AC 2008-724: THE PEDAGOGY OF THE SURVEYING LABORATORY

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THE PEDAGOGY OF THE SURVEYING LABORATORY

Abstract

Surveying and surveying laboratory (field work) fifty years ago were standard fair for most engineering programs in all disciplines. Today, in the 21st Century, surveying is no longer an integral part of all engineering programs; in fact, it is not even a standard part of many Civil Engineering (CE) programs. Plane surveying, the determination of the location of points on or near the surface of the earth, is rapidly becoming a lost art in the civil engineering curriculum. This paper is not an attempt to resurrect surveying in the modern CE curriculum. It looks at surveying field work in an historical perspective; to highlight changes in the art of surveying and how they have impacted both the teaching and practice of surveying, and to point out conceptual features of surveying field work and show how selected activities were particularly suited to teaching fundamental concepts applicable to a wide range of engineering disciplines. There is a bit of nostalgia in the paper, but most important there is the identification of key skills that once were the prerogative of the surveying lab and suggestions for how these skills might be brought into the CE curriculum again and perhaps serve a useful role in other engineering disciplines as well.

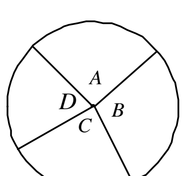
A few of the topics that will be explored in this paper include:
(1) the relationship between the precision of instruments used in measurement and the nature of the methods used to adjust values that are the result of random errors;
(2) how methods have changed over time due to technological advances in equipment; and
(3) how techniques used for long distance surveys such as triangulation, trilateration and Global Positioning Systems (GPS) have changed or been modified over time and why.

A major focus of the paper is to "separate the chaff from the wheat," that is, to separate what is fundamental and not subject to change over time from what is transient and temporal, with the objective of designing a modern state-of-the-art laboratory experience.

Introduction

The history of surveying instruments and their applications dates back to early Egypt. A review of the literature on the history of surveying instruments used for boundary location and the construction of civil works such as roads, bridges, buildings, etc., did not reveal any observations on the relationship of the precision and accuracy of state-of-the-art instruments and the techniques used for the adjustment of observed measurements. Perhaps it was just the result of innate judgment that resulted in the methods for adjusting measurements to agree with known physical relationships. For example, it is obvious that the sum of the interior angles in a circle as shown in Figure-1 must be equal to 360º.

Fig 1



$$\Sigma(A + B + C + D) = 360^\circ$$

Plane Geometry of a Circle
(Defined relationship)

When these angles are measured with an instrument the individual angles may or may not add up to 360º. A method had to be developed to adjust the angles such that, after adjustment, they would equal to 360º. In order to develop a rational method, it was necessary to understand the nature of the errors in the measurement of the angles. An obvious initial consideration is that the error should be distributed among the angles in proportion to their size. A more careful analysis of how the angles are measured results in the realization that the magnitude of an individual angle has virtually no bearing on the error in the magnitude (value) of the angles, resulting in a method for adjusting the angles by increasing or decreasing each angle uniformly to bring the sum of angles into compliance with the defined relationship.

Pedagogically having the students know and be able to apply this relationship is a training concept. Being able to understand why this relationship is used is the essence of education. Developing this insight in our students is important for their general education. In this case surveying is merely an excellent medium for the illustration of these concepts.

The body of this paper illustrates how the methods used to adjust surveying measurements are related to the instruments and how they are used. As the quality of surveying instruments in terms of precision and accuracy developed, the methods of adjustment changed. In some circumstances, standard procedures reverted back to earlier methods. Changes and advancements in instrumentation were a major factor in this evolution (see discussion of the measurement of angles later).

