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A TRIGONOMETRIC METHOD FOR MONITORING GROUND-TILT CHANGES ON COMPOSITE VOLCANOES

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INTRODUCTION

Spirit-level tilt (also called tilt-leveling) has been used to measure and detect changes in ground tilt on volcanoes since the technique was developed in 1968 at the Hawaiian Volcano Observatory (HVO)(Kinoshita and others, 1974); it has become an established method of volcanic deformation monitoring. Since its introduction as a deformation monitoring tool, the spirit level tilt technique has been applied at Mount St. Helens (Lipman et.al.,1981); at various volcanoes in the Cascade Range, including Mount Shasta and Lassen Peak (Dzurisin et.al.,1983); at La Soufriere volcano, Guadaloupe (Fiske, 1979); on various active volcanoes within the Taupo volcanic zone, New Zealand (Otway et.al.,1984) and at Karkar volcano, Papua New Guinea (McKee et.al.,1981). The technique is also currently used in Costa Rica by Observatorio Volcanologia y Sismologia de Costa Rica (OVSICORI) on Arenal and Poas volcanoes and in Colombia by Instituto Geologico y Minas (INGEOMINAS) at Ruiz volcano. A complete description of the original spirit level tilt technique can be found in Kinoshita and others (1974). Yamashita (1981) also presented a detailed description, and a Spanish translation of this paper was published by Van der Laat V. (1982).

The original spirit-level tilt technique required the use of two or three large invar rods and rod stays, a level, and a micrometer plate. When 3-meter rods are used, station sites on which an equilateral triangle 40m on a side can be placed are limited to relatively level areas with no more than 2.5 m elevation difference between monuments at the triangle apices (1.5 meters if 2-meter rods are used). Sites such as these tend to be rare on composite volcanoes unless located at the base or the summit. In addition to site limitations, the 3-meter long invar rods are difficult to transport on small vehicles, helicopters or other aircraft.

The limitations of the original spirit-level tilt technique described above prompted us to find an alternate method that was suitable for steep slopes and easily portable. A compact, light-weight precise trigonometric leveling method was developed to measure tilt changes on composite volcanoes. The method uses a theodolite, Electronic Distance Meter (EDM) and three target/prism pairs mounted on plumb poles.

SYSTEM REQUIREMENTS

To determine the instrumental requirements for a trigonometric method of measuring ground tilt the desired threshold of tilt detection must first be decided. Ground tilts of several tens to several hundreds of microradians (Urad) are common before volcanic eruptions (Newhall, 1984), and in this light, a detection threshold of 10 Urad was decided to be appropriate. This 10-Urad figure represents a two sigma confidence level in measurements between pairs of marks and is comparable to the detection capabilities of the spirit-level technique reported by Kinoshita and others (1974) and Sylvester (1978) for small aperature (40m) benchmark arrays.

To meet this detection requirement, a one-second, or better, theodolite is required. Depending on the instrument and operator, a one-second micrometer theodolite can measure angles accurately to +/-0.7 to +/-1.4 seconds of arc (Ruger and Brunner, 1982). More precise micrometer theodolites and some electronic theodolites can measure angles to +/-0.5 seconds of arc (Whalen, 1984). EDM manufacturers report the accuracy of their instruments as +/- a constant number of millimeters (usually 1-5) plus a few parts per million (PPM). In short range work, such as that in tilt measurements (shot length usually less than 100m), the PPM figure is usually not of consequence. Therefore, an EDM with as small a constant error as possible is desirable and is actually the limiting factor in the accuracy of the method. Figure 1 shows the theoretical effect of random reading and pointing errors from EDMs and theodolites of differing accuracies on the flexibility of tilt measurements assuming equilateral triangular arrays of varying sizes.

Finally, the target/prism pair must be capable of being fixed at a height which can be reproduced to +/- a few tenths of millimeters with each reoccupation of the station. There are several theodolites, EDMs and target/prism mounting systems which meet these specifications.

