is also capable of position-controlled cycling

The wiring diagram for the hardware used in the cyclic loading system is shown in Figure 3. The output signals from the USB-6212 device are routed through each of the relays, which effectively create a single pull, triple throw switch at the motor controller. This allows the winch to be programmatically set to three states: running up, running down, or powered off. When 10 V and 0 V are output to analog output channel zero (AO0) and analog output channel one (AO1), respectively, the winch runs down. Conversely when 0 V and 10 V are output to AO0 and AO1, respectively, the winch runs up. When 0 V is sent to both AO0 and AO1, both the normally closed (FWD) and normally open (REV) contacts on the motor controller remain disconnected. With only one relay, there would be no way to programmatically stop the motor as either the FWD (winch runs down) or REV (winch runs up) contact would always be connected to common (COM). The two sensitive relays shown in Figure 3 have been wired specifically so that when both output channels carry 0 V, the motor is stopped. In the event of a power outage or unexpected computer shutdown while the user is away, the motor will stop, preventing damage to any equipment in the system.

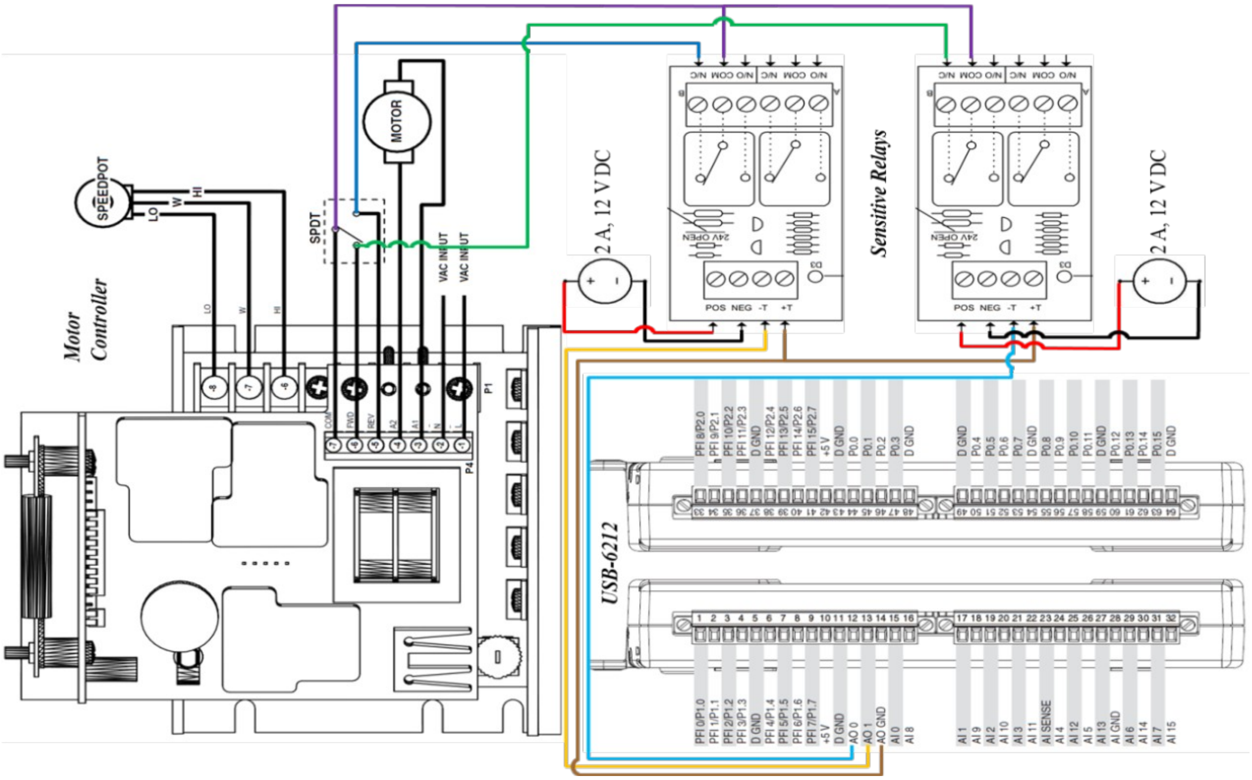
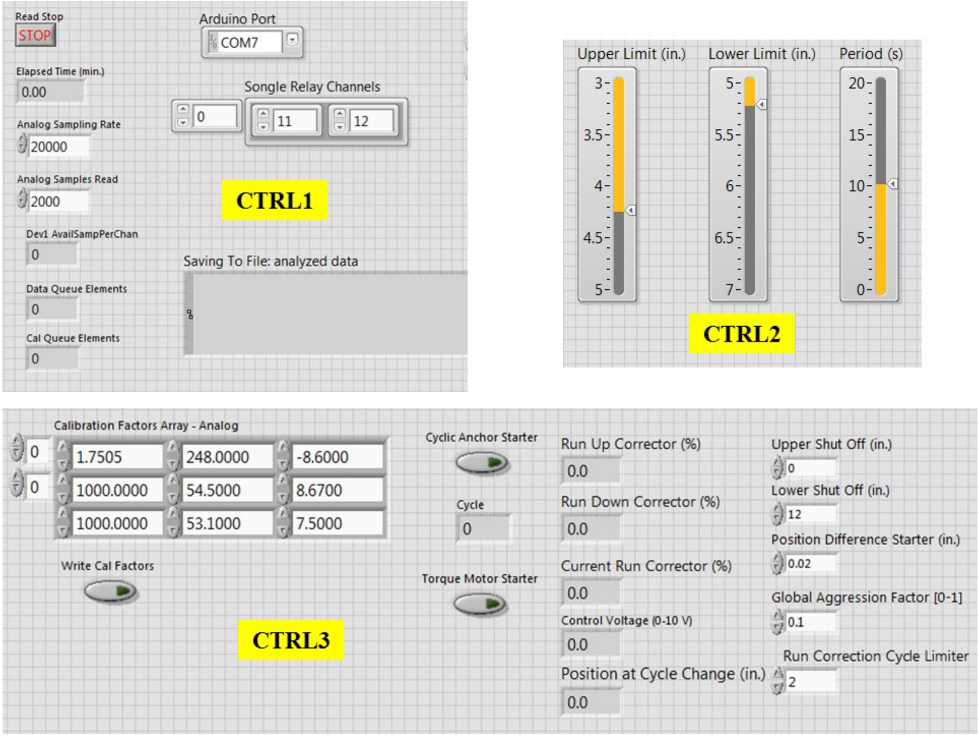


