DID YOU KNOW? *Newsletter No. 103 - October 2022*

Dr. Harry Nara (who directed PDI Founder, Garland Likins, into Civil Engineering) had done some classified work for the Department of Defense on missile projectiles into sand which led to his interest in pile driving.

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The Incremental Rigidity Method: More Direct Conversion of Strain to Internal Force in an Instrumented Static Load Test

By Van E. Komurka, P.E., D.GE., F.ASCE

Axial static load tests (top-loaded and bi-directional compression, and tension) have an important role in design and construction of all deep foundation types: driven piles, augered cast-in-place piles (ACIP), drilled displacement piles (DDP), helical piles, drilled shafts, etc. (referred to herein as piles). Static load tests' usefulness, particularly in the design phase, is greatly enhanced by determining load-transfer response. Load-transfer response refers to the way in which the surrounding geomaterial causes changes in internal axial pile forces, mobilizing shaft resistance and end bearing, both as a result of relative pile-soil movement (t-z and Q-z relationships, respectively). The objective of an instrumented static loading test is to determine mobilized resistance forces based on measured internal pile forces.

Load-transfer measurements are commonly obtained using strain gauges installed at various locations along the pile. Strain measurements' reliability may be excellent, but converting strain measurements to internal force is not straightforward, as it depends on the pile's physical characteristics (i.e., composite-section elastic modulus, E, and cross-sectional area, A, not always easily or accurately determined) at the strain measurements' locations. This reality is at best misrepresented, and at worst misunderstood, by the notion that strain gauges measure internal forces. They do not; they provide readings that are an intermediate step in calculating internal forces. The E and A required to convert strain to internal force can, and do, vary by location within a pile. Some can be measured, but are more often assumed, assigned presumptive values, estimated, based on constitutive relationships, or back calculated. The uncertainties and inaccuracies of these methods can introduce significant errors into internal pile force calculation, and therefore into calculated mobilized unit shaft resistances. The Incremental Rigidity ("I.R.") method offers more direct determination of a pile's physical characteristics, and therefore more direct conversion of strain measurements to internal forces and mobilized unit shaft resistances.

Static load tests are typically performed using step-and-hold test load increments. For each load increment, internal pile forces are calculated at each strain gauge level, and a resulting internal force profile (as a function of depth or elevation) is determined. Internal pile forces at each strain gauge level are calculated using the product of E and A, and measured strain, at that level by:

$F = EA\varepsilon$ [Eq. 1]

From classical strength of materials, the product EA is defined as axial rigidity (referred to herein simply as rigidity). Since strain is measured, conversion of strain to internal force has conventionally involved somehow determining the values of E and A separately, potentially at each strain gauge level. Knowing the modulus and area along any drilled foundation's length is problematic. Assuming either modulus or area to be uniform along the pile length is generally incorrect, and can lead to errors in internal force calculations. However, knowledge of these two individual values is not strictly required; a review of Eq. 1 indicates that only determination of their product, EA, is required.

The Incremental Rigidity method relates changes in test load to changes in strain to determine a direct relationship between internal force and strain. The key to the I.R. method is the premise that after a pile's shaft resistance is fully mobilized between a strain gauge level and the test load source, subsequent incremental increases in test load (ΔQ) result in incremental increases in internal force (ΔF) equal to ΔQ, and proportional strain increases (Δε), at that level. The quotient of change in test load and change in strain, ΔQ/Δε, is the change in incremental rigidity, Δ(EA). Plotting Δ(EA) against strain for an individual strain gauge level resolves into a virtually straight line after a pile's shaft resistance is fully mobilized between a strain gauge level and the test load source, sloping from larger to smaller incremental rigidities with increasing strain for piles containing concrete or grout (Fig. 1).

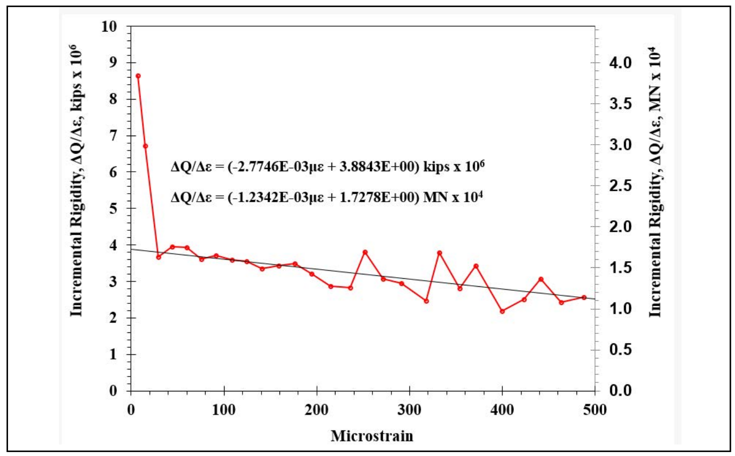

Figure 1. Incremental Rigidity Diagram for One Strain Gauge Level

Rearranging Eq. 1 results in:

$F/\varepsilon = EA$ = Rigidity of Composite Pile Material [Eq. 2]

Working with ΔQ (since it is measured during the test), and recognizing that ΔQ = ΔF after the incremental Rigidity plot resolves to linear, the equation for the I.R. line in Fig. 1 is:

Incremental Rigidity of Composite Pile Material = $(dQ/d\varepsilon) = (dF/d\varepsilon) = a\varepsilon + b$ [Eq. 3]

which can be integrated with respect to strain to:

Internal Force in the Pile = $F = 0.5a\varepsilon2 + b\varepsilon$ [Eq. 4]

Inspection of Eq. 4 indicates that, using the Incremental Rigidity method, internal forces in the pile at interpretable strain gauge levels can be determined using only strain measurements, without knowledge of separate values for modulus or area. Obviously, this is of special benefit for non-uniform piles. However, even for apparently uniform piles, it is recommended that the I.R. method be applied, and potentially different relationships be used, at individual strain gauge levels.

