Evaluation of Survey Control Stations Height Stability in Subsidence Zones

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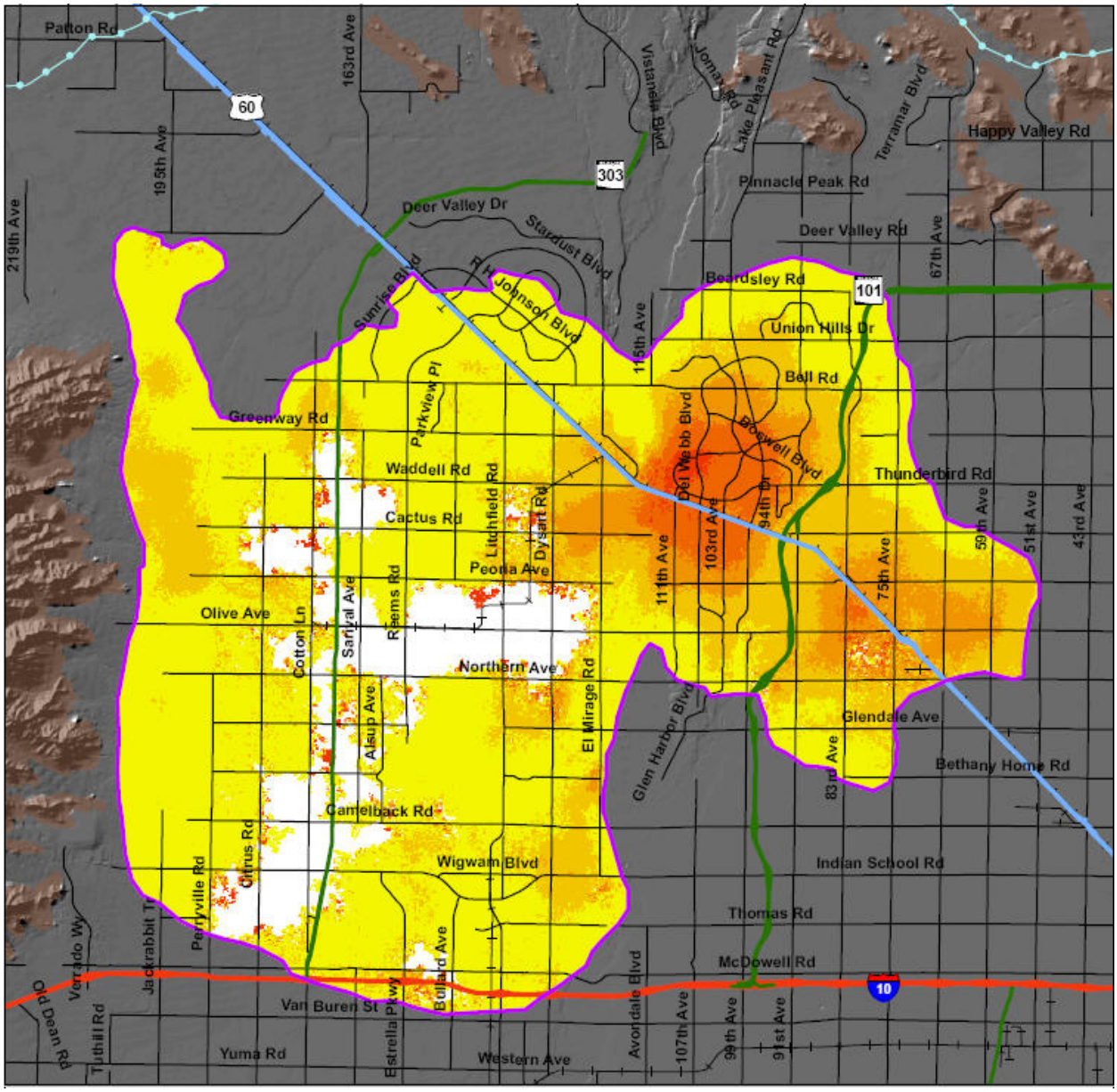

Evaluation of Survey Control Stations Height Stability in Subsidence Zones

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Abstract:

This paper will compare land subsidence findings by the Arizona Department of Water Resources (ADWR) InSAR (Interferometric Synthetic Aperture Radar) program data, and data collected at the National Geodetic Survey (NGS) survey control stations. NGS control that will be evaluated will include differential level runs starting and ending on bedrock control, data collected at a Continually Operating Reference Station (CORS) and horizontal control stations that were used for the Geodetic Densification and Cadastral Survey (GDACS) project in Maricopa County. The CORS site in Peoria Arizona designated as AZPE is in a major subsidence feature that is covered by the ADWR InSAR study area. Data from this station will be compared to the findings of the InSAR study, and provide an on the ground validation of the InSAR techniques. The presentation will also review the current NGS policy on coordinate updates for CORS and make recommendations as to the placement of CORS in the future (specifically in exposed bedrock), and on managing CORS within a subsidence area. A compare and contrast of survey mark stability within a subsidence feature will be made. Specifically NGS 3D rod, concrete monuments, and marks on structures will be compared for stability. The presentation will conclude with plans that the City of Tempe and Surprise have for installing bedrock mounted CORS in conjunction with the Arizona Height Modernization program. The presentation will also discuss the plans that the City of Surprise Geodetic Survey has for managing survey control stations within the subsidence zone. A discussion of active, and semi-active control will be presented.

Keywords: Time-Series InSAR Data, Subsidence, ellipsoidal height, Height Modernization, CORS stability

Survey Control Stations (Benchmarks) Defined

Survey control stations can be separated into many categories such as physical construction and positional stability. Physical construction can include brass disk in bedrock, concrete cylinder, or deep driven rod. Stabilities are typically ranked from high stability to those likely to be subject to motion and are often linked to the construction method (e.g. bedrock being most stable, deep driven rods being next most stable, with surface settings like concrete being least stable).

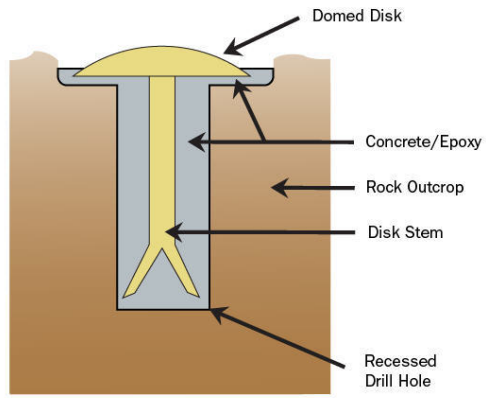


Figure 1a

Bedrock marks

Bedrock marks can have a variety of construction methods but are all classified as being either directly set in (Figure 1), or connected to bedrock (Figure 2).

