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Reliability of Strain Gauges and Load Cells for Geotechnical Engineering Applications

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ABSTRACT

Strain gauges and load cells are often used to measure strain and load in concrete or steel components of geotechnical structures. Reliability problems are frequently cited for these instruments. The purposes of this paper are (a) to discuss the factors that affect the reliability of strain gauges and load cells used for geotechnical engineering applications, (b) to suggest the instrument types that have historically performed most reliably and are therefore preferred by some engineers, (c) to indicate which instruments should prove to be the best choice for future projects, and (d) to establish realistic survivability rates to be used in planning instrumentation programs. These objectives were accomplished by searching published literature and by surveying the opinions of more than 40 knowledgeable geotechnical engineers. The results of the survey as well as published information have been compiled and are included in the paper. The primary considerations for instrument reliability are instrument characteristics and selection. Other considerations include proper planning of the instrumentation program, ability of the instrument to perform the intended function, and field installation and handling techniques. Vibrating wire strain gauges are generally preferred for reliable strain measurement. Electrical resistance strain gauged load cells are generally preferred for reliable load measurement. Planning of an instrumentation program should anticipate the probability that one-quarter to one-half of the instruments may not survive installation or the period of monitoring.

Strain gauges and load cells are used to measure the strain and load in concrete or steel components where there are complex soil-structure interaction problems. Strains and total stresses in soils that are measured with extensometers and earth pressure cells are excluded from this paper. Geotechnical instrumentation may be used during construction of or in-service life of a structure to ensure safety, cost economy, and design and construction method adequacy and to monitor long-term performance. A wide variety of strain gauges and load cells is available to the geotechnical engineer for these purposes.

Geotechnical instrumentation programs commonly are plagued with problems relating to instrument-type selection, real performance characteristics, and installation procedures. The purposes of this paper are (a) to discuss the factors that affect the reliability of strain gauges and load cells used for geotechnical engineering applications, (b) to suggest the instrument types that have historically performed most reliably and are therefore preferred by some engineers, (c) to indicate which instruments should prove to be the best choice for future projects, and (d) to establish realistic survivability rates to be used in planning instrumentation programs.

An interpretation of the opinions of more than 40 knowledgeable geotechnical engineers is presented. These engineers participated in a survey conducted by the authors. The purpose of this survey was to determine what the geotechnical practitioner knows and believes about load and strain measurement in structural members. Given the wide variety of instrument types and manufacturers available, it is rarely possible for one or two individuals to maintain hands-on experience with all currently available instruments. Elaborate instrumentation schemes have failed due to lack of attention to critical details by the user, manufacturer, or designer. The distilled experience of many engineers who have suffered the consequences of instrument or program failures should help reduce the incidence of future failures.

TYPES OF STRAIN GAUGES AND LOAD CELLS AVAILABLE

Several types of strain gauges and load cells exist and are available from numerous manufacturers. Cording et al. (1), Dunnicliff and Sellers (2), and Dunnicliff (3) list and describe in great detail many available instruments as well as their use. Tables 1 and 2 give lists of strain gauges and load cells commonly used in geotechnical engineering and example sources. No judgment of the adequacy of these sources is intended in any way. Addresses of common instrument suppliers are given in Dunnicliff and Sellers (2) and a recently published buyers' guide (4).

Strain Gauges

Mechanical strain gauges are used to measure small changes of length between two reference points attached to a structural member typically 2 to 18 in. apart. The gauge consists of a rigid metal bar with a dial gauge and mechanical linkage. During reading, two posts on the gauge are held in temporary contact with the reference points.