Traverse Adjustment[3]

The traditional way of establishing horizontal control is to layout a closed traverse. A traverse is a plane polygon of three or more sides. Each side of the traverse is the hypotenuse of a right triangle. When oriented in a north-south direction, the projection of the side in the east-west direction is called the departure, and the projection in the north-south direction is called the latitude. The angle that the side makes with a north-south reference line is called the bearing of the side. Because the sides and the angles are measured with varying degrees of precision, the sides of the polygon do not close. This failure to agree with the geometry of the closed figure is called the error of closure.

$$\Sigma \text{ Interior Angles} = (n-2)\ 180^\circ$$

The final location of the corners of the traverse (coordinates) requires that the error of closure be reduced to zero. This is accomplished by adjusting the latitudes and departures of the sides to achieve an error of closure equal to zero.

There are two traditional methods for adjusting the latitudes and departures of a closed traverse[1], The *compass or Bowditch rule* and the *transit rule*. The essential difference between these two rules is the assumption made regarding the order of precision of the measurement of the angles and distances of the traverse. In the early 19th century the precision with which to measure distances and angles were approximately the same. Because of this, Commander Bowditch developed the Compass Rule, which adjusts the latitudes and departures in proportion to the length of each side of the traverse to the sum of the perimeter of the traverse.

ALSn = Adjustment to Latitude of Side (n)
TEL = Total Error in Latitude
Perimeter = the sum of all sides

ALSn = (Length of Side (n) / Perimeter) x TEL

ADSn = Adjustment to Departure of Side (n)
TED = Total Error in Departure
Perimeter = the sum of all sides

ADSn = (Length of Side (n) / Perimeter) x TED

Compass Rule

This method of adjustment applies equal weight to the measurement of the sides of the traverse and the angles. This is because the precision of the measurement of both sides and angles were approximately equal.

As improvements occurred in the instruments for measuring angles, it became clear that the ability to measure the angles was superior to the ability to measure the sides of the traverse. This led to the use of the transit rule. The transit rule adjusts the latitude of each side as a proportion of this latitude to the sum of the latitudes of all sides; similarly, the departure of each side is adjusted as the proportion of that departure to the sum of the departures of all sides.

ALSn = Adjustment to Latitude of Side (n)
TEL = Total Error in Latitude
SL = the sum of all latitudes

ALSn = [Latitude of Side (n) / SL] x TEL

ADSn = Adjustment to Departure of Side (n)
TED = Total Error in Departure
SD = the sum of all Departures

ADSn = [Departure of Side (n) / SD] x TED

Transit Rule

The interesting characteristic of this method is that it favors the angles in the traverse over the length of the sides. Then, near the end of 20^{th} century, the development of electronic distance measuring (EDM) equipment, coupled with the precision and accuracy of optical theodolites, increased the precision and accuracy with which the distances could be measured. The ability to measure angles and distances again became comparable, resulting in a return to the Compass Rule for traverse adjustments.

It is of pedagogical value for the students to be exposed to illustrative examples such as this in order for them to appreciate the relationship between practice and theory. The basic concepts of establishing horizontal control by means of a traverse have not changed. But the pedagogy for manipulating the data has changed due to the changes in instrumentation. This concept is common to virtually all aspects of engineering measurements regardless of discipline. Exposing the student to the process by which the "what" in the practice of their profession has led to the "why" something is done in a certain way enhances their ability to contribute to the advancement of the discipline.

Horizontal Control

In the 17th century the US Coast and Geodetic Survey was established in recognition of the need to determine the location of points in the United States. Nationwide this was accomplished through the use of a method called triangulation. In this method a rather long base line is measured on one coast, say 25 miles, using a steel tape and taping bucks[6]. Using a transit to ensure that the line is straight and leveling to determine the elevations of the ends of the tape, a very precise measurement is made of the base line (a very long and tedious task). See Figure-2 on the left is a metric leveling rod, in the center a taping buck. The elevation of the end points of the tape are determined with dumpy level as shown in Figure-3.

