BENCHMARKS FOR ACCURATE LEVELING
(Pellissier - 5/93)

Leveling work cannot be more accurate than the stability and integrity of each of the benchmarks which are used in the leveling circuit. The development of high accuracy in leveling instruments must be matched by a parallel development of carefully designed and carefully installed benchmarks if the desired accuracy is to be attained. This is especially important if the measurement of the long term stability of a structure or a machine is required.

A "suitable" or "appropriate" bench mark for highly accurate leveling is surprisingly difficult to attain. The desired properties of such a mark are quite simple to describe. The H5 is capable of accuracy of about +/-3 microns in 30 meters. The benchmarks used should be at least that good. Marks which are that stable are suitable for measuring the earth tide effect which has of magnitude of about +/- 2 x 10 (-7). If a network of six marks are spaced around a circle of 100 meter radius we are asking that the relative elevations of the marks not change by more than 10 microns due to any cause, long term or short term (about 1/10 part per million).

Much effort has been expended by many people on this problem, with varying degrees of success. The difficulty lies in the fact that when looking at our world, there are many things which occur in the range of a few parts per million which must be considered.

As an example, consider establishing a set of benchmarks in a level field. The soil under foot has a thermal expansion of several parts per million per degree. It also expands and contracts with changes in water content - some soils far more than others. Diurnal and weekly temperature changes extend a meter or two below the surface. Annual changes of a degree of two can be detected at eight to ten meters below the surface. Except in unusual circumstances, the soil and the strata across a site will be neither uniform nor level so that these near-surface thermal changes will not be uniform. The simple rule then is, a benchmark attachment point should be deep - and isolated from the overlying soil. So that they act as a unit, they should all be the same depth below the natural surface. How deep is a matter of cost and difficulty, but the first rule is that eight to 10 meters is probably as deep as makes any sense in most cases.

Between 1964 and 1974 I obtained excellent results with sets of monuments in widely varying soils with hole depths of about eight meters. The marks, used with a tiltmeter, easily supported earth tide measurements and long term crustal deformation studies.

One additional advantage of having the attachment point be deep is that the local loading effect of a person or a truck does not reach it. This loading effect is especially serious when trying to work on the surface of ordinary reinforced concrete floors or sidewalks. One must carefully check each proposed mark in such circumstances because on the same floor, one spot may be stable to better than a micron, and a spot ten meters away may deflect fifty microns when a person stands on it.

These short term motions are almost always accompanied by large and unpredictable motions due to loading, rainfall, seasonal changes, etc. - so a concrete floor can seldom be relied upon for any accurate work. In general, a concrete floor is never well tied to the underlying earth. Usually a polyethylene sheet is present which guarantees that no real connection exists between the bottom of the concrete and the fairly loose layer of dirt or sand beneath the floor.

One can cut a hole in the floor and install a column or pier, usually of concrete, which provides the appearance of massive stability, but what usually results is a heavy, unstable, unreliable benchmark. There are three reasons for this. First, the column is not usually deep enough. Second, it is rarely isolated from the surrounding soil with a casing. Third, concrete is probably the worst possible material to use for a mark.

Concrete, with a bit of steel, is frequently used. There is enough steel to control cracking, but the finished unit really acts like, shrinks like, and swells like concrete without steel. Concrete, from the time it is poured, shrinks a few tens of parts per million per month for a few months and then settles down to shrink a few tens of parts per million per year for the rest of its life. Superimposed on this shrinkage (which is caused by a slow, continuing crystallization of the cement in the structure) is a length change due to changing moisture content (annual rainfall, etc.) which can easily amount to a few tens of parts per million per year

A concrete pillar three meters long can be expected to shorten 50 to 100 microns per year, and to cyclically change by 10 to 100 microns per year, even if its temperature is held absolutely constant for its entire life. The same concrete has a thermal expansion coefficient of ten or so parts per million per degree, so a three meter column will grow 30 microns with each degree of increase in temperature. The thermal changes are usually easy to sort out with insulation and a thermometer. The moisture related and long term changes are nearly impossible to isolate, and they are truly impossible to predict.