Electrical resistance strain gauges are either of the unbonded or the bonded type. In the unbonded resistance wire gauge, the wire is looped around posts fixed to either end of the gauge. The most common, the Carlson gauge, incorporates two wires, which change in length in opposite senses when the gauge is strained and so permit temperature compensation as an added feature. In the more common bonded resistance strain gauge, a wire or foil is bonded to a plastic film that is attached by the user to the structural member being monitored. Great

TABLE 1 Types and Sources of Strain Gauges[a]

Category	Type of Instrument	Example Sources
Surface Mounted Strain Gages	Mechanical	Huggenberger Soiltest Prewitt
	Bonded Electrical Resistance	Micromeasurements Bean
	Weldable Electrical Resistance	Ailtech Hitech Micromeasurements
	Vibrating Wire	Irad Gage Slope Indicator Geokon
Embedment Strain Gages	Bonded Electrical Resistance	BLH Brewer Micromeasurements
	Unbonded Electrical Resistance	Carlson Huggenberger Ailtech
	Vibrating Wire	Irad Gage Geokon Telemac

[a]Modified from Dunnicliff and Sellers *(2)*.

TABLE 2 Types and Sources of Load Cells[a]

Type of Instrument	Example Sources
Telltale	Geokon Local machine shop
Mechanical	Interfels Proceq Roctest
Hydraulic	Gloetzl Soil Instruments Petur
Vibrating Wire	Gage Technique Irad Gage Telemac
Electrical Resistance Strain Gage	Brewer Slope Indicator Irad Gage

[a]Modified from Dunnicliff and Sellers *(2)*.

skill and experience are needed for field installation of bonded gauges. Success in using these instruments depends on many painstaking steps including surface preparation, bonding, waterproofing, and physical protection, which is usually difficult to attain under field conditions. If designed, installed, and used correctly, these gauging systems can be extremely stable and reliable. A third, and less commonly used, resistance strain gauge, the Ailtech gauge, incorporates a friction-bonded wire resistance element inside a small steel tube welded to steel shim stock and is relatively easy to install. Installation problems are also alleviated in the weldable resistance bonded strain gauge in which an electrical resistance strain gauge is bonded to steel shim stock in the factory and integral electrical leads are attached and sealed. The user has only to grind the surface of the metal structural member and weld the gauge in place with a portable battery-powered capacitive discharge spot welder. This is a relatively simple, easily learned technique.

A vibrating wire strain gauge consists typically of a 2- to 6-in. length of tensioned steel wire free to vibrate at its natural frequency when plucked. For surface mounting, the ends of the wire are anchored to posts clamped or welded to the steel structural member. Changes in frequency and hence in wire tension occur when the gauge is strained. The wire is plucked by an electromagnet either intermittently or continuously. The vibrating wire then induces an AC voltage of the same frequency in the plucking coil; this voltage is remotely recorded. Frequency change is related to strain. Potential problems include thermal mismatch between the gauge and the structure, wire creep, slippage at the wire clamps, and wire corrosion. It appears possible to avoid these problems by proper design and material selection. The potential for zero drift remains, however, and prudent users should install dummy gauges from the same batch mounted on free-standing structural elements that experience no stress but are subjected to the same environment, for the same periods of time, as the active gauges.

Strain gauges may be embedded in concrete or shotcrete directly instead of being mounted on a steel member. In this case it is important to recognize that having measured strain it may be desirable to convert it to stress for more meaningful interpretation of forces in structural members. This is easy and reliable for steel because the modulus of steel is constant and creep effects are negligible. For concrete or shotcrete, however, creep and other extraneous strains may be extremely large and under these conditions interpretation of data even from a 100 percent reliable strain gauge can be exceedingly difficult. If these problems are recognized, strain gauges may be used as follows: Resistance wire or foil gauges may be bonded to a reinforcing bar or a short section of a reinforcing bar. Unbonded resistance strain gauges such as the Carlson gauge may be embedded directly in concrete. An Ailtech gauge or a vibrating wire strain gauge mounted between two end flanges may be similarly embedded. In all cases a dummy gauge should be embedded in the same shotcrete or concrete not subject to stress but kept in the same environment as the active gauges.

