Establishment of Calibration Base Lines

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Abstract

The calibration of electronic distance measuring instruments involves the determination or verification of instrument constants and the assurance that the measured distances meet accuracy specifications. To assure that the measuring accuracy as well as operating precision capabilities of an instrument has not significantly deteriorated, a known distance of high accuracy or, preferably, a sequence of distances forming a calibration range or base line is required. Experience shows that a base line consisting of four in-line monuments spaced at specific intervals will meet the needs of users. Specifications and recommended procedures for establishing calibration base lines are described in detail.

Introduction

Standards of length have existed since the surveying profession began early in the 19th century, the Survey of the Coast [subsequently named the U.S. Coast and Geodetic Survey (USC&GS), now the National Geodetic Survey (NGS)] adopted the meter as the standard for use in geodetic surveys of the United States. Land surveyors, on the other hand, employed the foot as their standard, as did most surveyors involved in engineering and associated surveying activities. For many years, the standardization or comparison of measuring devices with known values was rudimentary, even after the National Bureau of Standards (now the National Institute of Standards and Technology) developed methods for accurately determining the length of a tape or wire. Eventually, however, most surveyors had access to some means of ascertaining the length of their tapes to an acceptable degree of accuracy. A new dimension was added to the surveying profession when electronic distance measuring devices were invented. Use of these instruments introduced the capability of performing measurements with speed and a degree of precision not previously possible. The implementation of a CBL program ensures the accuracy of EDMI is equivalent to or better than measurements obtained previously.

Brief History

With the introduction of electronic distance measuring instruments (EDMI) in the United States in 1952, the standardization problem was compounded since EDMI measurements are affected by meteorological conditions other than temperature and by several instrument uncertainties that require frequent periodic reevaluations. Although the need for calibration base lines was evident, a test range specifically designed for EDMI reevaluations was not available for more than a decade. In 1963, the USC&GS measured a multi-monumented line in Beltsville, Maryland, using high-precision taping techniques (Poling 1965). The distance of the Beltsville base was approximately 1,800 meters, different from the 1,650 meter distance normally utilized. Later, a much longer line (about 9,050 meters) near Culpeper, Virginia, was measured using similar procedures. Although no major restrictions were placed on the use of these base lines, few surveyors other than those from federal agencies used these facilities to calibrate their equipment.

As more surveyors acquired EDMI, the surveying profession became concerned about the accuracy of their measurements. It has been shown that whereas accuracies attributed by the manufacturers to the instruments are reliable, errors in the observations, which are often systematic, can result from normal usage due to a reduction in the efficiency of electronic and mechanical components. Periodic maintenance, preferably by the manufacturer or a designated representative, is required to minimize such errors. It is equally important to verify the instrument constant and evaluate the measuring accuracy at more frequent intervals.

A known distance is not required to check the instrument constant, but rather can be achieved simply by measuring all distances between three points in-line. A comparison can then be made with the sum of the shorter lengths and the end-to-end measurement. However, to check the accuracy and operating precision of the EDMI, a known distance, or preferably a sequence of known distances forming a calibration range, is required.

By 1970, a number of EDMI were available, and since then various manufacturers have produced many more models. Most of these models are short-range instruments. Because the equipment was being used for nearly all conceivable surveying problems, it was critical that observations meet project accuracies. To resolve the accuracy issue, NGS held in-house discussions and investigated several methods for establishing a calibration base line.

The original concept was to tape the distances between a number of monuments using several Invar-type tapes[1] and high-precision measuring techniques. Four calibration base lines were measured in this manner before discontinuing this time-consuming operation.

In 1977, NGS measured a new base line at its Corbin, Virginia, facility. The base line containing six monuments, with data published on five of the monuments, was measured using high-precision taping methods. This base line replaced the Beltsville base line for calibrating NGS equipment.

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[1] Invar is a steel-nickel alloy developed in France around 1900. Its unique property is that its coefficient of thermal expansion is about 1/25 that of pure steel. Similar alloys are known commercially by such names as L0-VAR® and MINVAR®.

In 2011, NGS established a new base line at its Corbin facility in conjunction with the 1977 base line. The new base line consisted of five forced-centering piers measured using total station theodolites with integrated high-precision EDMI.