Benchmark Installation Procedure

1. Drill 6" diameter hole 18 to 19 feet deep.

2. Install 20 foot length of 4" ID thin wall (1/8") casing. Cut off 12" above surface and vacuum loose dirt from bottom of hole.

3. Install 21 foot length of 2" galvanized pipe with end plug welded to coupling for invar riser.

4. Tamp bottom of hole, using 2" pipe as a tamper.

5. Center bottom of pipe in bottom of casing. Pour 6" of quartz sand into annular space between 2" pipe and casing.

6. Raise casing 4". Tamp sand with 1/2" diameter steel rod 24 feet long. Be sure that 2" pipe remains centered in casing.

7. Add 6" more sand, raise casing, tamp, and repeat until casing has been raised 26 inches. Clamp casing in place at surface using a clamp made of two 2 x 4's 24 inches long and two 1/2 inch bolts 8 inches long.

8. Assemble a pin guide tube 20 feet long, using 1/2 inch diameter threaded electrical conduit. Lower the guide into the hole, between the casing and the pipe, until it is about even with the bottom of the casing. Secure it at this height by clamping it with visegrip pliers which rest on the top of the casing. Drop a pointed

pin down the 1/2" guide tube. Using a simple A-frame or tripod, hoist the 1/2 inch drive rod into the air and lower it into the guide tube. Drive the pin with the 1/2" steel rod by raising the rod 3 or 4 feet and then "throwing" it down the guide tube. The 1/2 inch rod is an ideal driver for the 1/2 inch pins because all the energy in the descending rod is smoothly transferred to the pin. Do not simply pound on the top of the rod with a hammer. This is slower, less effective, and much of the energy simply goes into mushrooming the top of the rod.

9. Remove (hoist) the drive rod out of the guide tube. Move the guide tube in the bottom of the hole to a new location, drop in a new pin, lower the drive rod, and drive the new pin. Insert and drive more guide pins in a symmetrical pattern into the sand. Add sand as necessary to cover the tops of the pins. The first few pins will tend to move the pipe sideways, so it is important to be sure that the pipe remains centered well enough so that the guide tube can reach any spot in the annular space to insert a new pin. Try for a reasonably uniform distribution of pins around the pipe. The final result desired is a sort of homemade expansion bolt type connection which uniformly loads the bottom of the drilled hole with a strong radial force.

10. Continue driving pins until it takes at least 25 blows with the drive rod to set a pin. At Kodiak, Alaska in holes in solid shale, only 5 to 8 pins were required for each of the three monuments. At Pearblossom, in the Mojave desert, in an unconsolidated alluvial fan the monuments needed about 95 to 110 pins apiece. Usually only 20 or 30 pins were needed.

11. The test for monument integrity consisted of using a pipe wrench with a three foot handle and twisting the 2" pipe. We found that a husky worker could apply about 500 foot pounds of torque to the 2" pipe with this arrangement. When this man was unable to rotate the 2" pipe, we considered it to be an acceptable monument. If he could, more pins were driven. Subsequent testing a day and a week later, with a total of 27 monuments never showed a loosening. One set of three monuments in California visited ten years later for removal of the tiltmeter, did not move even though about 1000 foot pounds was applied to each of the 2" pipes with a long wrench.

12. When 500 foot pounds are applied to the pipe, which has a radius of about 1/10 foot, the resisting forces at the pipe wall are

about 5000 pounds in the direction of the circumference of the pipe. It seems reasonable to believe that at least one half of that amount could be assigned as a vertical holding force. In a further test, a week later, with sensitive tiltmeters installed on these marks, moderately hard and then rather violent pounding with a hammer on the 2" pipe showed no observable vertical motion on the tiltmeter, which had one micron resolution. The first five tiltmeters using 15 monuments were subjected to quarterly tests for three years which applied about 250 foot pounds to each monument to assure that they were still tight. None ever failed this test. None of the total of nine tripartite tiltmeters installed on 27 marks ever gave any indication that a monument had failed.