SYSTEM DESCRIPTION

The trigonometric tilt leveling system presently in use consists of a Wild T-2000 electronic theodolite, a Wild DI-5 EDM and three target sets with tripods (figs. 2 and 3). Instrument specifications reported by Wild and confirmed by Whalen (1984) indicate that the mean of the T-2000 direct and reverse zenith angles is good to +/- 0.5" of arc (standard error). The DI-5 EDM measures distances reportedly good to +/-3mm and +/-2ppm. The target sets for this system consist of a tiltable target/prism combination, spaced apart vertically the same distance as the theodolite telescope and EDM to negate eccentricity. These target sets are mounted on plumb poles held upright by light-weight tripods. The plumb poles are not calibrated and need not be because the target height is always set the same on all three plumb poles by either using them in the fully collapsed position or fixing them in an extended position with a hose clamp or other device. Each tripod-target set is labeled and placed in the same configuration on all the triangular benchmark arrays.

SITE INSTALLATION

The ideal tilt station monument array is an equilateral triangle with the longest possible sides (fig. 4). The exact orientation of the trianglar array will be determined by the geological structure being studied, and on composite volcanoes, one side of the triangle is first laid out radial to the vent or summit area, then the third monument to complete the array is positioned in the most favorable site. Although the exact configuration of the triangle is not important, it is important that the sighting distances be approximately equal and that the ground slope be nearly uniform between the instrument and targets to minimize refraction errors.

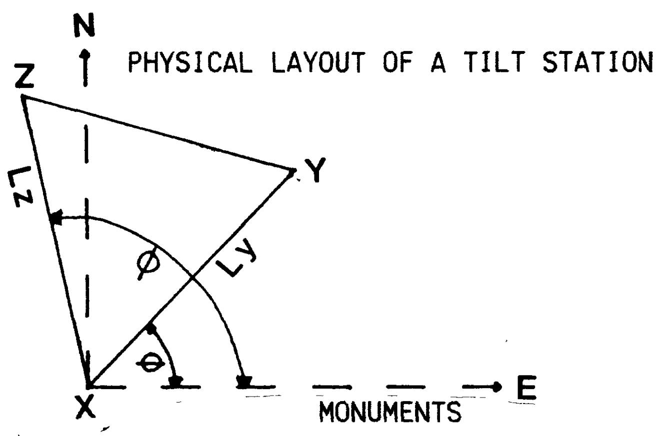
Once the southernmost vertex of the triangle is located, the vertices are labled X, Y, and Z counterclockwise; with X being the southernmost benchmark. In order to calculate the tilt vector (see below), the distances from monument X to the other monuments, Y and Z, must be measured. This can be done with a tape measure directly if the triangle is not too large, or indirectly by measuring the slope distance and horizontal angle from the instrument site in the center of the triangle to each station with the EDM and theodolite and solving the triangle. Bearings from east must also be taken from X to Y and X to Z with a compass to orient the triangle. The triangle parameters are assumed not to change and are used as constants in subsequent tilt calculations.

The formulae to determine the componants of the tilt vector are as follows:

$$\tau(N) = \frac{\cos\emptyset}{L_y \sin(\emptyset-\theta)} \cdot \Delta(Y-X) \quad + \quad \frac{\cos\theta}{L_z \sin(\emptyset-\theta)} \cdot \Delta(X-Z) \times 1000000$$

$$\tau(E) = \frac{-\sin\emptyset}{L_y \sin(\emptyset-\theta)} \cdot \Delta(Y-X) \quad - \quad \frac{\sin\theta}{L_z \sin(\emptyset-\theta)} \cdot \Delta(X-Z) \times 1000000$$

Where Ly, Lz, Y-X and X-Z are in meters and $\tau(N)$ and $\tau(E)$ are in Urad (equations modified from Eaton (1959)).



Ly = 40.97m

Lz = 40.36m

θ = 46.0°

Ø = 102.0°

When installing a ground tilt station it is important to site the monuments in similar substrates. This will eliminate, to a large degree, spurious noise effects caused by differential substrate response to diurnal thermal or seasonal hydrologic effects. Monuments placed in bedrock should not be used with monuments placed in soils.

Several types of monuments, in addition to those described by Yamashita (1981), can used as measurement points. Where bedrock is present (usually a lava flow), stainless steel anchor bolts are placed. In our experience, bedrock is the most stable (and thus preferred) substrate for monument installation. A hole is drilled with a rotary hammer drill to a depth of 3-3.5 inches. The battery operated hammer drill is very easy to use and will drill a 1/2 inch diameter hole in volcanic rock in 1 to 5 minutes. Once the hole is made, an anchor bolt (4-inch by 1/2-inch stainless steel) is pounded into the hole to refusal and center punched to provide a unique point of contact for the plumb pole (fig. 5). The use of anchor bolts in bedrock is superior to brass benchmarks for several reasons: 1) no concrete is required, 2) installation time is shorter, 3) anchor bolts are cheaper than benchmarks ($3.75 vs $9.00 ea), 4) anchor bolts are extremely difficult to steal.