Load Cells

Load cells measure force, or load, in a structural member. Telltale load cells consist of an unstressed sleeved steel rod usually installed alongside a tieback tendon or rock bolt. The lower end of the rod is attached to the tendon and movement is measured between the upper end and the bearing plate at the anchorage head. Load is determined from in situ calibration during stressing or is based on the tendon dimensions and properties. Direct access is usually needed for readings and telltales can be difficult to install alongside tendons.

Mechanical load cells are infrequently used and few are available in the United States. They may incorporate elastic spring washers or a torsion lever system. Reading is by a dial gauge.

Hydraulic load cells consist of two thin circular steel plates welded together around the edge to form a fluid-filled chamber. The fluid pressure is measured directly by a bourdon gauge or remotely by a pneumatic, hydraulic, or electrical transducer. The hydraulic load cell must be installed between two rigid steel bearing plates and can be provided with a center hole for tieback applications. Hydraulic load cells have successfully withstood driving when mounted on concrete piles and are continuing to function after 2 years according to Green et al. (5).

Both electrical resistance and vibrating wire strain gauge load cells are essentially based on the same concept of operation. A steel or aluminum alloy cylinder is loaded in compression on the ends of the cylinder. Bonded resistance strain gauges are mounted in various bridge configurations typically on the outside of the cylinder at midheight. Alternatively, vibrating wire strain gauges can be similarly mounted or mounted in longitudinal drill holes in the cylinder wall. Solid center load cells for compressive load measurement usually incorporate a spherical seating to avoid edge loading effects. Hollow center load cells, commonly used for tiebacks, are sensitive to eccentric loads and also should be mounted between spherical seat washers or other devices to minimize end effects. Arguments sometimes arise about the true load on a tieback as a result of overlooking eccentricity or inadequate mounting provisions.

COMMON USES

Strain gauges and load cells are commonly used for instrumenting the following types of structures:

- Excavation bracing--struts, soldier piles, and rakers;
- Tiebacks--bar, strand, and wire;
- Retaining walls--cantilevered concrete, steel sheet piles, and Reinforced Earth embankments;
- Tunnels and shafts--steel liner plate, steel sets, cast-in-place concrete, segmented precast concrete, and shotcrete;
- Dams--concrete arch and concrete gravity;
- Locks--concrete;
- Cofferdams--steel sheet piles;
- Pavements--concrete and asphalt;
- Shallow foundations--spread footings and rafts;
- Deep foundations--concrete, steel, or wood piles and caissons;
- Pipelines--water, gas, oil, and sewer;
- Offshore structures--towers and drill rigs; and
- Nuclear waste isolation--in situ tests.

Instrumentation serves a variety of functions depending on the needs of individual projects. Instrumentation can be used during research and development programs or to provide input to the design or remedial treatment of a structure. Construction safety, costs, procedures, and schedules can be controlled with instrumentation as the structure is built. After the structure is built, instrumentation can be used to monitor long-term performance.

FACTORS THAT AFFECT INSTRUMENT RELIABILITY

An attempt was made to identify the most important of the factors that affect the reliability of strain gauges and load cells used for geotechnical applications. Eight factors were listed in the survey distributed to the participating geotechnical engineers. The results of this survey are given in Table 3.

"Instrument characteristics and selection" was chosen as the most important of the factors that affect reliability. Wilder et al. (6) identified several pertinent controlling factors in instrument design, selection, manufacture, and installation. A more complete list to aid the user in selecting the most suitable instrument for a specific application follows:

- Instrument principle;
- Accuracy;
- Sensitivity;
- Measurement range;
- Reliability;
- Environmental factors--temperature limits, humidity, and corrosive agents;
- Operating life;
- Quality control;
- Manufacturer's reputation; and
- Cost.

All of the necessary characteristics of an instrument application should be assessed and then used in selecting an instrument that will perform to those specifications. If no such instrument exists, the specifications must be relaxed or the application modified to reflect the available instruments. In some cases an instrument can be custom designed for a particular job.