Responsibility for Base Lines and Costs

Although this publication describes the establishment of calibration base lines in cooperation with NGS, private surveyors should not be deterred from establishing their own calibration base line.

The requesting organization is responsible for selecting the sites, setting the monuments, and providing experienced surveyors to perform the observations. The requesting organization is also responsible for procuring necessary supplies, such as concrete, lumber, and other miscellaneous materials.

Subject to personnel availability and funding constraints, NGS conducts a cooperative program to provide the public with a means to detect and correct EDMI errors. Participant responsibilities and costs are detailed in the NGS EDMI Calibration Base Line (CBL) policy. The latest policy is available in the Policies section of NGS' website: http://www.geodesy.noaa.gov/INFO/Policy/.

Calibration Range

Design

The typical base line configuration consists of four monuments[2] set in a straight line. To be considered a straight line, the intermediate points must not be off-line by more than two arc minutes. The range should not be less than 900 meters; a shorter overall length will not adequately determine scale. When spaced properly, a four-monument design provides 6 distinct distances when measured in both directions and a total of 12 distances when a complete calibration test is performed.

The monuments take their names from their relative distance from the initial, or 0, point. Hence, a point set at a distance of 120 meters from the 0 point is called the 120 meter point, a point set at a distance of 390 meters from the 0 point is called the 390 meter point, etc.

Based upon EDMI used to support the NGS CBL program, monuments are to be spaced following a "multiple of 30 meters rule" (see page 7). Monuments placed at 90 meters to 150 meters, 360 meters to 420 meters, and 900 meters to 1,410 meters from the initial or "Om" monument (figure 1) would satisfy spacing requirements. The monuments at 360 meters to 420 meters and 900 meters to 1,410 meters are identified as intermediate and terminal points, respectively.

[2] Many existing base lines have been established with extra monuments for calibrating tapes. NGS no longer provides this service.

Figure 1. Example of a calibration base line configuration

To ensure six distinct distances, the distance from the 0 point to the second intermediate point must not be a multiple of the distance from the 0 point to the first intermediate point. Example: If the first intermediate point is 120 meters, the second intermediate point must be greater than 240 meters. This also applies for the terminal point; the terminal point must not be a multiple of either of the two intermediate points. Once the intervals between points have been determined, care must be taken during marksetting to maintain those distances to within a few centimeters.

NGS advises the use of the "multiple of 30 meters" rule to obtain the best results from the original measurement, as well as subsequent use of the calibration range. Most EDMI are designed with the basic instrument "yard stick" (wavelength) of 2, 3, 5, or 10 meters. A distance is measured by counting the number of full wavelengths and adding the final (usually partial) wavelength. The component of the instrument which determines (resolves) the partial wavelength is called the resolver. In modern instruments, the resolver itself may generate a small (+/- 5 millimeter) measurement error. (The error in older instruments was as much as +/- 0.3 meters.) To avoid contaminating sub-centimeter level calibration measurements with varying resolver errors, the same section of the resolver should be used for each measurement. Setting the monuments on a multiple of 30 meters will enforce this requirement. Any resolver error included in the computation then becomes nearly a constant for all measurements. The error can be disregarded when determining the instrument constant, but it must be compensated for if a sub-centimeter level length measurement or calibration is desired. The test for resolver error has been described in professional journals (Couchman 1974, Rueger 1978).

Because the calibration range is designed for length calibration only, the elevations, orientation, and positions of the monuments only need to be approximated. Connecting a CBL to the National Spatial Reference System (NSRS) is not required.

Site Selection

Numerous considerations enter into the selection of a calibration base line site.[3] These considerations are as follows:

1. Access. The location should be easy to reach, with minimum restrictions, and safe for public use. The adjusted base line distances will be a matter of public record; the base line site must be accessible to the public.

2. Terrain. As a first consideration, it is important the site terrain be geologically stable and unsusceptible to undue surface movement. Areas of fill must be avoided.