If no bedrock is present, several methods of monument construction exist. One method is to dig a hole 0.5-1.0 m deep and pound a 3-4 meter-long piece of 1/2-inch reinforcing rod (rebar) into the bottom of the hole until the end is at about ground level. A collar of concrete and stones is then built around the rebar in the bottom of the hole (fig. 6). The hole is then back filled, and the top of the rebar is used as a monument. As with the anchor bolt installation, the top of the rod is center punched to provide the plumb pole a unique point of contact. This type of construction is best where shallow soil creep may be a problem. This type of mark is not suggested for use in very humid climates because the rebar will rust rapidly. However, in the dry climate of the altiplano near Cotopaxi Volcano in Ecuador, marks such as these have been stable for twelve years.

If soil creep is not a consideration, a hole is dug about 3/4 m deep, and three 2-3m long pieces of rebar are driven at angles away from the base of the hole into the ground leaving the rods exposed in the hole. The hole is then filled with rocks mortared into place with concrete in successive layers to just below ground level. Concrete is then used to bring the construction to ground level (fig. 7). A benchmark or anchor bolt is then placed in the concrete. This type of installation is time consuming and may require 1-1.5 hours or more per monument to complete.

Other types of benchmark installations are also possible depending on physical conditions encountered at the site and availability of tools and materials. For further information on setting benchmarks see Floyd (1978).

MEASUREMENT PROCEDURES

The target sets are numbered 1-3 and the tripods are set up in the same configuration on every triangle; 1 on X, 2 on Y and 3 on Z. The target tripods are leveled over the monuments, and the theodolite/EDM pair is precisely leveled in the center of the triangle. The triangle is treated as a leveling loop beginning on the YX side with the initial reading on the Y target followed by two readings on X, two readings on Y and a final reading on X (Table 1). Each reading consists of measuring direct and reverse zenith angles and the slope distance. The zenith angle is computed for each reading and successive Y-X angular differences are computed. If the spread of the differences of the three sets is less than 2 seconds, the next next leg of X and Z readings can be taken. If the spread is larger than 2 seconds, additional readings should be made until consistency is obtained. The last reading on the X target is carried down as the first reading for the X and Z leg. Two readings are taken on the Z target followed by two readings on the X target and finally one reading on the Z target. Again, a maximum spread of 2 seconds is allowed (Table 1). As a measure of the accuracy of the readings taken, the closure leg of Z and Y is read in a similar manner. When the three sides of the triangle have been read, the average of the angular differences are summed to find the "field closure" which is not really the closure in the spirt leveling sense, but rather a measure of how consistantly the angles were measured. Ideally, the differences would sum to zero. In practice, if the sum is less than or equal to 1.0" the data are considered good. If the readings sum to a value greater than 1.0" the triangle must be remeasured.

Thus far, experience with the T-2000/DI-5 system has shown that sighting distances up to 130m can be used with good results if there is no strong heat shimmer, but that sighting distances less than 100m allow for the best repeatability of measurements in a wide range of viewing conditions.

CLOSURE DETERMINATION OF ERROR AND DATA REDUCTION

Recording and data reduction for this method of tilt surveying is slightly more involved than for the the original spirit-level tilt method. Position I and position II (direct and reverse) readings must be taken and the average angle computed. Temperature and pressure readings must be taken once for each leg to correct the distance data. Because the sightings are generally taken parallel to the ground, temperatures are taken at instrument height.

If a programmable calculator or lap top computer is available, a simple BASIC program can be written to calculate the exact closure and perform the rest of the data reduction while on site. If no calculator or computer is available for field use, the triangle level loop is considered "closed" if the the "field closure" value described above is less than 1.0".

Elevation differences between the instrument and the targets are calculated for each reading by taking the cosine of the zenith angle and multiplying by the corrected slope distance (Table 2). Once the elevation differences between the targets are obtained, the data reduction proceeds exactly like the original method outlined by Yamashita (1981) and reproduced as an example below.