Survey respondents considered matching of available instruments to program needs the next most important of the factors that affect reliability. "Proper planning of the instrumentation program," "the ability of the instrument to perform for the intended use and environment," and "field installation and handling" tied for second place.

The other factors listed on the survey had less importance than did the ones just named. Nevertheless they affect instrument or data reliability and include the following (ranked according to survey results):

- Instrument mounting,
- Monitoring procedures and personnel,
- Calibration requirements, and
- Data interpretation.

Some respondents ranked all of the factors as having equal importance. Perhaps some factors are redundant and others too simplistic. This may have led to a problem in ranking. A more extensive survey could have been used to evaluate strain gauges and load cells separately.

Data interpretation is, appropriately, the tail end of the process as the survey results indicate. Interpretation is an engineering or scientific function. Different approaches may yield different interpretations of the same reliable data. But no one, except by accident, will be able to interpret truly unreliable data, except to ignore it.

Other factors, which affect reliability more than do the ones listed, were offered by respondents. These include

- Expertise and motivation of the person or persons doing the work,
- Manufacturer's instrument quality,
- Contract provisions for protection of the instruments, and
- Understanding of the thermomechanical characteristics and limitations of the instrumented structure.

COMMONLY USED TYPES OF STRAIN GAUGES

Although there are many varieties of strain gauges, they fall into three general categories: mechanical, electrical resistance, and vibrating wire as discussed earlier. The second two types can be surface mounted or embedded and read remotely. The decision to use one type of gauge instead of another should be considered on a case-by-case basis. No one type is best for every application and instrumentation team. Manufacturers are often extremely helpful in determining which gauge to use for a particular application. However, it is advisable to consult more than one manufacturer, to remove any bias that may occur, as well as colleagues for up-to-date user in-

TABLE 3 Strain Gauge and Load Cell Reliability Survey[a]

I.	The most important factors which affect the reliability of strain gages and load cells used for geotechnical engineering applications are: (Please rank numerically with 1 being the most important)	**Rank**
	A. Proper planning of instrumentation program	2 (tie)
	B. Instrument characteristics and selection	1
	C. Instrument mounting	3
	D. Field installation and handling	2 (tie)
	E. Calibration requirements	5
	F. Monitoring procedures and personnel	4
	G. Data interpretation	6
	H. Ability to perform for intended use and environment	2 (tie)
	The following factor affects instrument reliability more than any listed above:	(See text)
II.	Respondent has used strain gages and/or load cells for the following types of structures (Check all applicable)	**Instrumentation used by respondents**
	A. Retaining Walls	73 %
	B. Tunnels	73 %
	C. Pavements	33 %
	D. Shallow Foundations	37 %
	E. Deep Foundations	59 %
	F. Dams	53 %
	G. Pipelines	25 %
	H. Excavation Bracing	49 %
	I. Tiebacks	54 %
	J. Other	33 %
III.	Based on actual experience, the following types of instruments are the most reliable: (Indicate which are most reliable and state for what application)	**Preferred by respondents**
	A. Surface Mounted Strain Gages	
	Mechanical	11 %
	Bonded Electrical Resistance	21 %
	Weldable Electrical Resistance	17 %
	Vibrating Wire	51 %
	B. Embedment Strain Gages	
	Bonded Electrical Resistance	33 %
	Unbonded Electrical Resistance	9 %
	Vibrating Wire	58 %
	C. Load Cells	
	Telltale (e.g. for tiebacks or piles)	4 %
	Mechanical (e.g. a proving ring)	4 %
	Hydraulic	20 %
	Vibrating Wire Strain Gage	29 %
	Electrical Resistance Strain Gage (Most common type)	43 %
IV.	The following survivability rates should be used in the planning of instrumentation programs: (Circle one for each category)	**Average for all respondents**
	A. Strain Gages.....25%.....50%.....75%.....100%	62 %
	B. Load Cells......25%.....50%.....75%.....100%	74 %

[a]Total number of respondents = 40 (60 percent of mailing).

formation. In the survey, respondents had the opportunity to indicate the type of gauge they thought was most reliable on the basis of actual experience. A general preference for one type of gauge does not mean that other types should not be used for certain applications.