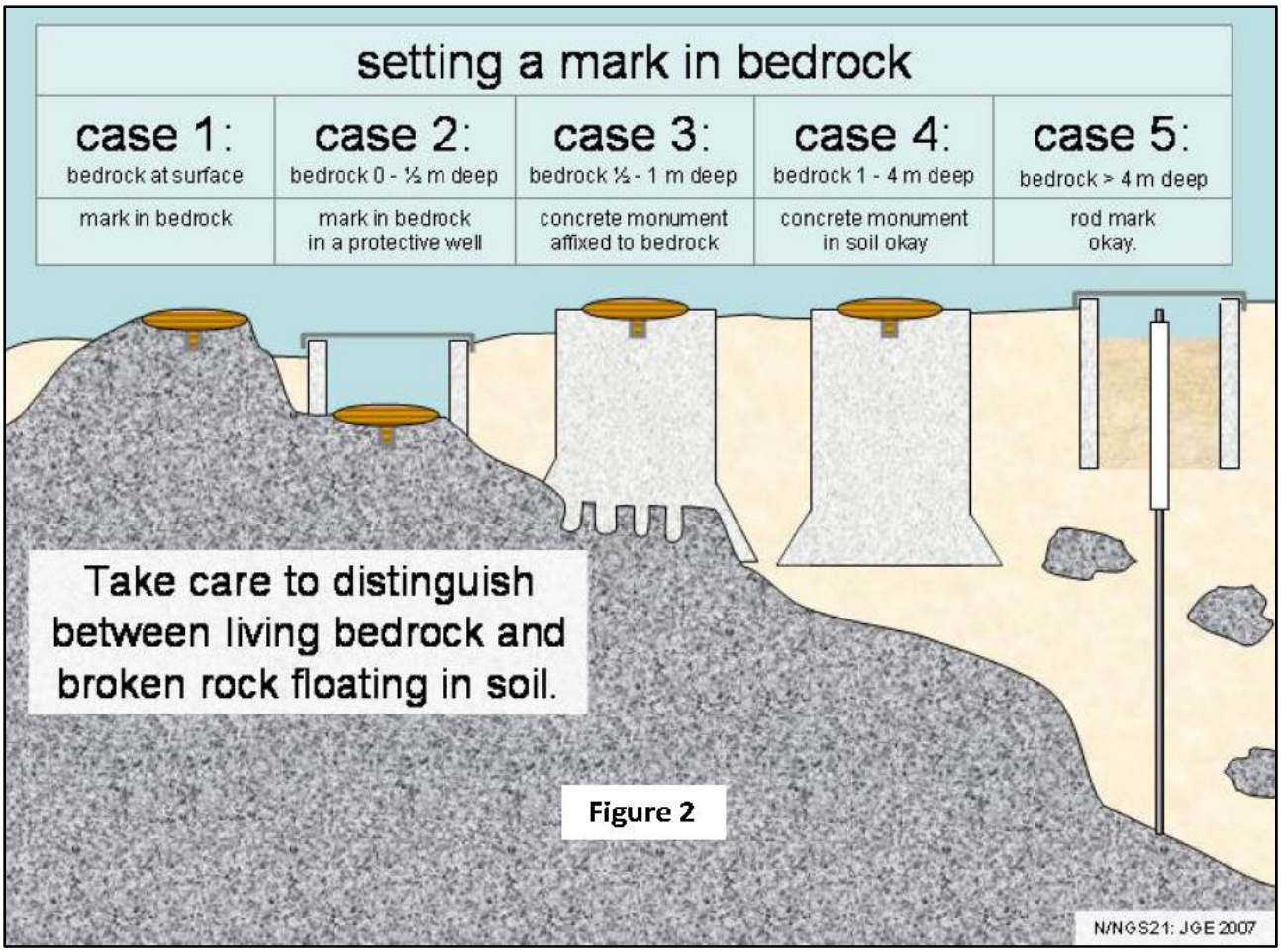


Figure 2

Non-bedrock Marks

Non-bedrock marks are classified as any mark set in a soil layer that is over bedrock. These soil areas can include alluvium, colluvium, illuvium, etc. Non-bedrock marks are typically deep driven rods (Figure 3), concrete marks (Figure 4a, 4b) and shallow setting surface marks like pipes, rebars, or other custom made driven-in monuments like the Berntsen G3250 (Figure 5). All of these marks have a lesser stability than bedrock because they are subject to motions that happen in the soil layer over the bedrock.