Figure 3. Wiring diagram for the control system hardware.

The diagram shown in Figure 3 depicts the requisite wiring for the simple version of the system; to use the enhanced version of the system, the manual SPEEDPOT LO, W, and HI connections can be directly replaced via the same outputs from the VSI2 Signal Follower Option board.

DATA ACQUISITION INTERFACE

This section focuses on the control signals managed by the program as it is the most unique aspect of the cyclic loading system. It also includes a brief overview of the front panel, or user interface. An overview of the front panel of the LabVIEW program for the enhanced version of the system is shown in Figure 4. The controls on the front panel are annotated by general function for easy interpretation; CTRL1 involves signal acquisition with the USB-6212 device (and Arduino for the low cost relay option), CTRL2 involves cyclic loading characteristics, and CTRL3 involves instrument calibrations as well as control checks and fine-adjusters to ensure proper operation. CTRL3 includes hard-stop/override position limits to prevent damage to equipment in the event either load limit is not attained within a given cycle (such as during anchor pullout in an axial loading application).



Arduino Port
COM7

Elapsed Time (min.)
0.00

Songle Relay Channels
0
11
12

Analog Sampling Rate
20000

Analog Samples Read
2000

Dev1 AvailSampPerChan
0

Saving To File: analyzed data

Data Queue Elements
0

Cal Queue Elements
0

Calibration Factors Array - Analog

0	1.7505	248.0000	-8.6000
0	1000.0000	54.5000	8.6700
	1000.0000	53.1000	7.5000

Cycle
0

Run Up Corrector (%)
0.0

Run Down Corrector (%)
0.0

Current Run Corrector (%)
0.0

Control Voltage (0-10 V)
0.0

Position at Cycle Change (in.)
0.0

Upper Shut Off (in.)
0

Lower Shut Off (in.)
12

Position Difference Starter (in.)
0.02

Global Aggression Factor [0-1]
0.1

Run Correction Cycle Limiter
2

Figure 4. Front panel interface of the enhanced cyclic loading system control program.