TRIANGLE SIDE	DIFFERENCES (meters)
Y-X	0.01677m
X-Z	-0.09169m
Z-Y	0.07492m (calculated)
Z-Y	0.07488m (observed)

	-0.00004m closure error

Thus, .00001m is added to the first two differences and .00002 is added to the third.

	ADJUSTED READING 6-7-88	CHANGE (m)	PREVIOUS READING 6-30-88	
Y-X	0.01678	-0.00009	Y-X	0.01687
X-Z	-0.09168	0.00013	X-Z	-0.09181
Z-Y	0.07490	-0.00001	Z-Y	-0.07488

REDUCED VERSION OF FORMULA USING ABOVE VALUES

$$\tau(N) = (-0.0061(\Delta Y-X) - 0.0208(\Delta X-Z)) \times 1000000$$

$$\tau(E) = (-0.0288(\Delta Y-X) + 0.0215(\Delta X-Z)) \times 1000000$$

$$\tau(N) = (-0.0061(-0.00009) - 0.0208(0.00013)) \times 1000000 = -2.2$$

$$\tau(E) = (-0.0288(-0.00009) + 0.0215(0.00013)) \times 1000000 = +5.4$$

MAGNITUDE IN MICRORADIANS = $\sqrt{N^2 + E^2} = \sqrt{-2.2^2 + 5.4^2} = 5.8$

BEARING IN DEGREES * = $\mathrm{Tan}^{-1}\left(\frac{E}{N}\right) = \mathrm{Tan}^{-1}\left(\frac{5.40}{2.20}\right) = 67.8$

IF τN IS POSITIVE, VECTOR IS IN THE NORTH HALF, DOWN

IF τN IS NEGATIVE, VECTOR IS IN THE SOUTH HALF, DOWN

IF τE IS POSITIVE, VECTOR IS IN THE EAST HALF, DOWN

IF τE IS NEGATIVE, VECTOR IS IN THE WEST HALF, DOWN

* The bearing is measured from the abscissa into the indicated quadrant. Magnitude is 5.8 microradians in a south 67.8 east direction.

PRECISION

As of this writing, the T-2000 system has been in use for about one year; thus, it is probably premature to affix a hard and fast number on the precision of the system. The precision of this trigonometric system is undoubtedly somewhat less than a spirit-level system but, as was pointed out by Savage et.al. (1979) and Sylvester (1978), factors such as benchmark instability and topographic effects make the measurement of ground tilt with small-aperature benchmark arrays accurate to only about +/- 10Urad regardless of the measuring precision.

Field testing thus far indicates that on a triangle with sides approximately 100m long, we can reproduce results to +/- 5 microradians over a period of months. The system has yet to be tested on a volcano through the course of an eruption, but the indicated precision lies well within the magnitude of ground tilt often measured on active volcanoes. Therefore, although less precise than the spirit-level instrumentation,the trigonometric method is suitable for measuring ground tilt on volcanoes.

SUMMARY

The trigonometric tilt-leveling system is a compact, light-weight alternative method of measuring ground tilt changes on volcanoes. This tilt measuring system permits volcanologists to obtain tilt data in locations where it was previously unfeasible. This measuring system greatly facilitates work on remote volcanoes where access is often by jeep or foot, and tranportation of bulky equipment is difficult. Triangular arrays can be up to five times larger than the standard spirit-level tilt triangle, thereby allowing a longer baseline to be measured, creating a more precise measure of vertical deformation.

The trigonometric tilt-leveling system can also be used to measure small trilateration networks (the DI-5 EDM can measure 2.5 Km to a single prism). If a more powerful EDM, capable of measuring distances of 10 Km or more, is used with the precise theodolite, the result would be an instrument system capable of performing all geodetic volcano monitoring tasks.

The biggest drawback of the currently used T-2000 based system, or any trigonometric leveling system, is cost. Precise theodolites are expensive, and a complete system such as that described herein cost approximately $28,000 in 1986, whereas a system such as that described by Yamashita (1981) cost approximately $10,000 in 1986. The high cost is offset by the versatility of the trigonometric system and because separate instruments need not be purchased to measure vertical and horizontal deformation.