Mechanical surface strain gauges were least preferred by survey respondents as shown in Section III of Table 3. Mechanical gauges are inexpensive, reusable, rugged, and reliable but offer limited resolution. This type of gauge requires direct physical access to place the gauge on the reference points. Remote reading is not possible. Gauge length can be relatively large, which may be a distinct advantage on concrete, and this type of gauge should not be overlooked where access is available.

Approximately one-third (38 to 42 percent) of the respondents preferred electrical resistance strain gauges for strain monitoring installations. Resistance gauges possess many advantages and provide a higher degree of resolution than do mechanical gauges. Long-term reliability is somewhat doubtful due to the tendency for the gauge zero to drift, the frequent intrusion of moisture, and uncertain temperature effects. Because these gauges function on resistance changes, extremely long lead wires cannot be used without special signal-enhancement electronics. Factors that are of importance when using bonded electrical resistance strain gauges include

- Gauge location and mechanical protection;
- Thermomechanical properties of structure to be gauged and relative stiffness;
- Adhesive--materials used, surface preparation (roughness, cleanliness), clamping pressure, curing temperature and humidity, time for mechanical-thermal equilibrium, and calibration techniques;
- Waterproofing method; and
- Lead wire characteristics and mechanical protection--bridge circuitry, grounding, electrical shielding, connection to gauge, and physical properties (resistance to moisture ingress).

Considerable skill is required to successfully install bonded resistance strain gauges in the field and this job is best left to experts. Many of the problems can be avoided by using weldable resistance strain gauges with integral leads. These gauges can be successfully installed by either skilled engineers or technicians with limited training and practice.

Vibrating wire strain gauges were preferred by more than half (51 to 58 percent) of the survey respondents for most applications. Vibrating wire gauges provide a high level of resolution without being readily affected by moisture or lead wire length. They are sometimes reusable (at least in part) when surface mounted. As mentioned earlier, wire fatigue can occur over extremely long periods of time. Manufacturers have taken steps to correct this by heat treating the wire and limiting the wire tension. Zero drift has also been observed with some gauges but can to some extent be compensated for with dummy gauges. Recently new, low-profile, low-inertia, weldable vibrating wire gauges have become available. These gauges can be easily installed with a portable battery-powered capacitive discharge spot welder (7). These gauges are smaller, easier to protect, and will more readily survive driving when mounted, for example, on driven steel piles. Vibrating wire strain gauges have been used successfully in Europe, including the U.S.S.R., for the past 30 or more years. Only in the last 10 years have they been manufactured in the United States. Interestingly, the European gauges tend to be significantly more expensive and more heavily engineered than their U.S. counterparts and are still preferred by some government agencies that require long-term reliability and are able to justify the extra cost of procurement. The following factors, similar to those that relate to electrical resistance gauges, are important when using vibrating wire strain gauges:

- Gauge location and mechanical protection,
- Thermomechanical properties of the gauged structure relative to the gauge,
- Mounting method, and
- Cable location and protection.

COMMONLY USED TYPES OF LOAD CELLS

Telltale and mechanical load cells were not preferred by the survey respondents for reliable load measurement possibly because of their recent introduction (telltales) or limited availability (mechanical load cells). Telltale load cells are not very precise but can be valuable for measurement of load distribution in tieback tendons or piles. Mechanical load cells are commonly used for soils laboratory testing but few field versions are available.

Twenty percent of the respondents preferred hydraulic load cells for reliable measurement of load in structures. Hydraulic load cells are less readily available in the United States but can be reliable and have the advantage of simplicity and low profile. Important factors to be considered when using all load cells are

- Load cell location and protection;
- Accessibility--need for remote monitoring;
- Eccentricities;
- Insufficient reaction, bending in support plates;
- Calibration requirements;
- End effects;
- Weatherproofing;
- Temperature effects on the load cell and its mountings; and
- Lead protection, where used.