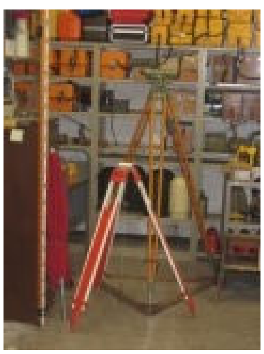


Figure 2

Figure 3

Figure 4

In the 1940's this technology permitted the measurement of horizontal distances to one part in 100,000. Then a network of triangles was constructed across the country where only the angles were measured. This also was a tedious task. However, this was the most practical means of traversing the country because only one base line needed to be measured and through the network of triangles a series of points across the country could be established through the mathematical procedure known as triangulation. Each angle within the network of triangles was measured with great precision. As a check or closure a line in the last triangle on the west coast was measured as was the initial line and its value checked against the calculated value of the line. This method was used because of the relative ease and precision with which the angles could be measured

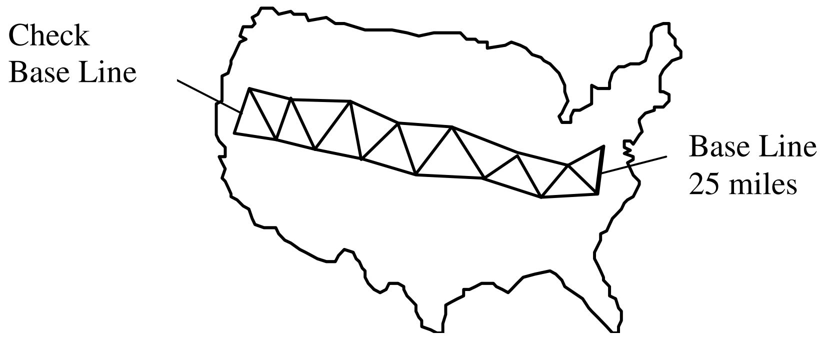


Figure 5

The check line on the west coast permitted the adjustment of all the points on the network. Here again the advent of Electronic Distance Measuring (EDM) instruments allowed the sides of the triangles to be measured and the location of the corners to be established using the mathematical technique called tri-lateration. The congruency of triangles has not changed but the method of determining congruency has changed from Angle-Side-Angle (ASA) to Side-Side-Side (SSS) Figure 5.

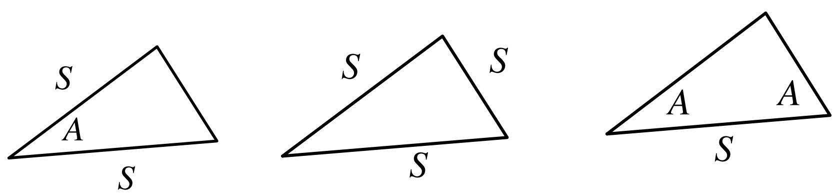


Figure 6

The importance of horizontal control remains the same. The technology and advancement in instrumentation has made the techniques used different. In this case, a method that was once used and replaced by a different method came back into use because of developments in instrumentation. In virtually every development the final application results in a saving in cost and quality of product.

Vertical Control

Vertical control is very important. The flow of water, the locations of antenna for all kinds of transmission towers, and ground elevations for flood control are just a few of the many engineering tasks that are dependent on accurate vertical location. The vertical location of points on or near the surface of the earth has been accomplished in many varied and unique ways. Establishing a standard or reference for measurement has always been an important part of measurement. The use of the force of gravity has been the reference for establishing vertical location for most of history, especially when the size of the area under consideration may be considered flat. Even when an area is large enough to be influenced by the curvature of the earth, the surface of water was used to determine a level surface. This characteristic of a liquid stabilizing due to the pull of gravity led to the development of the bubble level. The greater the length of the radius of curvature for the bubble tube the greater the precision with which you can determine a level line of sight. See Figure 6 of a precise level that can discern vertical differences in elevation of $1/10^{th}$ of a millimeter. (See appendix for an overview of Differential Leveling[2].)

Technology has made a number of advancements in the instruments for determining vertical location. An understanding of the optical geometry of prisms and the ability to suspend them in a stable condition in the line of sight of a level provided the technology to create the automatic level. One of the most difficult tasks in leveling has always been the ability to establish a level line of sight using level screws and a spirit bubble. The automatic or self-leveling level virtually eliminated the human errors that resulted from an individual's inability to level the instrument. See Figure 7 a cut-a-way of a self leveling level and Figure 8 a close-up the prism assembly that maintains a level line of sight for the instrument. With the advent of computers and the shrinkage in size of computer components it became possible to develop a leveling instrument that could automatically read the leveling rod when the rod is calibrated with the barcode system, thus eliminating the human error associated with the readings of the numbers on the rod see Figure 9.