The ideal site would have a gradual downward slope from the "0-meter" monument to the middle of the line, then a gradual upward slope to the terminal point, with the ends of the line

[3] Site selection considerations no longer support calibration of microwave instruments.

at approximately the same elevation. This profile of an ideal grade would allow inter-visibility between forced-centering piers. It also allows inter-visibility between tripod setups over concrete posts. The differences in elevations from the initial point should seldom exceed one percent of the distances involved. To ensure uncertainties of computed horizontal distances fall within acceptable tolerances, the slope between monuments should not exceed three percent.

In many cases, the ideal terrain cannot be found, and a compromise may be necessary. The essential considerations are that all monuments should be inter-visible and that grade tolerances are followed as closely as possible.

3. Manufactured and natural obstacles. For best results, an EDMI lightwave must not travel through inconsistent atmospheric conditions. The lines should not cross pavement (but can run parallel), waterways, or pass closer than 6 meters (20 feet) from trees, telephone poles, or other structures. In addition, lines should not pass through fences, particularly metal mesh fences. As an added precaution, establishment of a range within 0.4 kilometers (0.25 miles) of high-voltage (greater than 4,000 volts) transmission lines, microwave towers, radio masts, or radar facilities should be avoided.

As per NGS policy, any relaxation of site selection considerations must be cleared by NGS prior to establishment of the base line.

Monumentation

Standard Range

NGS will not support installation of ranges with substandard monumentation. Monuments with significant mass placed in relatively undisturbed soil have the best long-term stability. Three types of monuments will satisfy NGS requirements.

Concrete post monuments with survey disks are sturdy, stable, and economical. This type of monument is poured-in-place and may be recessed up to 5 centimeters below grade to help maintain preservation. They may also be flush with the ground to aid in recovery, but only in well-protected areas. Disks may also be set in drill holes in bedrock or rock outcrops. Disks must have a well-defined center point, such as a one millimeter in diameter drilled hole. A center punch should not be used. For concrete post setting instructions refer to Appendix B of NGS publication *Bench Mark Reset Procedures,* Curtis L. Smith, 10, 2007. Forced-centering piers provide convenience and stability. See Appendix C for pier setting instructions. Before using either type of concrete monument, the monument must have undergone a complete frost cycle or have been in the ground for at least six months.

Disks or forced-centering adapters should be stamped with a unique designation. The designation should include the date of establishment. Following is an example of stamping for a standard four-monument base line measured in 2014:

0 M	120 M	390 M	1200 M
2014	2014	2014	2014

Base Line Layout

Once site selection considerations have been met, we recommend the following procedures for monument installation:

Concrete Posts

1. Set a stake at the initial monument site and mark the center point with a small tack or nail.
2. Set up a total station theodolite over the stake at the initial monument site.
3. Set a stake with a center point at the terminal monument site.
4. Set intermediate stakes with center points at appropriate intervals. To help ensure the final monuments will be within 2 arc-minutes of the terminal point, the stakes should be set within 20 arc-seconds of the line.
5. The interval distances and alignment for all stakes should then be verified with the instrument centered over the initial stake. Any adjustments to the stakes should now be made.
6. Set out two reference stakes at each monument site stake (MSS). Each pair of reference stakes are set out at right angles to one another in an area where they will not be disturbed during mark setting. Distances between all three stakes should be carefully measured and recorded.

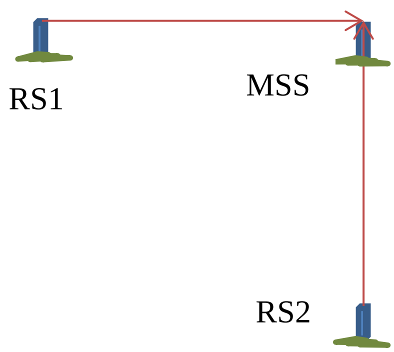

Figure 2. Typical layout of two reference stakes (RS) locating a monument site stake (MSS)

7. Before digging the holes for the monuments, check the distances from the reference stakes to ensure the disk will be centered in the top of the concrete monument.

