UNITED STATES DEPARTMENT OF THE INTERIOR
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Dry Tilt: A Ground Deformation Monitor as Applied to the Active Volcanoes of Hawaii

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INTRODUCTION

Ground deformation associated with active volcanic processes was first recognized in Hawaii by Jaggar (1926), who noted that a horizontal pendulum seismometer installed in Whitney Vault near the summit of Kilauea volcano effectively recorded long-term changes in ground tilt. No additional instrumentation to monitor this phenomenon was developed until 1958, when ten water-tube tilt meters were installed around the summit of Kilauea by Eaton (1959) and staff of the Hawaiian Volcano Observatory. These instruments measured water level changes in tubes spanning concrete piers; hence the name "long-base water tube tiltmeter." These devices were sufficiently precise, but were limited to areas where the elevation difference between piers was no greater than one centimeter in an equilateral triangle with 25-50 meter sides. In addition, the highest precision was obtainable only during heavy cloud cover or at night, owing to thermal expansion and contraction of water in the system during daylight hours.

In order to circumvent these difficulties, D.B. Jackson began development of a system of precise level tilting at the Hawaiian Volcano Observatory (HVO) in 1968. This procedure involved precise leveling of a benchmark array using a Zeiss Ni2 spirit level and Invar leveling rods. Because no fluid was involved, the term "dry tilt" was quickly adopted. The procedure has also been called "Spirit level" and "precise level" tilt. Dry tilt is used here largely for historical reasons - the term has gained wide acceptance among volcanologists in Hawaii and elsewhere.

Early tests showed that significant ground tilting could be detected by measuring benchmark pairs 150-200 m apart. In order to shorten the base and still resolve meaningful tilt vectors, a Wild N-3 precision level and precise Invar level rods were acquired in 1969 (Kinoshita, 1974). Subsequent experience at the Hawaiian Volcano Observatory has established dry tilt as a reliable and cost-effective means of monitoring ground deformation at active Kilauea and Mauna Loa volcanoes (Figure 1).

Since its introduction to Hawaii in 1968, the dry tilt technique has been applied at La Soufriere volcano, Guadaloupe (Fiske, 1979); and at Kelud and Merapi volcanoes in Indonesia (Dzurisin and Yamashita, 1979); and in southern California as a monitor of earthquake-related deformation (Sylvester, 1979). The purpose of this report is to describe the dry tilt technique practiced in Hawaii, as a guide to those interested in applying similar procedures to volcanic and structural deformation elsewhere.

ACKNOWLEDGMENTS

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STATION INSTALLATION

Site Choice

The ideal configuration of a dry tilt station is a 40 meter base equilateral triangle with one vertex in the south quadrant. To establish the vertices of the triangle, a point is marked in the approximate middle of the site where the tilt station is to be installed. A transit is then plumbed over this point and a bearing in a southerly direction taken (the exact bearing depending on terrain and optimum geological orientation for the triangle).

A distance of 23.1 meters is measured from the instrument along this bearing, and the resulting point is marked. The two remaining vertices are then located 23.1 meters from the center point by turning successive 120 degree angles from the first marked point (Figure 2). After all the vertices are established, each leg of the resulting triangle is measured and recorded. Each leg should be roughly 40 meters in length. The elevation of the vertices are also measured to ensure that the elevation difference between vertices is no greater then the maximum length of the rods being used. Ideally, only the middle and upper part of each rod should be used because refraction close to ground level can cause appreciable errors.

When the configuration is acceptable, the vertices are labelled X, Y, and Z counterclockwise; with X being the southernmost site. A benchmark is then permanently affixed at each vertex, and the central instrument site is marked with a nail or bar. The procedure outlined above can be modified as dictated by local conditions. The 40 meter equilateral triangle is considered optimum, but neither size nor shape is critical to the measurement of tilt. Linear, triangular, square, and hexagonal arrays have all been employed to advantage. A 23 meter shot length is near optimum for precise level instruments currently available, but this requirement is not rigid. Likewise, the station orientation and lettering scheme described above is standardization adopted for the sake of convenience, but can be modified as appropriate for specific installations.

