DID YOU KNOW? *Newsletter No. 107 - September 2023*

The first 3D printed bridge is located in Madrid and was constructed with micro-reinforced concrete.

GRL Engineers, Inc. Pile Dynamics, Inc.

Optimal Arrangement of Strain Gages in Deep Foundation Load Testing

(Why 2 is better than 3, but 4 is better than 2)

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This article utilizes data collected at the FDOT I-395 Signature Bridge project[1] in downtown Miami, FL. The Signature Bridge project is designed to improve traffic flows at the intersection of I-395/SR836/I-95 while creating over 30 acres of community gathering space that reconnects local neighborhoods. The project has many innovative design and architectural aspects, one of them is the use of Auger Cast In-Place Piles (ACIP) for foundation support. While ACIP foundation elements have been used on other bridge projects, this is the largest project where ACIP piles have been utilized. As such, numerous quality control measures were deployed. These included the use of Thermal Integrity Profiling (TIP) to evealuate structural integrity and pile shape, and Bi-Directional Static Load (BDSLT) testing to evaluate axial load capacity. The BDSLT testing included internal strain gage measurements and this data has provided real-world statistics on strain gage mortality while illustrating the optimal distribution of gages in a deep foundation element. The data set includes eleven BDSLT tests with installed sisterbar vibrating wire strain gages. All piles were ACIP piles with nominal 30-inch (760 mm) diameter and approximately 110 ft (34 m) deep. Three strain gages were specified per level with spacing of 5 ft (1.5 m) between each level.

Why 2 Is Better Than 3

The plane-strain condition (ie. only strain in the direction of loading) is a key assumption of the conversion of measured strain to axial force. Any bending in the foundation element, whether due to eccentric loading, irregular soil resistance, non-uniform cross-sectional area or any other reason will cause an uneven distribution of strain in the cross-section. According to Euler beam theory, the total strain will be a superposition of axial strain (in which we are interested) and bending strain which for the purposes of an axial load test data analysis is disregarded. The statistics discussed below pertain particularly to axial compressive or tensile load testing of foundations, with a presumption that axial strains due to applied loading will be significantly greater than incidental bending strains induced by load eccentricity. Therefore, obtaining the strain at the centroid is key to computing the net axial force.

Typically, two or more strain gages per level are installed in a test element if a reinforcing cage is installed. This arrangement allows for an estimate of the strain at the centroid of the element to be computed as an average of the individual strain measurements. A single opposed (180º apart) strain gage pair is the most common arrangement. Although not explicitly specified, the implied three gage arrangement at Signature Bridge was an equal spacing of 120° around the perimeter of the reinforcement cage (**Figure 1**).

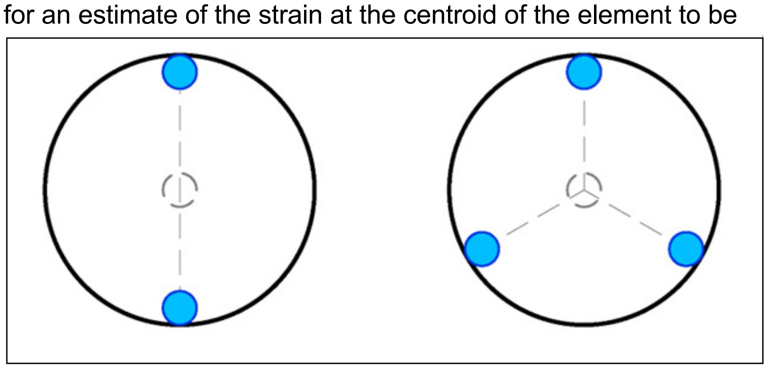

Figure 1. *Typical arrangement of opposed pair and triplet strain gages in pile cross section with computed average (dashed lines)*

Strain gages installed within cast-in-place elements in the field have a relatively high probability of failure λ. For drilled shafts, heavy rebar cages must be picked by crane, tilted from horizontal to vertical and then inserted into the excavation. Concreting then takes place, either via the tremie method or by gravity pour, either of which is a dynamic process with plenty of opportunity to damage a gage. For ACIP piles, the rebar cage is typically lifted only at the head only for insertion into the wet grout. This necessitates inducing a bend into the cage, followed by rapid insertion of the cage into grout under self-weight. In the Signature Bridge case history testing program, from a total of 677 sisterbar strain gages installed in eleven test piles, seventeen strain gages failed to function during testing for a λ of 2.5%.

In order to compute the average strain at the centroid of the pile cross-section, the gages at a given level must be arranged symmetrically. If there is no redundancy with independent opposed pairs of gages, then all the gages at a given level must function. Given *n* gages at a level, the probability of success in this situation is computed as the simultaneous probability of survival of all the gages S_n.

Although in practice if a single gage fails the remaining gage(s) are often still utilized to measure the strain; this is a suboptimal solution because the average of only two strains will not represent the centroid strain if bending is present in the cross-section (**Figure 2**). Thus introducing errors.

Equation 1.
$$S_n = (1-\lambda)^n$$

Using **Equation 1**, the counter-intuitive result is obtained that installing three equally-spaced gages per level (presumably for redundancy) results in a <u>lower</u> probability of successfully obtaining the average strain at the pile centroid (92.6%) than using two gages in an opposed pair (95%), using the numeric values for this case history. This is because in either arrangement, the average strain at the centroid is not obtained if only one gage is lost, and assuming each individual gage has an equal probability of malfunction, there is a higher cumulative probability of losing one gage out of three installed than one out of two installed.