Forced-centering Piers

1. Set a stake at the initial monument site, and mark the center point with a small tack or nail.
2. Set a total station theodolite over the stake at the initial monument site.
3. Set a stake with a center point at the terminal monument site.
4. Set intermediate stakes with center points at appropriate intervals. To ensure the final monuments are within 2 arc-minutes of the terminal point, the stakes should be set within 20 arc-seconds of the line.
5. The interval distances and alignment for all stakes should now be verified with the instrument set up over the initial stake. Make any adjustments to the line or distances of the stakes.
6. Set tripods over stakes to ensure all piers will be inter-visible. Tripod heads represent the tops of piers. Note their heights for future reference.
7. At each pier site, construct a sturdy plumb bench with uprights on either side of the line at a

safe distance from the monument site stake. The uprights should be high enough to suspend a cross-member about a foot higher than the top of the tripod. Carefully mark the plumb point on the cross-member and measure the height down to the tripod. Remove the tripod.
8. Before digging the hole for the monument, use the plumb bench to ensure the stake has not moved.

Procedures

Electronic Distance Observations

The complete base line will be measured with two high-accuracy total station theodolites on two separate days. Observations will be made with all segments measured, both forward and backward, on each of the two days, with both instruments. The following procedure allows for significant atmospheric variations in the limited time available:

Day One: Beginning at one end of the base line, measure between all marks using both instruments. At the end of the day, there will be a total of 12 distinct measurement sets with each instrument.

Day Two: Start at the opposite end of the base line at approximately the same starting time as for Day One. Re-measure all marks using both instruments. Again, there will be a total of 12 distinct measurement sets for each instrument.

The calibration base line software will compare the results of the two days and warn the user of any poor comparisons. The spread between the mean of the observations with each instrument for each line segment, after corrections and on the same reference surface (i.e. mark-to-mark or horizontal), should not exceed:

$\delta = [0.0017^2 + (D * 10^{-6})^2]^{½}$
Where D = segment length and all units are in meters.

The spread between each day's mean for each line segment, after corrections, and on the same reference surface, should not exceed:
$\delta = [0.0015^2 + (D * 10^{-6})^2]^{½}$

In cases where additional monuments are set, the total number of measurements required for each of two instruments on each day is n(n-1), where n is the number of monuments.

Useful information regarding general observing procedures applicable to most EDMI can be found in NOAA Technical Memorandum NOS NGS-10, *Use of Calibration Base Lines* (Fronczek 1977).

Appendix A

Equipment for Establishing a Calibration Base Line

List of typical equipment:

Instrumentation

2 total station theodolite (manufacturer's stated distance measuring accuracy not to exceed 1 millimeter + 1 ppm)
4 slip-leg tripods (high-stability, heavy-duty, wooden)
4 tribrachs (max. 1" hysteresis)
1 tribrach adapter
1 reflector
2 sets of meteorological equipment (accuracy requirements for barometric pressure: +/- 2 millibars, air temperature: 0.5^{O} C, and relative humidity: +/- 2%)
1 nadir collimator (20 ppm)[4]

Peripheral Equipment

1 data collector w/CBL software
2 two-way portable radios
2 feet/meters measuring rod (for tripod heights)
1 umbrella

[4] Not required for forced-centering piers

Appendix B

Measurement Standards, Specifications, and Procedures

General

These instructions outline procedures for measuring a standard calibration base line with monumentation at prescribed distance intervals.

General Distance Observations

To meet the desired calibration base line accuracy, great care must be taken during all phases of the operation. It is critical the following metadata entries (as prompted by the software) are complete and accurate:

1. Standpoint station name (occupied point)
2. Target station name (observed point)
3. Instrument model and serial number
4. Reflector model and serial number
5. Date and time of observations (local time, using 24-hour clock)
6. Instrument/reflector constants (if known)[5]
7. Height of instrument and reflector above marks, recorded to millimeter accuracy [5]
8. Station elevation [5,6]
9. Instrument/reflector eccentricity, recorded to millimeter accuracy [5]
10. Atmospheric observations [5]
    - A. Temperature
    - B. Pressure
    - C. Relative humidity
11. Weather conditions/problem (wx code)

Elevation Differences

Leveling should be completed prior to making distance observations. The height differences between all monuments will have been determined and recorded using double-run, third-order (or better) procedures. Maximum allowable closures at any of the individual monuments will conform to third order standards and specifications, as stated in *Standards and Specifications for Geodetic Control Networks* (Federal Geodetic Control Committee 1984), available at: http://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm.
For digital barcode leveling, see *FGCS Specifications and Procedures to Incorporate Electronic Digital/Bar-Code Leveling Systems*, available at:
http://www.ngs.noaa.gov/FGCS/tech_pub/Fgcsvert.v41.specs.pdf

Descriptions

Descriptions for each mark should be submitted using NGS' WinDesc software available on the NGS website at: http://www.ngs.noaa.gov/ .