Benchmarks

The benchmarks currently used at HVO are die cast brass with a 1x2 cm rounded nipple in the center (Figure 3). Alternately, standard aluminum tablets with a machined stainless steel nipple can be used. The nipple assures that the base of the rod rests on the same part of the benchmark each time the station is occupied. At present our benchmarks are cast in Palo Alto, California by the Palo Alto foundry.

Benchmark Installation

Bedrock is the most stable base for benchmark installation. To set a benchmark in bedrock, a hole slightly larger than the stem of the benchmark is drilled with a star drill. A pad of cement is layered around the hole, and the benchmark tapped into the cement pad until it resists movement. A plastic or paper cover will prevent rapid drying and cracking of the cement, and the life and stability of the benchmark are improved. If it is not possible to place the benchmark in bedrock because of excess soil depth, a hole 30 cm in diameter is dug to a depth of about 1 meter. A 2 meter rod is then driven within the hole until it begins to resist strong pounding. If total resistance is not encountered within 2 meters, a second or third rod can be coupled to the first by means of a sleeve and crimping tool or by having the ends of the rods and sleeves threaded. Threads at the ends of the rods can be protected from damage during pounding with a heavy steel bar drilled slightly larger than the diameter of the rod. The bar is placed over the head of the rod during installation (Figure 4). The head of the rod is driven about 20 cm below ground level and the benchmark attached to the rod with epoxy or a heavy duty crimping tool. The hole is then filled to the level of the benchmark with cement (Figure 4).

THREE ROD SYSTEM

If three rods are available, they are labeled X, Y, and Z and leveled with stays on the corresponding benchmark. The rods are then rotated 180° and the level bubble checked to insure that the rods are vertical and that the level bubble is true. The instrument is then leveled over the center mark of the triangle and the initial reading taken on Y rod, followed by two readings on X rod, two readings on Y rod, and a final reading on X rod. If the maximum difference Y minus X between the three sets of readings is no greater than 5×10^{-3} cm, the next set X minus Z can be taken. If the difference is larger then 5×10^{-3} cm, additional readings of Y minus X should be made until consistency is obtained. The last reading taken on X rod is carried down as the first reading for the set X minus Z. Two readings are taken on Z rod, then two readings on X rod, and finally one reading on Z rod. Again a maximum difference of 5×10^{-3} cm is allowed (Figure 5). As a measure of the accuracy of the readings taken, the closure leg Z minus Y is read in a similar manner.

When the site is again reoccupied, the same rods must be used at the same benchmark.

TWO ROD SYSTEM

If only two rods are being used, they are labeled A and B. A rod is set up on station X, and B rod on station Y. Readings are similar to the three rod system. After a consistent Y minus X reading is obtained, the rods are switched and read again in a similar manner. After the second set of Y minus X is read, the B rod on station X is removed and leveled on Z station and the set Y minus Z is read. Finally, the B rod on station

Y is removed and leveled over station X and the closure leg Z minus X is read. Closure for the circuit is computed as described below. Note that systematic errors between rods are effectively cancelled by the rod-switching procedure outlined above.

RECORDING AND CLOSURE DETERMINATION OF ERROR

Closure is determined by algebraically summing the average readings of Y minus X, X minus Z, and Z minus Y. Closure error should be distributed equally among the three legs of the triangle.

FIGURE 5

Y rod reading	difference Y-X rod	X rod reading
1*108.273	-130.650	238.923*2
4*108.277	-130.649	238.926*3
5*108.268	-130.648	238.916*6

* order in which readings are taken

X rod reading	difference X-Z rod	Z rod reading
238.916	+33.301	205.615*1
3*238.914	+33.301	205.613*2
4*238.914	+33.302	205.612*5

Z rod reading	difference Z-Y rod	Y rod reading
205.612	+97.350	108.262*1
3*205.614	+97.351	108.263*2
4*205.616	+97.352	108.264*5

AVERAGES OF DIFFERENCES

RODS	DIFFERENCES (CM)	
Y-X	-130.649	
X-Z	+ 33.301	
Z-Y	+ 97.348	(calculated value)
Z-Y	+ 97.351	(observed value)

	+ 0.003 CM	closure error

Thus .001 CM is subtracted from each pair

	ADJUSTED READING		PREVIOUS READING	
	1/17/79	CHANGE (CM)		7/17/78
Y-X	-130.650	-.005	Y-X	-130.645
X-Z	+ 33.300	-.010	X-Z	+ 33.310
Z-Y	+ 97.350	+.015	Z-Y	+ 97.335