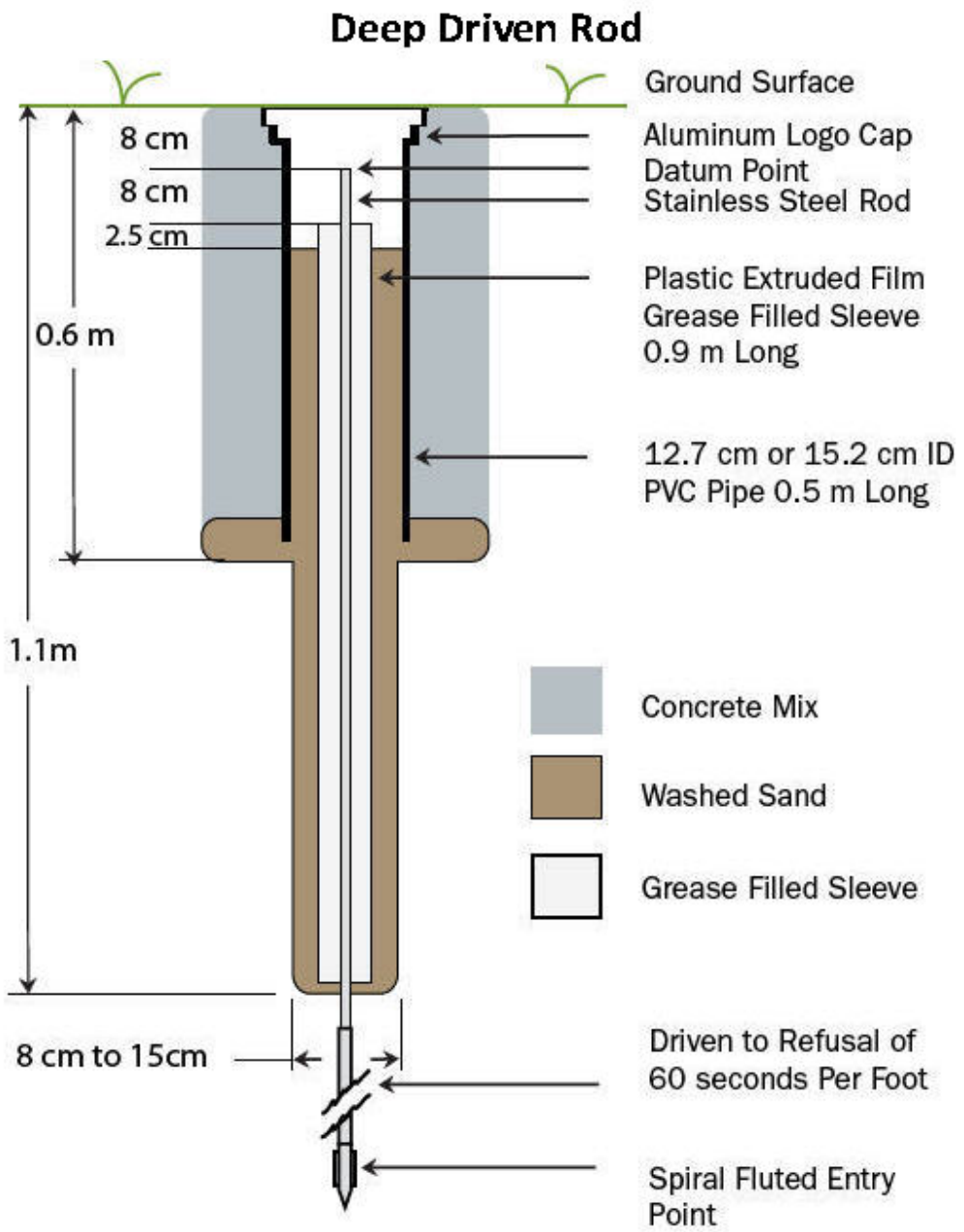


Figure 3

NGS Concrete Survey mark

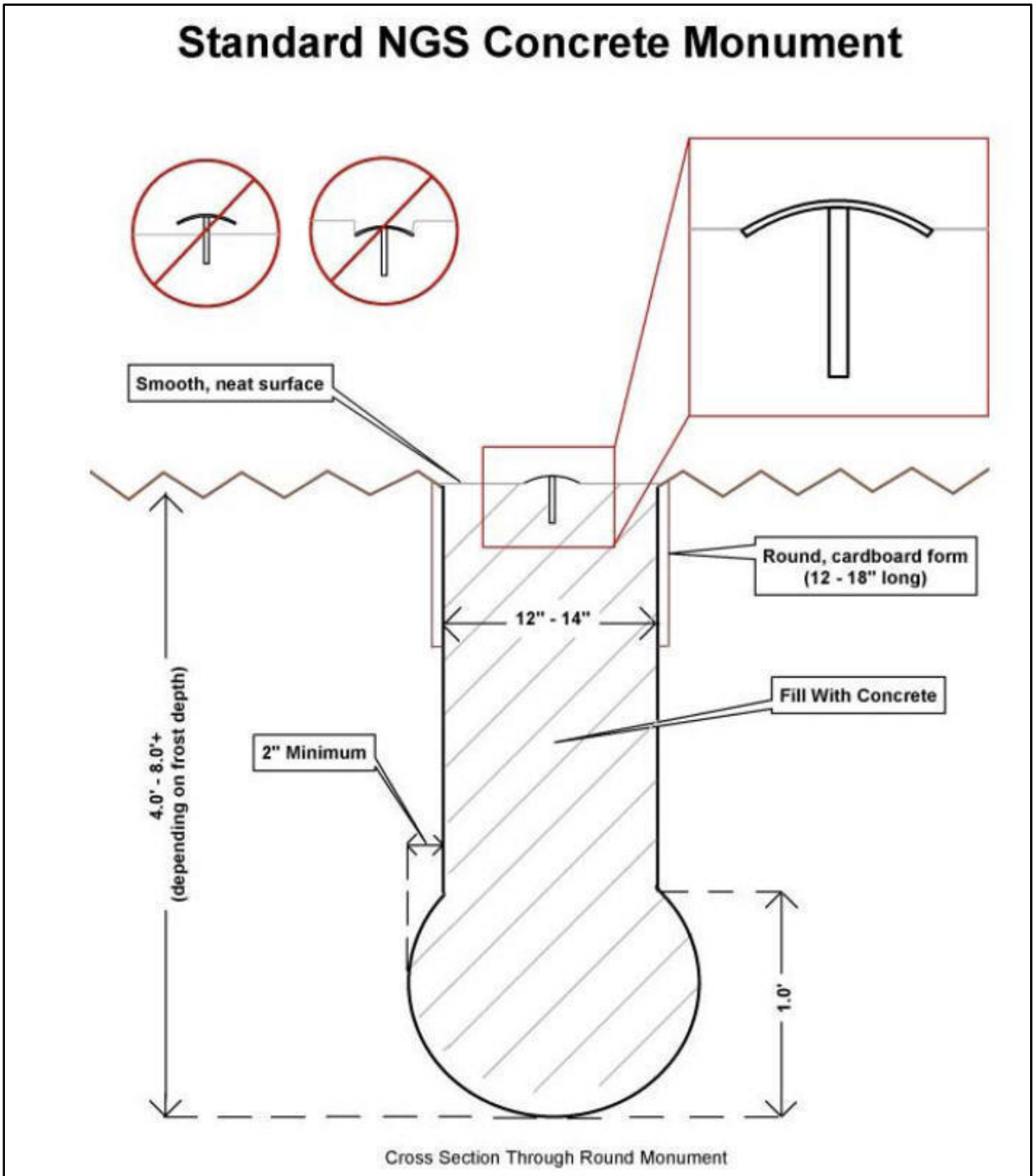