[5] Units of measurement must always be shown.
[6] Vertical datum must be shown.

Appendix C

Forced-Centering Pier Setting Guide

Appendix C

Guidelines for Setting a Type II Calibration Base Line Monument

Introduction

This document provides an illustrated guide for the construction of a Type II CBL monument (Figure 1). The monument is a forced centering pier consisting of a concrete-filled 6-inch PCV pipe (schedule 40 or better) projecting about 5 feet above ground level, set 2.5 feet into a 10-foot deep,18-inch diameter concrete foundation.

Construction of the monument involves purchasing materials, assembling components, and scheduling services. Commercially available materials can be used to construct the monument. Services may be required to machine certain stock materials, weld certain components, locate and mark any underground utilities at the construction site, drill the pier footer hole, and deliver concrete to the construction site. A vibrator must be rented to consolidate the semifluid concrete in the below-ground section of the pier.

Figure 1. Type II CBL Monument

Forced Centering Adapter

With a forced centering adapter (Figures 2 and 3), survey instruments may be efficiently attached to the monument in a repeatable position, without using specialized collimation instruments.

Materials for the forced centering adapter consist of an approximately ½-inch thick by 6-inch diameter stainless steel disk and an 8-inch long stainless steel J-bolt with 5/8-11 threads. Schedule services with a precision machine shop to drill and tap a 5/8-11 threaded hole through the center of the disk. The J-hook will be threaded into the hole with one-half inch exposed through the top. Schedule services with a welding shop to weld the J-hook into place at the bottom of the disk, making certain it is perpendicular to the top surface of the disk.

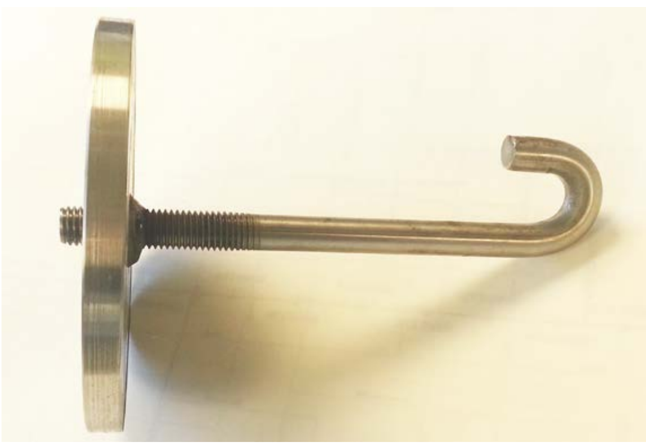

Figure 2. Forced Centering Adapter.

Figure 3. Forced Centering Adapter set into top of above-ground section of monument.

Below-ground Section of Monument (Foundation)

The below-ground section of the monument consists of an 18-inch diameter hole drilled to a depth of at least10 feet, filled with fiber reinforced concrete (Figure 4).

Materials for the below-ground section of the monument consist of at least 0.7 yards of concrete (minimum 3,500 PSI concrete with 1 ½ pounds of synthetic fiber per yard added to mix). A section of tubular cardboard form, about 2 feet long and 18inches in diameter,is placed at ground level to form the top of the foundation.

Schedule to have the construction site inspected for any underground utilities. Schedule to have an 18-inch diameter hole drilled to the depth of at least 10 feet. Ensure any loose soil remaining in the bottom of the hole is tamped down.