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FIGURES

	Y target reading		X target reading			Angular differences between targets
	Angle	Distance	Angle	Distance		
1*	90 37'10.7"	22.960m	90 39'42.9"	22.943m	*2	Y1-X2 = -2'32.4"
4*	90 37'09.7"	22.960m	90 39'42.7"	22.943m	*3	Y4-X3 = -2'33.0"
5*	90 37'10.4"	22.960m	90 39'42.5"	22.943m	*6	Y5-X6 = -2'32.1"
			Spread = 0.9"			Average Y-X = -2'32.4"

	X target reading		Z target reading			
	Angle	Distance	Angle	Distance		
	90 39'42.5"	22.943m	90 25'50.9"	23.043m	*1	X6-Z1 = 13'51.6"
3*	90 39'42.3"	22.943m	90 25'51.9"	23.043m	*2	X3-Z2 = 13'50.4"
4*	90 39'42.2"	22.943m	90 25'50.9"	23.043m	*5	X4-Z5 = 13'51.3"
			Spread = 1.2"			Average X-Z = 13'51.1"

	Z target reading		Y target reading			
	Angle	Distance	Angle	Distance		
	90 25'50.9"	23.043m	90 37'10.2"	22.960m	*1	Z5-Y1 = -11'19.3"
3*	90 25'51.3"	23.043m	90 37'09.2"	22.960m	*2	Z3-Y2 = -11'17.9"
4*	90 25'51.5"	23.043m	90 37'09.2"	22.960m	*5	Z4-Y5 = -11'17.7"
			Spread = 1.6"			Average Z-Y = 11'18.3"

Field Closure = (Y-X) + (X-Z) + (Z-Y) = +0.4"

Table 1. Example of successive readings of the tilt triangle legs. Angles are the average of zenith direct and zenith reverse readings. * indicates order in which the readings are taken.

Y1 = -0.24830m	X2 = -0.26505	Y1-X2 = 0.01675m
Y4 = -0.24819m	X3 = -0.26502	Y4-X3 = 0.01683m
Y5 = -0.24827m	X6 = -0.26500	Y5-X6 = 0.01673m

		Average = 0.01677m
X = -0.26500	Z1 = -0.17326	X -Z1 = -0.09174m
X3 = -0.26498	Z2 = -0.17337	X3-Z2 = -0.09161m
X4 = -0.26497	Z5 = -0.17326	X4-Z5 = -0.09171m

		Average = -0.09169m
Z = -0.17326	Y1 = -0.24825	Z -Y1 = 0.07499m
Z3 = -0.17330	Y2 = -0.24814	Z3-Y2 = 0.07484m
Z4 = -0.17333	Y5 = -0.24814	Z4-Y5 = 0.07481m

		Average = -0.07488m

Table 2. Elevation differences between the instrument and targets calculated by multiplying the cosine of the zenith angle by the corrected slope distance. Zenith angles and distances from Table 1.