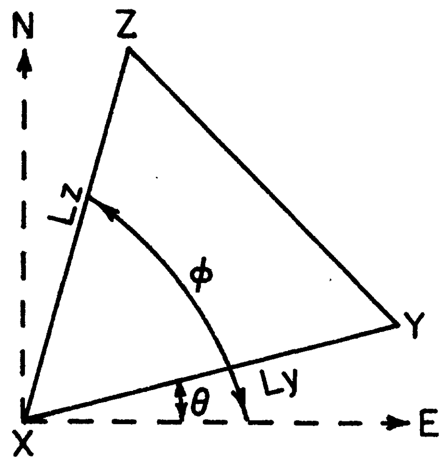
FORMULA TO DETERMINE TILT VECTOR AND MAGNITUDE

$$\tau(N) = \left[\left(\frac{-\cos\phi \times 10}{Ly\sin(\phi-\theta)}\right) \cdot (Y-X) - \left(\frac{\cos\theta \times 10}{Lz\sin(\phi-\theta)}\right) \cdot (X-Z)\right] \cdot 1000$$

$$\tau(E) = \left[\left(\frac{\sin\phi \times 10}{Ly\sin(\phi-\theta)}\right) \cdot (Y-X) + \left(\frac{\sin\theta \times 10}{Lz\sin(\phi-\theta)}\right) \cdot (X-Z)\right] \cdot 1000$$

Formula modified from J.P. Eaton, 1959

PHYSICAL LAYOUT OF STATION



Ly=40.20M

Lz=40.08 M

θ=14.5°

ϕ=74.5°

REDUCED VERSION OF FORMULA USING ABOVE VALUES

$$\tau(N) = (-0.077(Y-X) - 0.279(X-Z)) \cdot 1000$$

$$\tau(E) = (0.277(Y-X) + 0.072(X-Z)) \cdot 1000$$

$$\tau(N) = (-0.077(-.005) - 0.279(-.010)) \times 1000 = +3.18$$

$$\tau(E) = (0.277(-.005) + 0.072(-.010)) \times 1000 = -2.11$$

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FORMULA TO DETERMINE TILT AZIMUTH AND MAGNITUDE

MAGNITUDE IN MICRORADIANS $= \sqrt{\tau N^2 + \tau E^2} = \sqrt{3.18^2 + 2.11^2} = 3.80$

AZIMUTH IN DEGREES $= \mathrm{Tan}^{-1}\left(\frac{\tau E}{\tau N}\right) = \mathrm{Tan}^{-1}\left(\frac{2.11}{3.18}\right) = 33.5^{\circ}$

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

Magnitude is 3.80 microradians in a north 33.5° west direction.

INSTRUMENTATION

The instruments currently in use at HVO are the WILD N-3 level, WILD NAK2 self-level with GPM 3 micrometer plate, and three WILD GPL 3 precise Invar level rods with detachable stays. A surveying umbrella is used to shield the instrument and tripod from direct sunlight to minimize expansion and contraction of the instrument and tripod.

The NAK2 and N-3 are both suitable for reading a dry tilt station; but both have idiosyncrasies which may recommend them for a specific application.

WILD N-3 Level

The N-3 level has an extremely sensitive spirit level which must be leveled precisely before each reading is taken. It is also very sensitive to temperature changes, which causes the level bubble of the instrument to drift and force one to repeatedly "chase" the level. The N-3, however, is a stable instrument in the wind.

WILD NAK2 Level

The NAK2 level has a 360 degree circle built into the instrument and can be used to turn angles to one minute of arc. With the GPL3 micrometer plate removed, the NAK2 can be used to run second or third order level surveys. It has the added advantage of being self-leveling, which facilitates set-up and reading time. A disadvantage of the NAK2 is that the cross hairs tend to drift, and the instrument must therefore be peg tested each day to ensure internal calibration.

With the N-3 level, it typically takes 30-40 minutes to read a tilt station using three rods; with the NAK2, roughly 20 minutes are required.

If only two rods are used, reading time is about 30% longer.