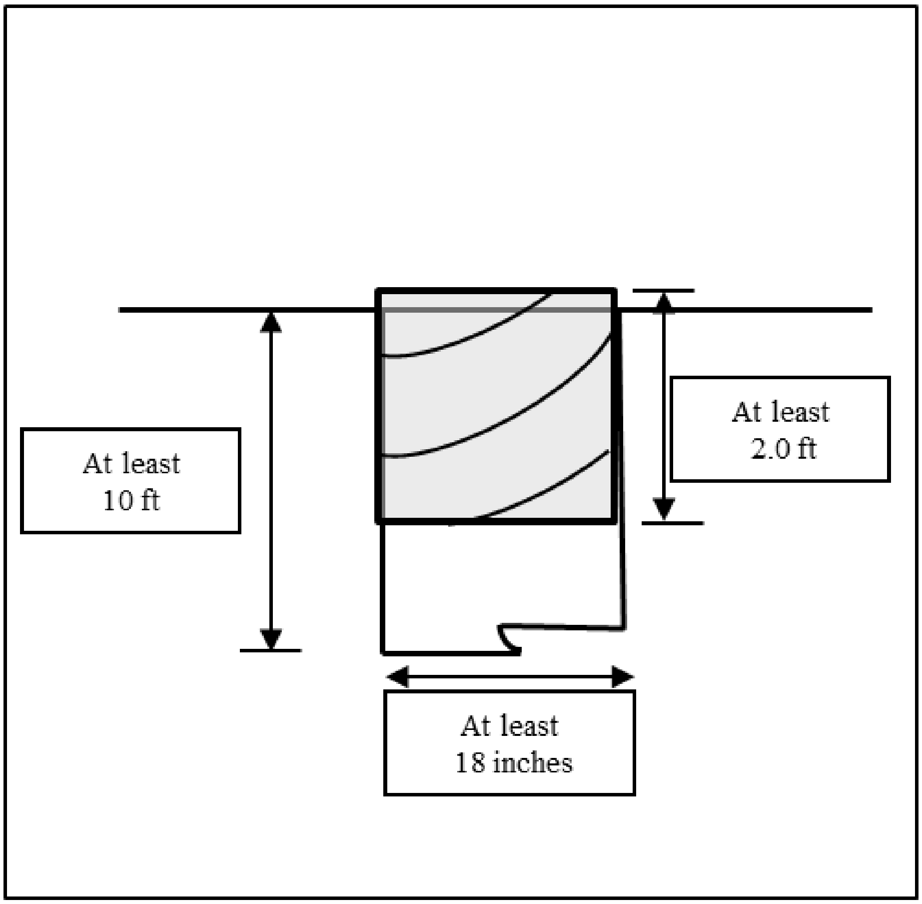

Figure 4. Below Ground Section of Type II Monument

Above-ground Section of Monument

The above-ground section of the monument consists of a forced centering adapter set into the top of a PCV pipe filled with concrete. The PVC pipe extends into and is bonded with the below-ground section of the monument (Figure 6).

Materials for the above-ground section of the monument consist of a thick-walled 6-inch OD (outside diameter) PCV pipe [schedule 40 or better]. Use a section of PVC pipe long enough to allow for the desired height of the finished pier above the ground (observing height), adding 2 ½ feet to be set down below the ground into the foundation. The top end of the pipe should be squared off and nicely finished. Bore multiple 2-inch diameter holes into the lower 2 ½ feet of the pipe to promote bonding with concrete inside and outside of pipe.