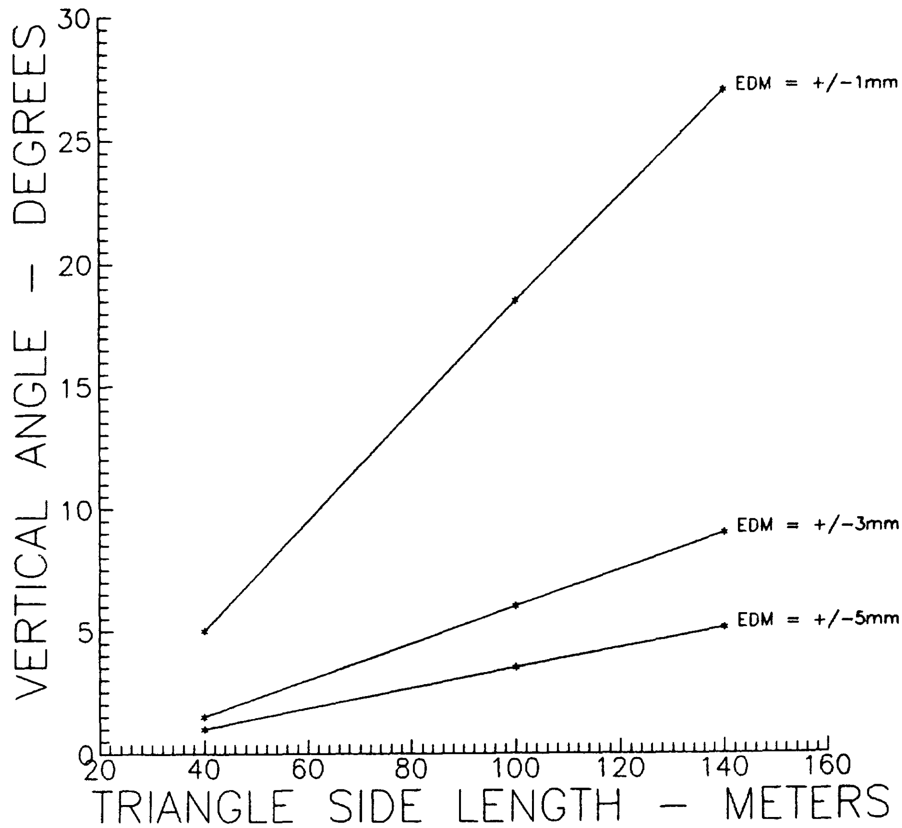

Figure 1a

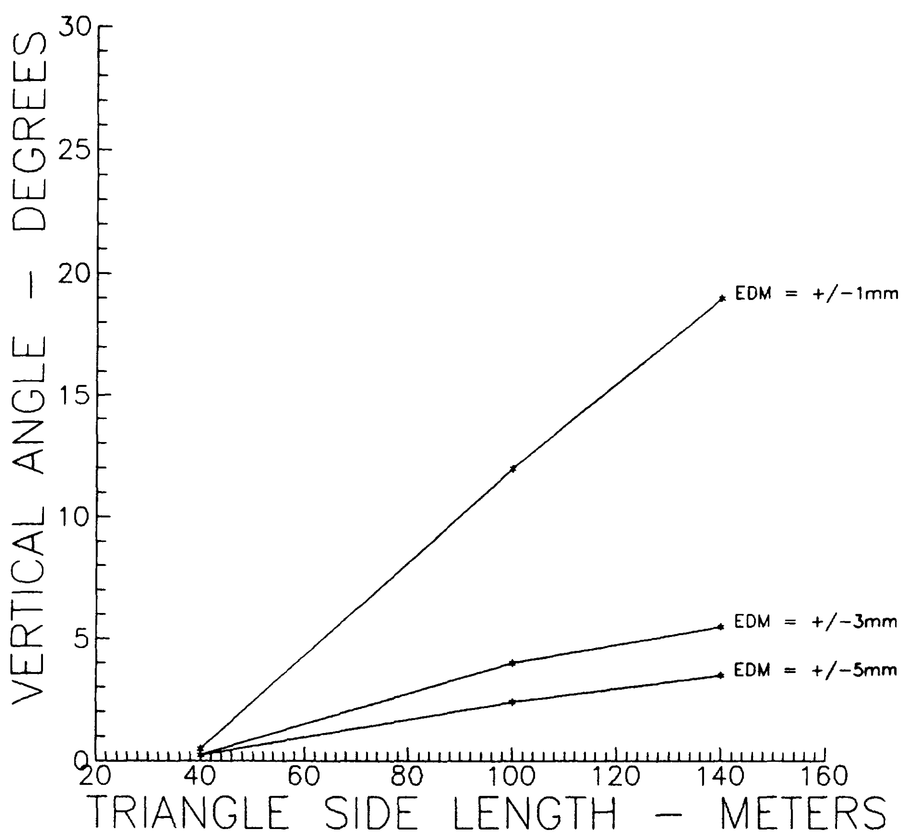

Figure 1b