The front panel also includes charts and additional numeric indicators of pile position, load, winch rate, and the sinewave control signal but these are omitted here for clarity. Monitoring the acquired data in the form of charts, graphs, and numeric indicators on the front panel was invaluable during system development, and often helped solve issues such as excessive signal noise, backlog of samples in the USB-6212 buffer, compatibility of control signals with hardware, and influences of temperature and environmental factors on long term measurements.

CTRL3 contains the most nuanced set of controls and so is described in greater detail here. The sensor calibration factors are recorded each time the Write Cal Factors button is depressed for accurate bookkeeping of the test. The Upper Shut Off and Lower Shut Off will stop the winch motor if the position sensor measurement is outside these limits (this is the hard-stop/override mentioned earlier). The winch motor will not begin cycling until the Cyclic Anchor Starter button is depressed and the position sensor measurement is within the offset described by Position Difference Starter from the desired position of the sinewave control signal. A cycle counter (simply called Cycle) increments by 0.5 any time a direction change is initiated. The automatic calibration feature is shown in the Run Up and Run Down Correctors as a deviation from the user-input calibration factors for the position/load sensors (a corrector value of 100% indicates no deviation). These correctors will not engage immediately, but *after* the motor has "settled in" a specified number of cycles defined by the Run Correction Cycle Limiter. The Global Aggression Factor specifies how quickly the motor speed will be adjusted by the controller to chase the position/load limits set in CTRL2. This feature allows the user to adjust the limits after a certain number of cycles in order to apply sequences of load packets to the pile. The automatic calibration and aggression factor are simultaneously applied via the following equations to carefully adjust the motor speed:

$$Run\ Down\ Corrector(\%) = Current\ Run\ Down\ Corrector + 100 \times \left(\frac{Desired\ Travel - Actu}{Desired\ Trave} \right. \quad (1)$$

$$Run\ Up\ Corrector(\%) = Current\ Run\ Up\ Corrector + 100 \times \left(\frac{Desired\ Travel - Actual\ Tra}{Desired\ Travel} \right. \quad (2)$$

These equations are updated at the instant of a motor direction change, at which time the position/load sensor measurement is stored in a register for calculating the actual travel during the next half cycle. The first term within the parenthesis of each equation adjusts the speed based on the desired travel (be it position or load) in any given cycle. This desired travel is simply the difference between Upper Limit and Lower Limit as defined by the slider controls in CTRL2. The second term within the parenthesis adjusts the speed to follow the absolute limits over time. If the global aggression factor is zero, the pile will drift out of these absolute limits slowly, eventually resulting in gross errors in actual vs. desired loading. If the global aggression factor is one, the pile will likely be overloaded as the system will chase the absolute limits too aggressively. Based on experiments, a factor between 0.1-0.2 is suitable for stable operation.

MANAGING LARGE DATA SETS

Performing long term cyclic tests presents a unique challenge for data acquisition – gathering a vast amount of data at a frequency great enough to capture damping characteristics, cyclic shakedown, and/or the onset of incremental collapse within any given cycle, while recording for test durations as long as a few days. Typical program usage might involve recording data from 10 channels at a frequency of 10 Hz, resulting in over 1.7 million lines and 17 million double precision data points logged to file during a test lasting 48 hours. This amount of data cannot be opened with the Microsoft Excel .tdms file converter add-in, since Excel 2007 and later only support 2^{20} or 1,048,576 lines of data. An efficient method to handle such a large amount of data may involve running a separate LabVIEW program, after the test is complete, that indexes all the data in the .tdms file and places it into a .txt file. The block diagram of this program is shown in Figure 5. The program arranges data points by column with each column representing a separate channel for easy interpretation.

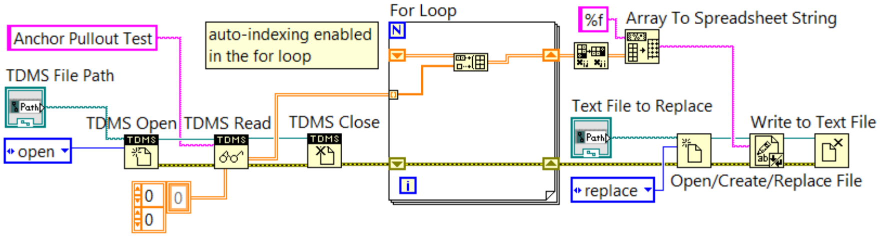


Figure 5. Writing data from .tdms to .txt file.