Figure 7

Figure 8

Figure 9

The laser has made may of the tasks associated with vertical position not only more accurate to determine but also able to be conducted with fewer personnel and thereby at a lower cost. But the fundamental principles of vertical location still remain the same. It is of value to the students to understand that the reasons for needing to know vertical location have not changed at all, but advances in technology have permitted the determination of vertical location with greater accuracy and precision and with lower overall cost.

The development of lasers requiring very little power for relatively long applications (sights) was also a key development in the realization of the automatic level. The reference for vertical control however still remains tied to a vertical reference line established by gravity. With the introduction of satellites the location of points, both horizontally and vertically, may now be established in reference to a geodetic ellipsoid (oblate spheroid) to within a few centimeters (less than an inch).

Methods of traversing

Historically, to establish the location of points necessary for the control of the boundary of properties and the construction of engineering works such as buildings, bridges, dams, etc., closed polygons were used to establish the control. The reason for using the closed figures was to establish the precision of the measurements in order to adjust them to achieve sufficient accuracy. The geometry of a closed figure made it possible to do this. When distance measurements were accurate to about 1 part in 5,000 (this corresponds to about 1 foot in a mile) and angles were measured to 1 minute (equal to about 1.5 feet in a mile), the adjustment of measurements was essential.

The advent of instruments that enabled angles to be measured to less than 1 second, which is far better than the ability of the human operator to point the instrument (5 or 6 seconds or a little over 0.1 foot in a mile), and the development of electronic distance measurement instruments led to linear measurements with precision in the order of over 1 part in a 100,000 (about 0.05 feet in a mile). This allows the surveyor to conduct a radial traverse, which requires only one instrument setup in place of the multiple set-ups involved in a traditional traverse. The importance of the geometric check afforded by a closed polygon is less critical when offset by the speed and ease of completing the radial traverse. If necessary a closed traverse is still appropriate. Figures 10a and 10b illustrate the closed and radial traverses.

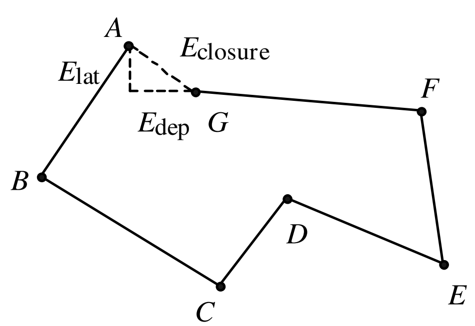


Figure 10a

Traditional Traverse
Error of Closure
Instrument setup at every corner

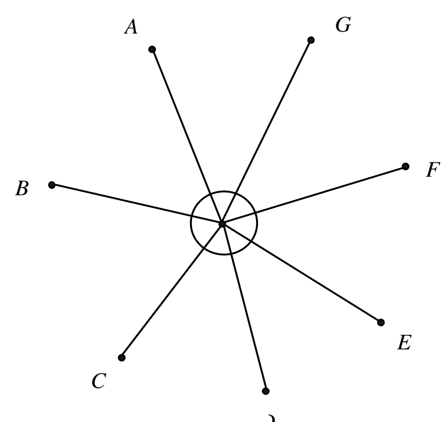


Figure 10b

Radial Traverse
Instrument setup once

Vertical-control surveys establish elevations for a network of reference monuments called *benchmarks*. Depending on accuracy requirements, control surveys have been run by either *differential leveling* or *trigonometric leveling*.

The ellipsoid is a mathematical surface obtained by revolving an ellipse about the earth's polar axis. Ellipsoids can be defined mathematically and are used to define the position of widely spaced points on large control surveys[4].