13. The completed mark consists of a 2" galvanized pipe firmly attached to the earth below, the bottom of a 4" casing in a 6" hole about 18 feet deep. The 2" pipe has a plug at the bottom which is blind drilled and tapped for a 1/2-13 stud. This is used to attach a central rod of 3/4" diameter invar. The actual mark at the surface is on top of this invar rod. The invar rod is supported at the center of the 2" pipe with loose fitting washers spaced about 18" apart by 1" tubes which slide down over the invar rod. The annealed invar riser rod has an expansion coefficient of about 1.5 parts per million per degree C. With some thermal insulation of the near surface part of the mark, only a very small diurnal effect is observed. If the marks are made reasonably identically, any diurnal thermal effects will be common to all of the marks and will not be observed at all.

These marks were used very successfully in measurements of the earth tide effect at all sites. Diurnal effects due to the monuments were below two microns in every installation.

Equipment and Parts

For each mark

4" thin wall steel casing, 20'
2" galvanized pipe, 21'
Coupling, tapped plug for 2" pipe
3/4" Invar riser, each end tapped 1/2-13
1/2-13 invar studs 1-1/2" long to join riser rods
100 lb. Del Monte fine quartz sand
25 to 50 1/2" dia. x 24" steel pins, pointed on one end

To Install

- Drill rig for 6" hole
- Vacuum cleaner and 25' hose
- 1/2" dia x 24 ft mild steel drive rod
- 1/2 " ID Electrical conduit and couplings (threaded conduit) drive guide, 30 ft
- Clamp to hold casing off bottom of hole
- 20 ft. tripod or guyed pole to hoist drive rod
- Pulley and hoist rope - 1/4" nylon
- Large pipe wrench and extension handle
- Skilsaw and metal cutting blades for casing and 2" pipe
- Flashlights
- Misc hand tools
- Gloves

This mark was developed to support a tiltmeter measurement program in the field in the 1960s. The goals were to have a design which would always result in a good stable mark, with a minimum of heavy equipment. The marks were relatively easy to install, easy to test, and they proved to be stable for years. So far as I am aware, there is no better mark design anywhere in the world today which can be applied to practically any soil condition. In addition, it is not expensive. We routinely installed three marks in one easy day with two or three men.

If I were requested to establish a set of stable benchmarks, I would use this design. The only time we ever had any trouble was at the Pearblossom site when we slowly realized that we might be driving pins for the rest of our lives. Even there, the process eventually yielded excellent marks.

At three of the sites, the marks were below the water table (we worked in wet holes). Three sites were well above the water table. At three other sites the water table annually rose above and dropped below the attachment points.