Figure 2

Figure 3

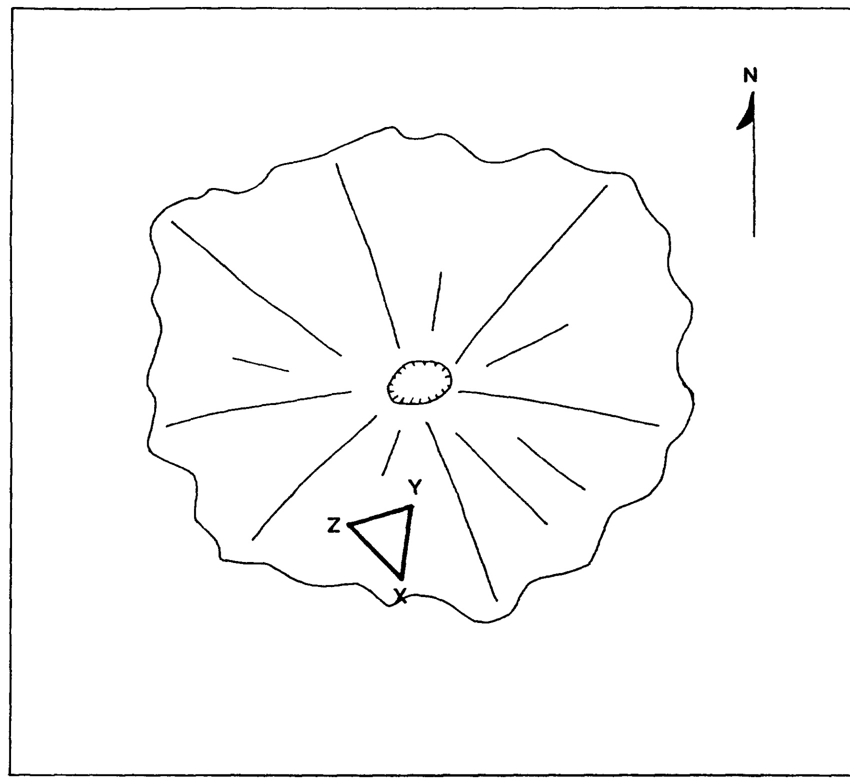

Figure 4

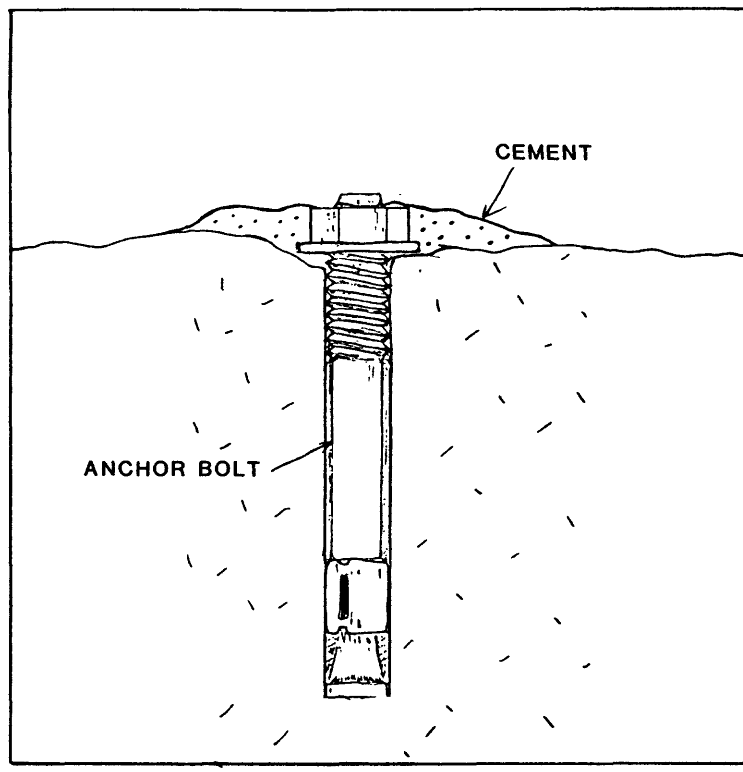