Electrical resistance and vibrating wire strain gauged load cells were preferred by 43 and 29 percent of the respondents, respectively. Factors that affect the use of these load cells are similar to those that affect the use of electrical resistance and vibrating wire strain gauges discussed previously. The major difference between the use of strain gauges and load cells is that load cells come from the manufacturer as one complete unit. The intricacies of mounting the strain gauges in the field are therefore avoided with load cells.

SURVIVABILITY RATES

The respondents to the survey were asked to recommend instrument survivability rates for planning instrumentation programs. The results were averaged and survivability rates for strain gauges and load cells were recommended to be 62 and 74 percent, respectively. Survivability rates recommended by respondents ranged between 25 and 100 percent. The specific numerical results are not as important as the need for owners, designers, manufacturers, and field personnel to face the probability that a significant number (one-quarter to one-half) of the instruments will not survive. Proper planning should be done to compensate for these instrument losses and to ensure that the required number survives to provide sufficient reliable data. Short-term survivability of instruments can be assumed to be better than long term. Both depend on the personnel doing the work, the duration of the instrumentation program, and the environment in which the instrument will be placed.

Many owners effectively encourage low survivability rates by using low-bid procurement procedures. Such procedures can result in the cheapest priced and poorest quality instruments being used. Reputable manufacturers can be forced to cut corners in design and manufacture to underbid their competition. Lengthy specifications aimed at circumventing this will often be unsuccessful. In contrast, adequately funded thorough work by competent organizations with appropriate experience can achieve a high success rate under extremely difficult and challenging conditions (8).

Despite these successes there are many outstanding problems yet to be solved; the nuclear waste disposal industry recently recognized this (9). The particular application of instrumentation to nuclear waste isolation makes extraordinary demands for reliability under extreme conditions not typically encountered in civil works.

CONCLUSIONS

"Instrument characteristics and selection" is the primary consideration for reliable use of strain gauges and load cells in geotechnical engineering. Other important considerations are

- Proper planning of the instrumentation program,
- Ability of the instrument to perform its intended function in the field environment, and
- Field installation and handling.

Vibrating wire strain gauges were preferred for strain measurements by the geotechnical engineers who responded to the survey. Electrical resistance strain gauged load cells were preferred to other types for measuring load in a structure.

Bonded electrical resistance strain gauges should only be installed in the field by experts. Field weldable gauges are available that can be more easily installed by geotechnical engineers or technicians.

Recently available, low-profile, weldable vibrating wire strain gauges possess a number of advantages over traditional gauges.

Conversion of strain to stress or load in concrete can be unreliable even when the best available techniques (i.e., controlled laboratory tests and dummy no-load gauges) are used. Direct measurement of load is preferable where possible (e.g., install a steel load cell across the full diameter of a concrete pile).

Good-quality load cells will give unreliable results if improperly installed between inadequate bearing plates.

Better quality, typically higher priced, instruments are often a better choice because they tend to provide more reliable data. In many cases gauges once installed can never be accessed again and the entire program may end in disaster if the gauges fail.

Planning of instrumentation programs using strain gauges or load cells should assume that one-quarter to one-half of the instruments will not survive through the entire program.

Low-bid procurement procedures encourage low-quality instruments, perhaps designed down to a price. Reliable data are less likely to be obtained from these instruments.

ACKNOWLEDGMENTS

The authors are grateful to those persons within Parsons Brinckerhoff Quade & Douglas, Inc., and Shannon & Wilson, Inc., and outside who assisted in the data gathering and preparation of this paper. The engineers who responded to the survey provided guidance and inspiration, and their contribution is acknowledged. In addition, the authors acknowledge John Dunnicliff and Bill Hansmire both of whom have helped the profession gain a better understanding of planning, design, installation, and monitoring of geotechnical instrumentation programs. Thanks also go to Regina Isidori for her patience and help in preparing the manuscript.

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