Recognizing this paradox, the project team decided to install the three specified gages at 0°, 90° and 180° around the rebar cage at each level (**see Figure 2**). The gage at 90° position was logged but the data was not used in the analysis of results unless one of the other gages malfunctioned. This resulted in a slight improvement in the overall test program; five of the seventeen malfunctions were gages at the 90° position, resulting in no effect on the data analysis.

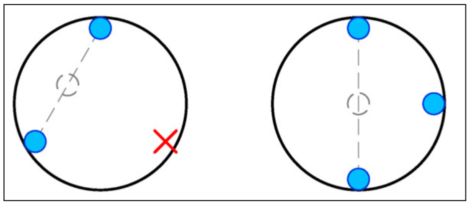

Figure 2. Strain gage triplet averaging results with defective gage (left), and with 0°, 90°, 180° arrangement (right)

Why 4 Is Better Than 2

A significant improvement in redundancy can be achieved by installing four strain gages per level, if they are treated as two independent sets of opposed pairs. If all gages function, then the average strain is computed from all four. However, if any one gage malfunctions, that pair is discarded and the average is computed from the remaining opposed pair only, which presumably should still yield a good measure of strain at the pile centroid. Note that the gages do not have to be spaced at 90° angularly; each pair needs only to be 180° opposed (**Figure 3**). Recognizing this provides flexibility when selecting gage locations around the reinforcing cage.

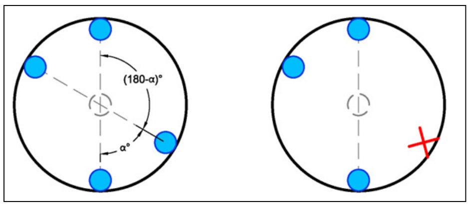

Figure 3. Averaging results for two opposed pairs of strain gages

The probability of success S_{2x2} (**Equation 2**) for this arrangement is computed as one minus the probability of simultaneous failure of both opposed pairs:

Equation 2.

$$S_{2\times2}=1-\left(1-S_2\right)^2=1-\left(1-\left(1-\lambda\right)^2\right)^2$$

Using the same λ of 2.5% results in a success probability of 99.8% (up from 95.0% using two gages in a single opposed pair). Clearly using four strain gages per level significantly improves the success probability, which depending on the test objectives, may convince design engineers that specifying four gages per level is worth the additional expense.

The I-395 Signature Bridge project is one of the first major highway bridges to be supported by ACIP piles in the United States. The use of both TIP and BDSLT technology was instrumental in getting these piles to be acceptable to the design team and Florida Department of Transportation. PDI's continued support of these technologies through the Static Load Tester (SLT) system, TIP Main Unit, TIP Reporter Software, Thermal Acquisition Ports allows these quality assurance measures to be easily applied to nearly any cast in place deep foundation element.

[1]*This article is adapted in part from a paper titled "Optimizing the Arrangement of Strain Gauges in Pile Load Testing" published in the ASTM Geotechnical Testing Journalm September 2020. [Sinnreich 2020].*

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GRL Engineers' Pennsylvania and Texas Offices Expand Team

Ricardo (Alex) Elias

In July, GRL-Texas office welcomed Alex Elias. Alex graduated from Baker College of Flint Michigan with a Bachelor of Science in Mechanical Engineering. Since then he's obtained his Engineer-in-Training (EIT) certificate and has worked on numerous deep foundation projects.

Sayed Rahman

Early August brought Sayed Rahman to the GRL-Pennsylvania office. Sayed earned his PhD. from Villanova University in Geotechnical Engineering and Environmental Engineering. Prior, he completed his Masters of Science in Civil and Environmental Engineering from the University of Massachusetts Dartmouth. He is a licensed Engineer-in-Training (EIT) for Pennsylvania.

Welcome Sayed and Alex!

Upcoming Events

Oct 1-4	GeoSaskatoon - Saskatoon, Canada *Visit Us at Booth #9* *Learn More*
Oct 5-7	DFI India - Vadodara, Gujarat *Visit Us at L5* *Learn More*
Oct 8-11	GeoVirginia - Smithfield, VA *Visit Us at Booth #23* *Learn More*
Oct 9-10	**Workshop: Advanced High Strain Dynamic Testing & PDCA Proficiency Exam - Vadodara, Gujarat, India** *Register*
Oct 11	**Seminar: Deep Foundation Industry Testing and Wave Equation Analysis - Cleveland, OH** 7 PDHs available. Space is limited. *Register*
Oct 12-13	**Workshop: High Strain Dynamic Foundation Testing Workshop - Cleveland, OH** 13 PDHs available. Space is limited. *Register*
Oct 17-18	OTEC - Columbus, OH *Visit Us at Booth #121* *Learn More*
Oct 25-27	SEAGC - Bangkok, Thailand *Learn More*
Oct 30 - Nov 2	SouthEastern Transportation Geotechnical Conference - Charlotte, NC *Visit Us at Booth #48* *Learn More*
Oct 31 - Nov 3	DFI 48 Annual - Seattle, WA *Visit Us at Booth #325* *Learn More*
Nov 1-3	Arizona Roads and Streets - Tucson, AZ *Visit Us at Booth #404* *Learn More*
Nov 15-16	**Workshop: PDCA Engineers Driven Pile Institute** - Baltimore, MD *Register*
Dec 4-7	10th SEFE - Sao Paulo, Brazil *Learn More*

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