While the text file is unwieldy to open, there is practically no limit to the amount of data that can be written to it, and MATLAB can import .txt files into its 'workspace'. It may take ~1 hour to initially load the .txt file, but subsets of data may be saved in the .mat workspace for further processing. These .mat workspaces load much more efficiently than .txt files. An alternative method uses an umbrella LabVIEW program to successively open identical instances of the main test program. This umbrella program is shown in Figure 6.

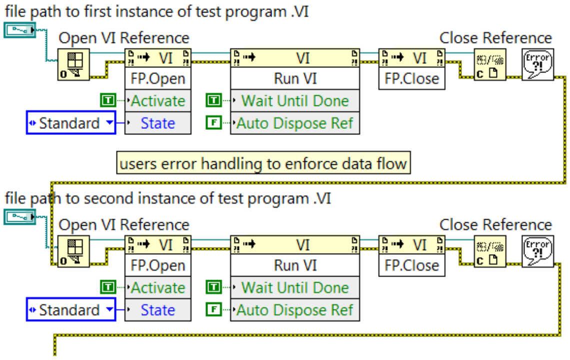


Figure 6. Umbrella program to open instances of the main control program.

To use this scheme, instances of the main test program must be saved to disk, and their file paths entered into the umbrella program file controls. Each instance of the main test program is modified to automatically stop based on some user defined condition, which can simply be a specified time interval. Additionally, the instances must write data to a separate group name, specified in the TDMS Write VI. Then, the umbrella program automatically opens each instance of the main test program to complete a full test. The result effectively circumvents the 2^{20} line limitation in Excel, with data placed in the same .xlsx file, but under different spreadsheets according to the group and channel handles specified in each instance of the main test program.

MEASUREMENT ACCURACY

Long term cyclic loading tests, especially those performed outdoors, are inherently subject to measurement errors due to temperature changes. With no means to check each instrument's unloaded reading (short of physically disconnecting the sensor from the system), the load or position limits used during cycling may be compromised due to measurement drift. Errors due to measurement drift can be programmatically eliminated by including an unloaded sensor in the acquisition. This unloaded sensor responds only to environmental changes, and its reading may be used to shift the readings from the sensor in the cyclic loading system as appropriate. Then a final check of the corrected sensor reading can be made upon completion of the test.

To better capture the long term drift recorded by the unloaded sensor, a running average of its readings should be calculated. This is achieved by appending sensor readings into an array indexed by the loop counter, included by default in any while loop. An example block diagram code used to produce a 10-minute running average of readings by indexing (given an acquisition cycle running at 10 Hz) is shown in Figure 7.

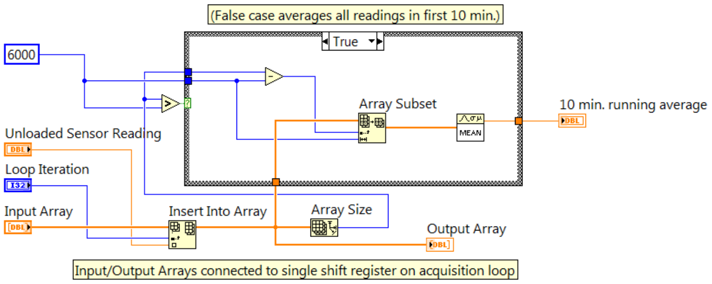


Figure 7. Running average of sensor readings via array indexing.

TYPICAL RESULTS

Results from a helical pile application are shown in Figure 8. In this test, the simple "sawtooth" version of the system was used to load the helical pile in two-way cycling, where the compression load limit was about ½ the uplift load limit. The anchor in this case exhibited incremental collapse and moved upward relatively rapidly; while in other tests, the anchors exhibited shakedown and did not move appreciably over thousands of cycles. A more thorough discussion of long-term cycling test results is presented in Newgard et al. (2015) and Newgard et al. (2019).