Precision

The precision of the N-3 as determined by field experience at HVO is about $\pm 2\text{-}3 \cdot 10^{-6}$ radians (Kinoshita, 1974).

The precision of the NAK2 is about the same, provided that close attention is given to peg testing the instrument on a regular basis. Proper procedure to peg test the NAK2 is given in the owner's manual; the N-3 requires no peg test.

SUMMARY

Dry tilt is a cost and manpower efficient method of monitoring ground deformation associated with active volcanism in Hawaii. Comparison of results from wet and dry tilt monitors at the same site reveals that the two procedures are generally in good agreement. Reduced precision of the dry tilt scheme is not a limiting factor in Hawaii, where ground tilts of 10-100 microradians commonly occur on timescales of weeks to months. The dry tilt method is favored over wet tilt in most field situations because dry tilt: 1) does not require a temperature-stable vault, and need not be read only on cloudy days or at night; 2) is manpower efficient, requiring two field personnel with three rods only about one hour per station and measurements; and 3) requires a minimum of sophistication in both instrumentation and implementation. As of December 1979, there were 20 dry tilt stations near the summit of Kilauea and more than one hundred throughout the island of Hawaii. Of the twenty summit stations, twelve are occupied on a quarterly basis and the remaining eight bi-annually. Of course, this schedule is subject to change based on other indicators of subsurface activity. The remaining sites around the island are occupied annually or once every two years depending on the state of the volcanoes.

EQUIPMENT LIST 1979

WILD NAK2 SELF LEVELING LEVEL	2369.00
WILD GPL3 MICROMETER PLATE	1155.00
WILD N3 PRECISION LEVEL	4190.00
WILD 2- 3meter GPL3 PRECISE LEVEL RODS	2268.00
WILD 2- 198-953 STAYS	1634.00
SURVEYORS UMBRELLA	35.00
KERN GK2-A SELF LEVEL	2280.00
KERN MICROMETER FOR LEVEL	1140.00
2 KERN INVAR RODS 3 METERS	1305.00
2 KERN ROD STAYS	570.00

EQUIPMENT PRICES FROM:

SURVEYORS SERVICE

P.O. BOX 1500

2942 CENTURY PLACE

COSTA MESA, CALIFORNIA 92626

PHONE (213) 860-3451

KERN INSTRUMENT CO.

GENEVA ROAD

BREWSTER, NY 10509

PHONE (914) 279-5095

CRIMPER

NATIONAL TELEPHONE SUPPLY CO.

51 SUPERIOR AVE.

CLEVELAND, OHIO 44103

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Jaggar, T.A., and Finch, R.H., 1926, Tilting and level changes at Pacific volcanoes, Proc. 3rd Pan-Pacific Sci. Cong., Tokyo, pp. 672-686.

Kinoshita, W.T., Swanson, D.A., and Jackson, D.B., 1974, The measurement of crustal deformation related to volcanic activity at Kilauea Volcano, Hawaii, Physical Volcanology Ed. Civetta et al, p. 93.

Sylvester, A.G., 1979, Dry tilt and short level line data, central southern California uplift, 1977-1979.