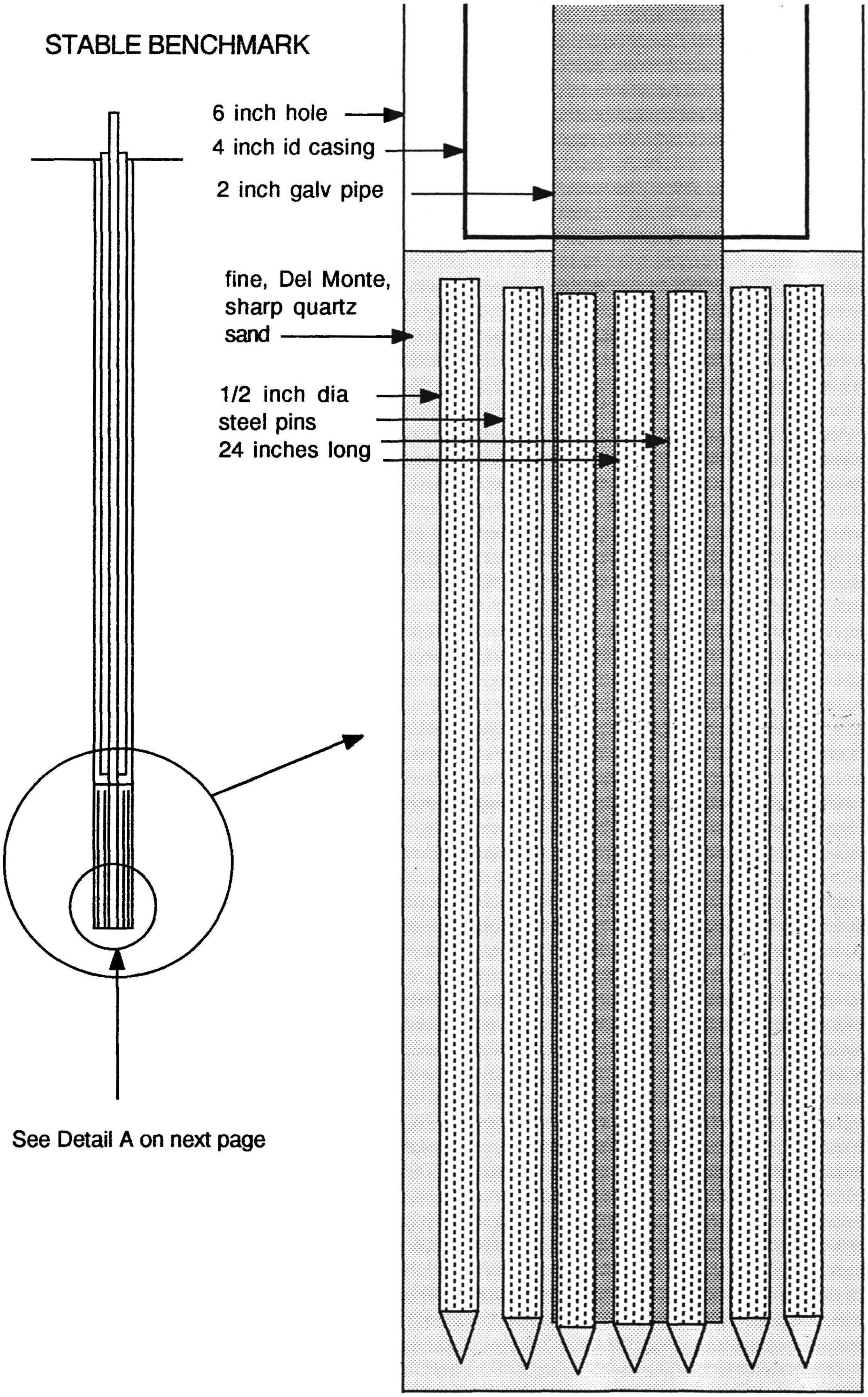
Even at the site where the water table rose and fell, the marks stayed solid. None were located near an active, pumping, water well so we did not observe the temporary subsidence and tilting due to water pumping which is normal in such circumstances. One instrument on the edge of an oil field did routinely measure the tilting due to oil extraction related subsidence of the center of the field.

Application for Horizontal Control

The integrity and stability of these marks over time has led me to believe that they would serve equally well as horizontal control points. The 2" pipe would need to be replaced by something stiffer - like perhaps a 6" pipe which would be some 27 times stiffer laterally.

I would probably start with a 6" pipe and a 10" thin wall casing in a 12" hole 15 to 20 feet deep. I would use 3/4" diameter pointed pins about four feet long (and a 3/4" steel drive rod) to keep the scale of things fairly constant. A suitable test for the assembly would be to use a long handled wrench and to apply about 1500 foot pounds of torque. A central invar rod would provide a vertical mark and a welded cap with a hole for the invar and a separate tooling ball could be used for the horizontal mark.

STABLE BENCHMARK



See Detail A on next page

STABLE BENCHMARK

DETAIL A