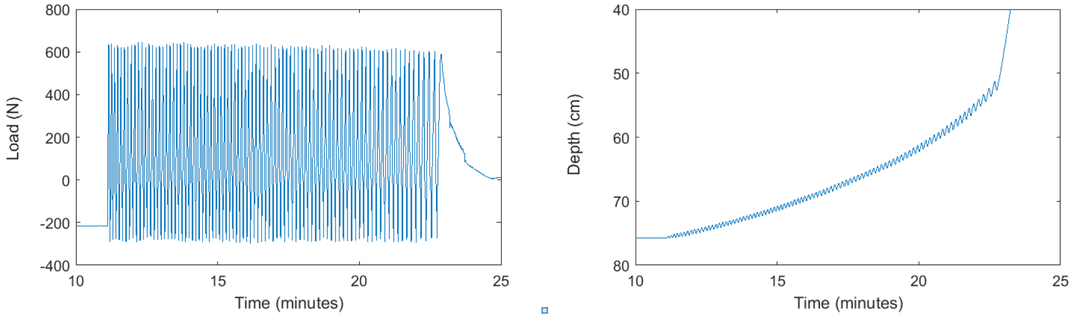


Figure 8. Loading characteristics from use of this system for a helical pile application.

CONCLUSION

The cyclic loading system described in this paper has been used to apply both vertical and horizontal cyclic loads to individual and paired helical anchor piles at load levels up to ~5,000 N, and cumulatively for hundreds of thousands of cycles. However, a variety of electric motors could be incorporated into the system, providing greater flexibility in testing. For example, the speed controller used in the current system is compatible with any 90 V DC armature electric motor. Such motors are available with power ratings ranging from ¾-hp (as used in the helical pile application presented herein) down to ⅛-hp, which may be more appropriate for cycling a ball penetrometer to determine remolded shear strength of clay. The control system handles simultaneous input/output tasks, automatically monitors loading accuracy, and manages very large data sets – all challenges somewhat unique to long term cyclic load testing. It also includes a few safety features to prevent damage to equipment during unsupervised cycling, such as the position limit motor shut off. An example test setup and cyclic loading response for a helical pile application was provided to illustrate the control system in practice.

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REFERENCES

Byrne, B.W. & Houlsby, G.T. (2003). “Foundations for offshore wind turbines.” *Philosophical Transactions of The Royal Society: Mathematical, Physical, and Engineering Sciences*, Volume 361, pp 2909-2930.

Cerato, A.B. & Victor, R. (2008). “Effects of helical anchor geometry on long-term performance for small wind tower foundations subject to dynamic loads.” Journal Deep Foundations Institute, 2 (1): 30-41.

Lesny, K. & Hinz, P. (2009). “Design of monopile foundations for offshore wind energy converters.” *In Contemporary Topics in Deep Foundations*, 512-519.

Liu, H.Y., Abell, J.A., Diambra, A. & Pisano, F. (2019). “Modelling the cyclic ratcheting of sands through memory-enhanced bounding surface plasticity.” *Géotechnique*, 69 (9): 783-800.

Newgard, J.T., Schneider, J.A. & Thompson, D.J. (2015). “Cyclic response of shallow helical anchors in a medium dense sand.” *Proc. Of Frontiers in Offshore Geotechnics III*, Oslo, Norway, 913-918.

Newgard, J.T., McCartney, J.S., Schneider, J.A. & Thompson, D.J. (2019). “Static and cyclic axial loading of single and multiplate helical anchors in sand.” *Proceedings of the International Symposium on Screw Piles for Energy Applications*, Dundee, Scotland, 27-28 May 2019. IHS BRE Press, 2019.

Nikitas, G., Vimalan, N.J. & Bhattacharya, S. (2016). “An innovative cyclic loading device to study long term performance of offshore wind turbines.” *Soil Dynamics & Earthquake Engineering*, 82: 154-160.

Yu, L., Zhou, Q. & Liu, J. (2015). “Experimental study on the stability of plate anchors in clay under cyclic loading.” *Theoretical and Applied Mechanics Letters*, 5 (2015) 93-96.

Zhu, B., Byrne, B.W. & Houlsby, G.T. (2013). “Long term lateral cyclic response of suction caisson foundations in sand.” *ASCE Journal Geotechnical & Geoenvironmental Engineering*, 139 (1): 73-83.