FIGURE I

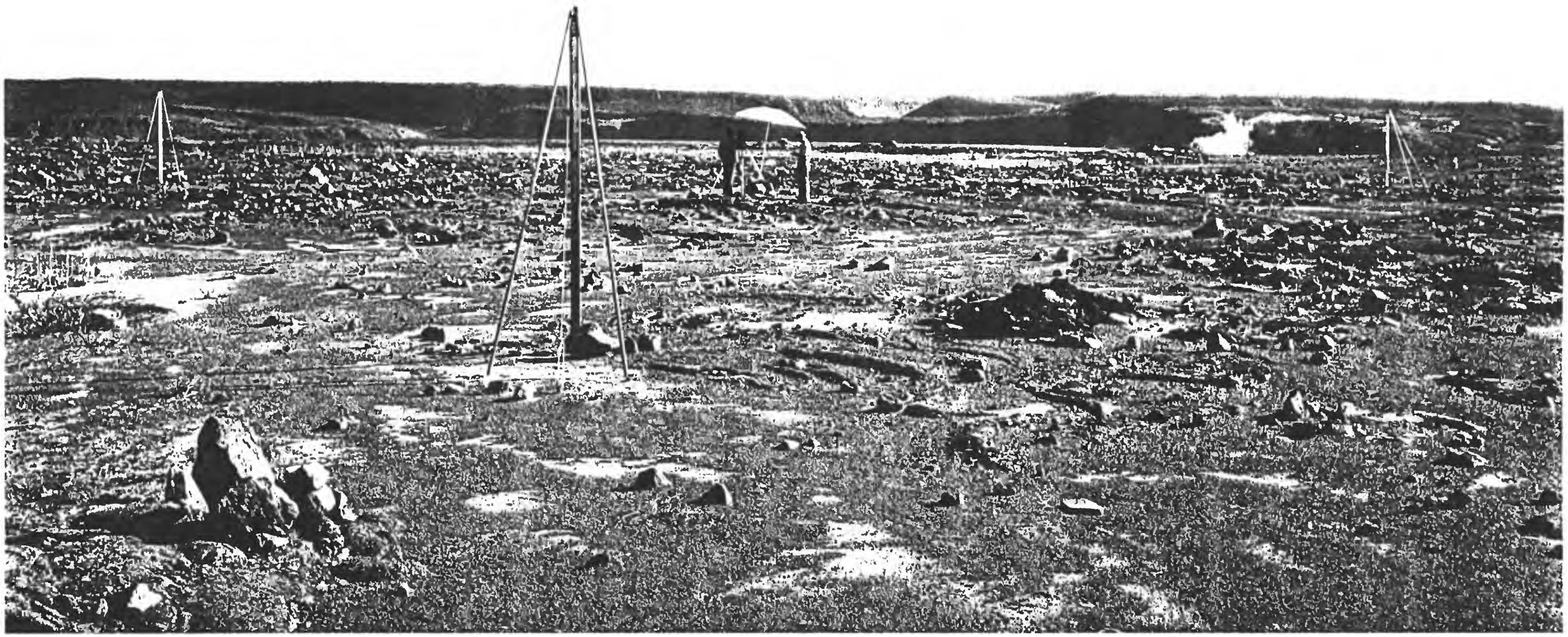
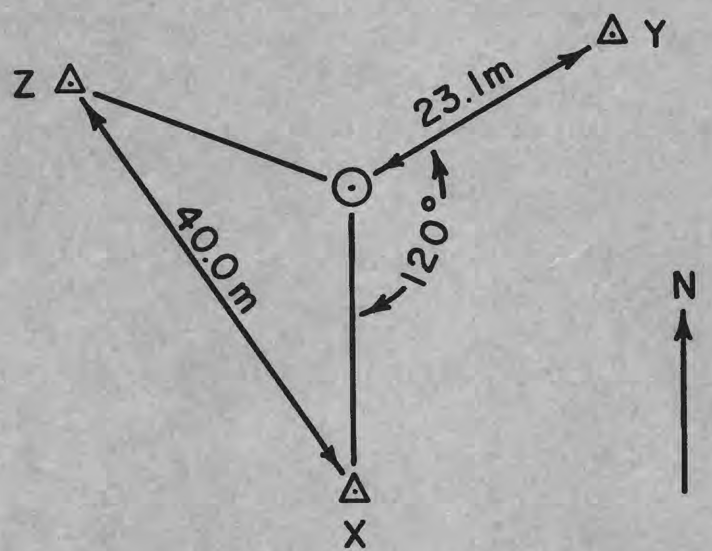