Some judgment must be applied in deciding which strain gauge levels provide interpretable results, and which do not. Since Incremental Rigidity method application depends on fully mobilizing shaft resistance between the load source and the strain gauge level, levels closer to the load source are more likely to be interpretable than levels further from the load source. Recognizing this, sufficient strain gauge levels should be located upstream from the pile's resistance balance point, even where the adjacent geomaterials' resistance may not be of particular interest (owing to low strength, scour, liquefaction, future excavation, etc.).

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GRL Engineers, Inc. provides static load test services related to design, instrumentation, data reduction, and interpretation, with special expertise in strain gauge data reduction. Further information on the Incremental Rigidity method is detailed in two technical papers which can be found on GRL's website at [https://www.grlengineers. com/ reference-papers/](https://www.grlengineers.com/reference-papers/), filter by author: Komurka.

Editor's Note: *For this successful research work and his outstanding contribution to foundation engineering, GRL's Van E. Komurka, P.E., D.GE, F.ASCE was awarded the coveted 2022 Martin S. Kapp Foundation Engineering Award by the American Society of Civil Engineers.*

PDI Celebrates 50 Years!

Pile Dynamics, Inc. celebrated its 50th anniversary with a two-part event on September 16th. The celebration and reception were held in Cleveland's University Circle – not far from where the company began at Case Institute of Technology (now Case Western Reserve University). The day started at the Cleveland Institute of Music, Mixon Hall, where PDI's CFO, Adrian Rausche, and Chairman of the Board, Mohamad Hussein welcomed PDI employees, founders, family, and distinguished guests, before handing the podium over to PDI Founder, Garland Likins and current PDI president, George Piscsalko. The duo spoke of Pile Dynamic's history from 1972 through the present state of PDI in the Deep Foundations industry. Guest speakers for the day included Silas Nichols PE, Principal Geotechnical Engineer for Federal Highway Administrations office of Infrastructure; Chris Schairbaum, Director of Innovation and Technology for Texas Instruments; and Peter Kandaris PE, Western Regional Manager of DiGioia, Gray & Associates. Additionally, an international panel took place with representatives from China, Sweden and Germany; GRL Engineers' President, Scott Webster, and PDI's Vice Presidents, Brent Robinson, and Wayne Dalton discussed future visions. The audience was entertained by CIM musical students; and the innovative spirit of Pile Dynamics resonated through each presentation.

A dinner reception was held at Cleveland's Historical Society, Crawford Auto-Aviation Museum where guests could revel in the museum's vast display of automotive models and motorcycles, walk through a historical exhibit of PDI, or take a ride on the historic Euclid Beach Park Carousel. Dr. Frank Rausche, toasted the festivities ahead of dinner being served. Guests were treated to heartfelt testimonials and well wishes from PDI employees, Ryan Allin, Greg Tenik, Wayne Dalton, Akshada Thakur, and Shannon Theodore, prior to visiting the dessert bar and listening to sounds of music from the 1970s as the night culminates.

"I look back in awe at what we have accomplished in 50 years and look forward to future challenges as we continue to evolve. I am honored to have been a part of this success story. None of this would be possible without the great vision of our founders, the early adopters of our methods, the many owners and designers that specify our products and methods, our loyal customers, our worldwide representatives, and our incredible staff. I thank you all for being an important part of our first 50 years and look forward with excitement to the continued success of PDI,"

George Piscsalko, President, PDI

Upcoming Events

Oct 2-6	Conference: ASCE SEI Electrical Transmissions and Substation Structures, Orlando, FL *Learn More*
Oct 4-7	Conference: DFI 47th Annual, National Harbor, MD *Learn More*
Oct 12	**Seminar: Deep Foundation Integrity Testing and Wave Equation Analysis Seminar, Cleveland, OH** *Register Today*
Oct 13 & 14	**Workshop: High Strain Dynamic Foundation Testing Workshop, Cleveland, OH** *Register Today*
Oct 16-22	Conference: 51st Annual Southeastern Transportation Geotechnical Engineering Conference (STGEC), Daytona Beach, FL *Learn More*
Oct 21	**Webinar: TIP Discussion Hours with Ryan Allin, P.E.** *Register Today*
Oct 24	**Seminar: State of Practice QC/QA of Deep Foundations, Portland, OR** *Register Today*
Oct 25-26	Conference: OTEC, Columbus, OH *Learn More*
Oct 26	**Seminar: State of Practice QC/QA of Deep Foundations, Boise, ID** *Register Today*
Oct 28	**Seminar: State of Practice QC/QA of Deep Foundations, Kansas City, MO** *Register Today*
Oct 28	**Webinar: PDA Discussion Hours with Ryan Allin, P.E.** *Register Today*
Nov 16-18	Conference: Piling and Ground Improvement, Sydney, Australia *Learn More*
Dec 6, 7, 8	**Webinar: PIT, CSL, & TIP** *Register Today*
Dec 14	**Webinar: Pile Driving Hammer Performance** *Register Today*

A complete list of PDI/GRL events can be found on pile.com or grlengineers.com

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