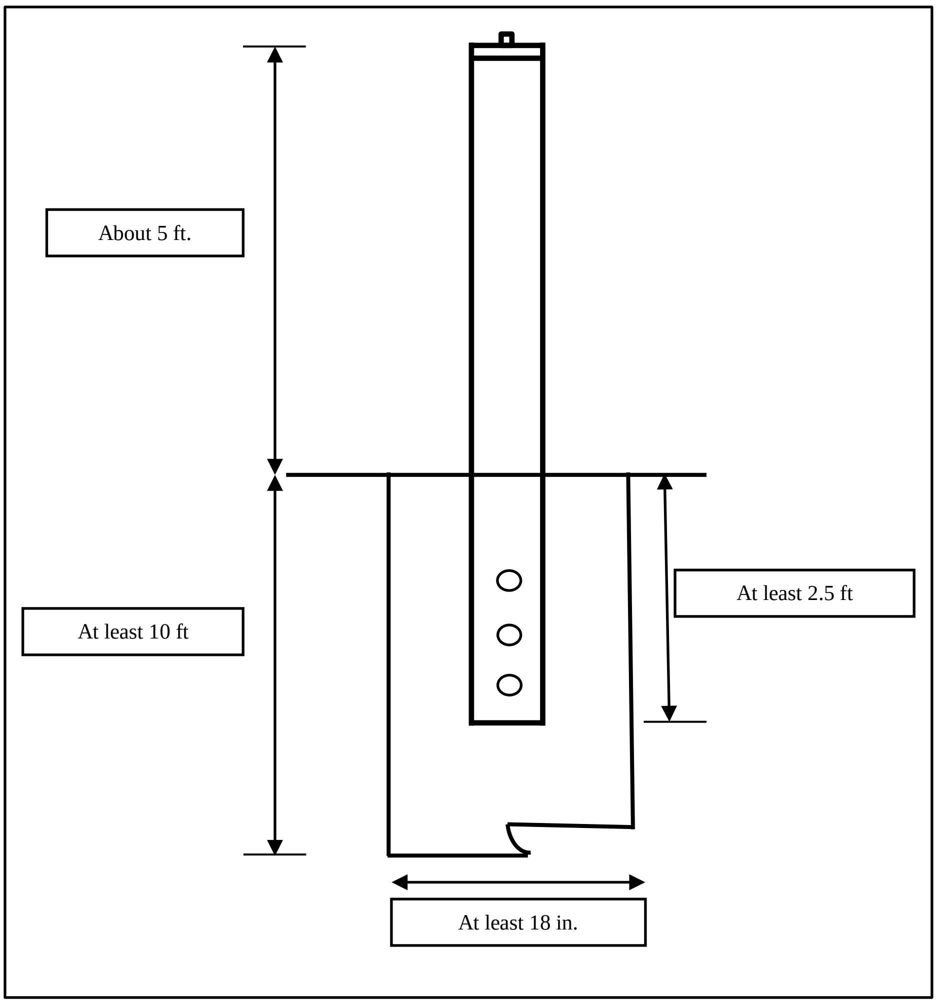

Figure 6. Above-ground Section of Type II Monument.

Setting the Monument

Figure 7. Filling the hole with concrete. After having drilled the 18-inch diameter hole to a depth of 10 feet and tamping any loose soil in the bottom, fill to within 1½ feet of the top of the hole with 3,500 PSI synthetic fiber reinforced concrete. Use a vibrator to consolidate the concrete. Insert the 1½ foot-long section of 18 inch diameter cardboard form into the hole.

Figure 8. Position the PVC pipe at the desired location in the drill hole. Mark the PVC pipe at 2 ½ feet from the bottom. Insert the PVC pipe into the hole until the mark on the PVC pipe is at the same level as the top of the form.

Figure 9. Level the top and brace the PVC pipe. With the PVC pipe positioned at the desired location in the hole, attach one end of a 2- by 4-inch board to the top of the PVC pipe using 2-inch drywall screws. Attach the other end of the board to a wooden stake driven securely into the ground using 3-inch drywall screws. Repeat this process using a second board at a 90 degree angle. Double-check the position and level of the PVC pipe in the hole to be sure it is securely braced.

Figure 10. Fill the PVC pipe and form with remaining concrete. With the PVC pipe braced, fill the PVC pipe to the top with concrete. While adding the concrete into the PVC pipe, tap the sides of the pipe with a hammer to consolidate the concrete. Finish filling the form at ground level to the top with concrete, consolidate with existing concrete, and finish off the top surface.

Figure 11. Install the forced centering adapter. Insert the forced centering adapter into the top of the PVC pipe tapping sides of the pipe with a hammer until the top of the adapter is fully seated. Ensure there is no air gap between the bottom of the adapter and the concrete inside the pipe.

Figure 12. Fine leveling of the adapter. Using a precision bubble level, fine level the top of the forced centering adapter by gently tapping on the top sides. Leave the braces in place for at least two days before removing them.

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