FIGURE 2



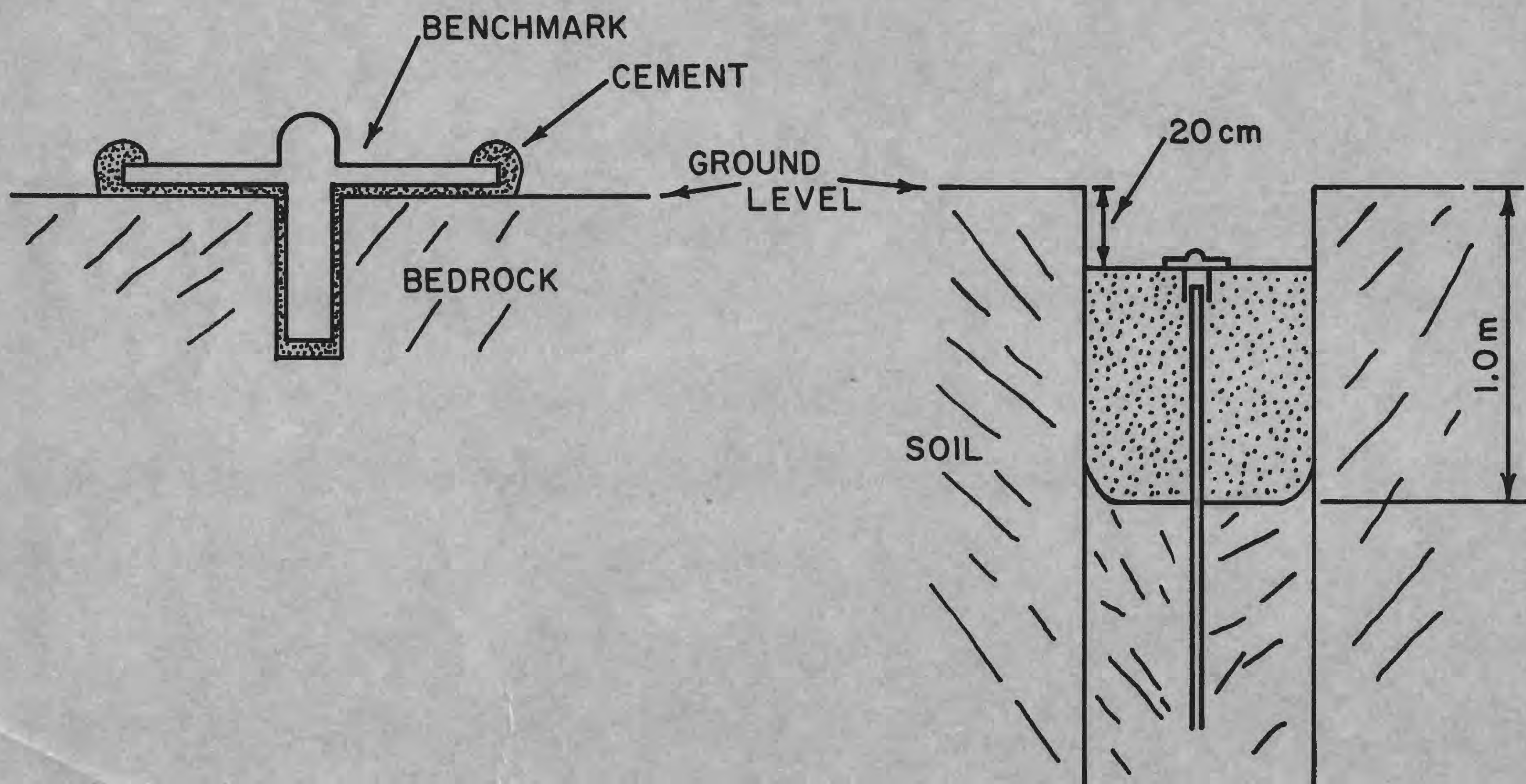

BENCHMARK
CEMENT
GROUND LEVEL
BEDROCK
20 cm
SOIL
1.0 m

FIGURE 4

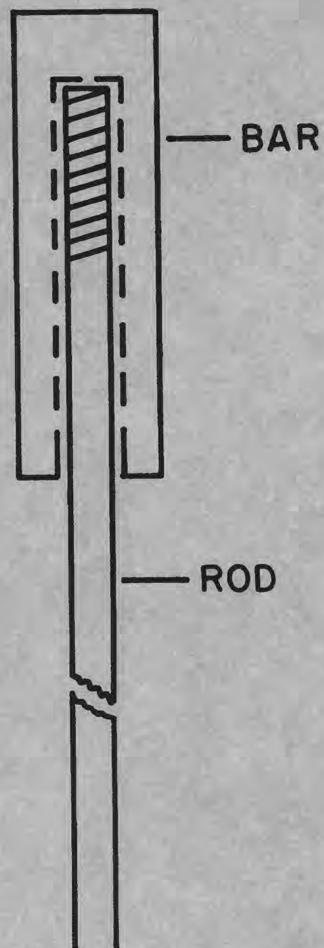


FIGURE 1