Now with a myriad of satellites orbiting the earth and high speed computers that can process millions of data sets in real time, the location of a position on the surface of the earth in reference to a mathematical ellipsoid can be determined to within a centimeter or two (about 0.05 of a foot). Position can now be identified to a global reference system.

The need for knowing the location of points and their relationship (distance and orientation) on or near the surface of the earth is essentially unchanged. The precision required and accuracy necessary for engineering works is ever changing and the instruments and procedures used will always be developing as advances in technology take place, but the fundamental concepts associated with measurement will remain unchanged.

It is the understanding of the fundamental concepts that are important for a students' career, the technology of the moment for one's first job, and an appreciation of how and why things are what they are so that they may add to the continuing development of our engineered world.

Conclusion

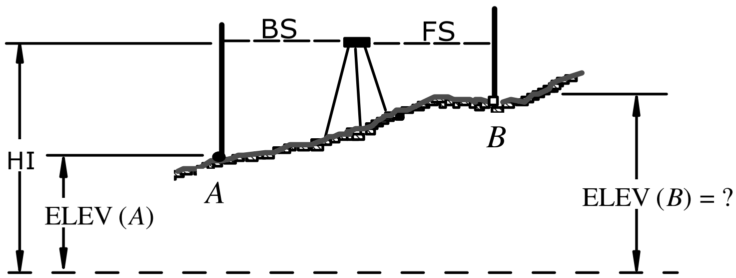
In the first half of 20th century, all engineering students in the US studied surveying regardless their discipline. Measurements are an essential part of not only every engineering discipline but virtually every field of study. The concepts of error, random and systematic, are also common to all disciplines. The value of surveying measurements was that they were of significant magnitude so that the students could "see" the difference between random and systematic errors. The influence of the instruments and their state-of-the-art features and the ability of the user to manipulate the instruments instilled in the student an appreciation of the experimental aspects of engineering. Time has provided technology changes, both in instruments and techniques, but fundamental concepts remained unchanged.

The surveying laboratory was (is today for those that take a laboratory) a wonderful experience for understanding the difference between *training* and *education*. The authors trust that this brief foray into the relationship between tools and techniques has been interesting and motivational for all educators not just engineers. In the Civil Engineering program at UDC we include the concepts articulated in this paper in our required surveying course. It is the authors' suggestion that the fundamental ideas that have been presented be incorporated into measurement courses in every discipline. For example, in the field of Biology, in the past we have seen the ability to observe and measure molecular relationships advance from optical microscopes to electron scanning microscopes. At each development the precision and accuracy of measurements improved while the importance of measurements remained unchanged.

APPENDIX

Differential Leveling [5]

A brief overview of the fundamental concepts of Differential Leveling



REFERENCE DATUM

Fig. 11

ELEV (*A*) = the elevation of point *A* (known or assumed)
ELEV (*B*) = the elevation of point B which is unknown.
BS = Backsight reading (height of line of sight above known elevation)
FS = Foreseight reading (height of line of sight above unknown elevation)
HI = Height of instrument (elevation of line of sight)

The *elevation* of any point may be defined as the vertical distance above or below an assumed reference datum on the earth's surface. The most commonly used reference datum is "sea level" with an assumed elevation of 000.00 feet or meters. By establishing a reference surface, the line of sight of a level instrument, the difference in elevation can be determined between any two points. When the elevation of one point is known, the elevation of the other point may be established.

Here, the level is set up near a benchmark in the direction of progress, and a rod is held vertically and elevation is read on the benchmark. When this reading is added to the elevation of the benchmark, the result will yield the Height of the Instrument (HI). Then a firm point beyond the instrument is chosen, in the direction of progress, and at nearly the same distance from the instrument as the benchmark. This point is called a Turning Point (TP). Subtracting this reading from the height of the instrument, will yield the elevation of the turning point. It is interesting to note that when the two points sighted from a single instrument setup are at approximately equal distances from the instrument, the instrumental errors are cancelled. This process can be continued indefinitely. This work must be carried on until a benchmark of known elevation is reached.

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