Figure 5

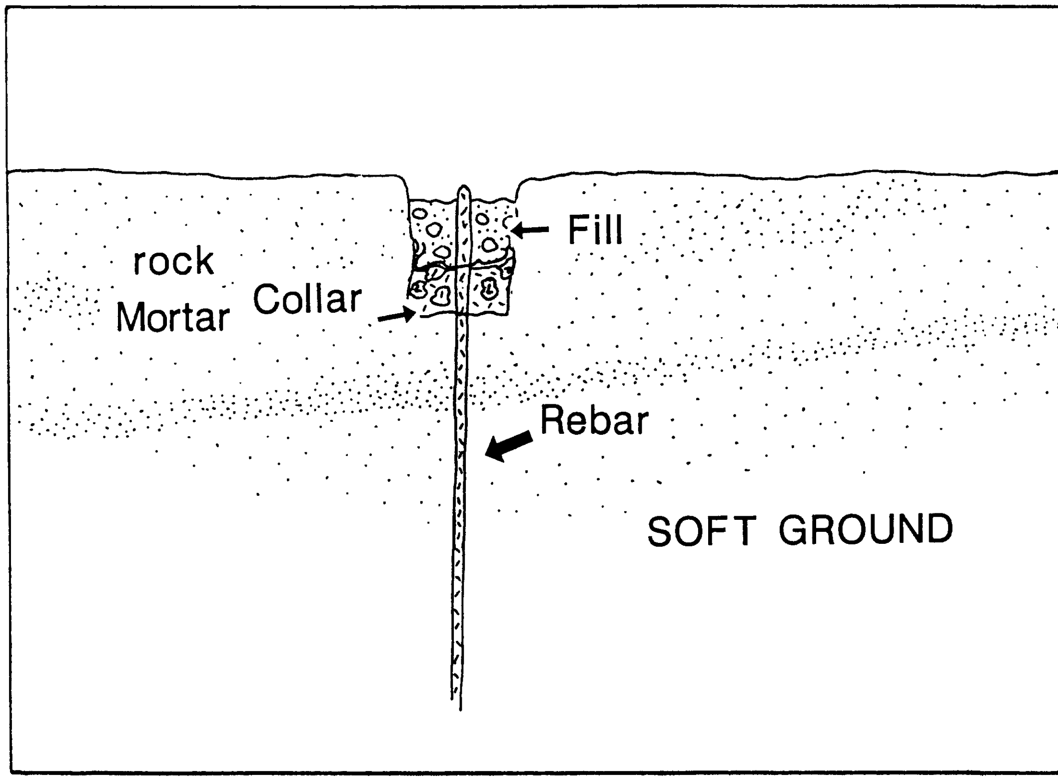

Figure 6

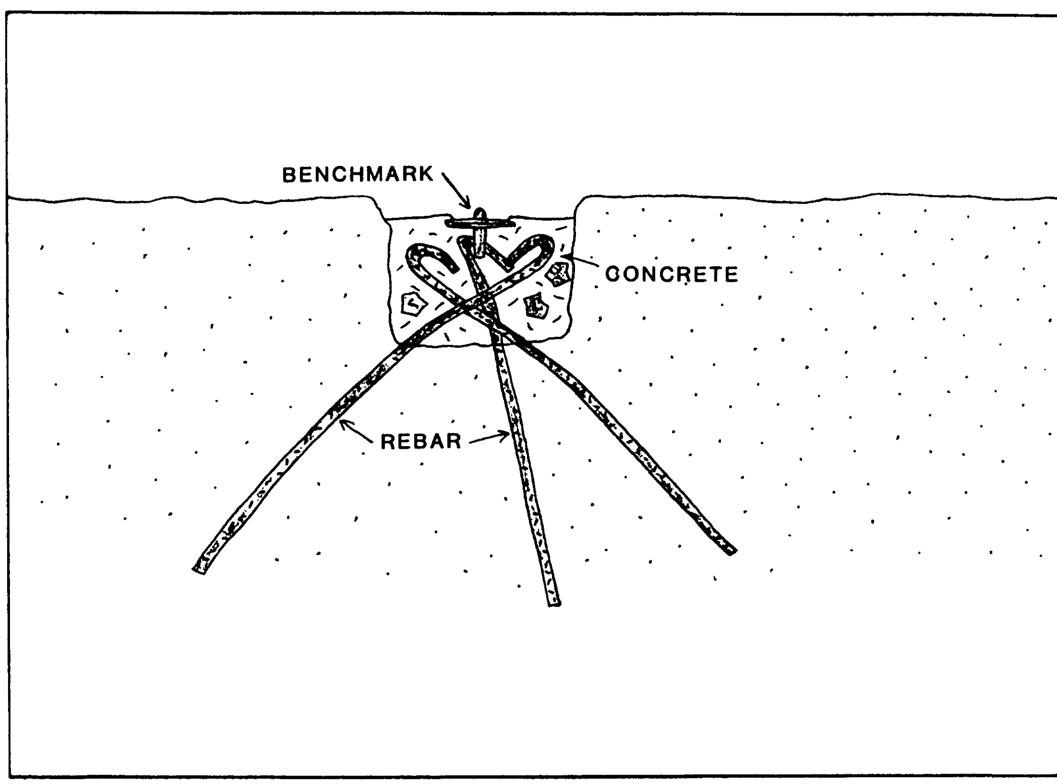

Figure 7