Figure 4a

NGS Concrete Survey mark

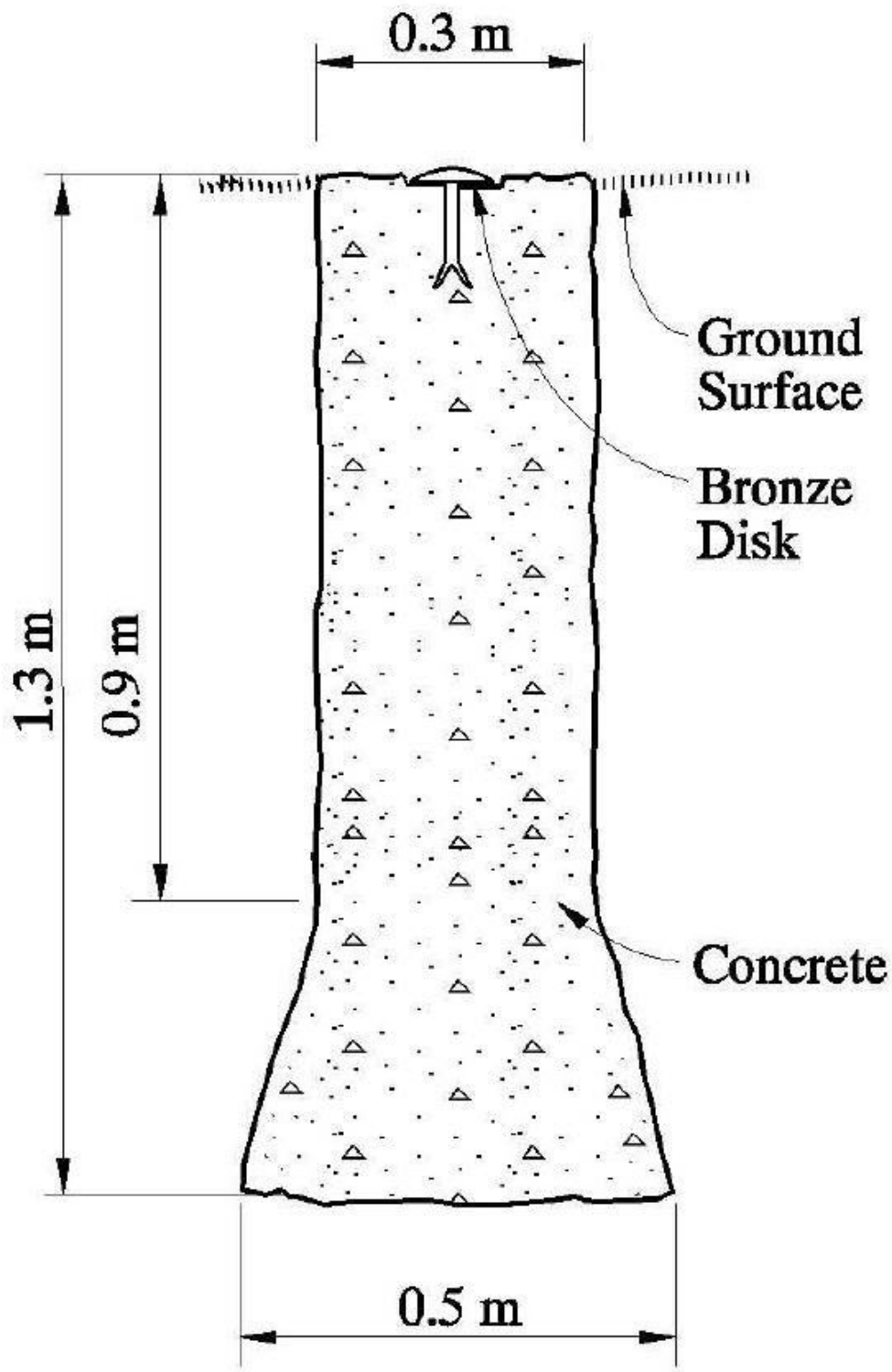


Figure 4b

Typical Surface Survey Drive-In Mark

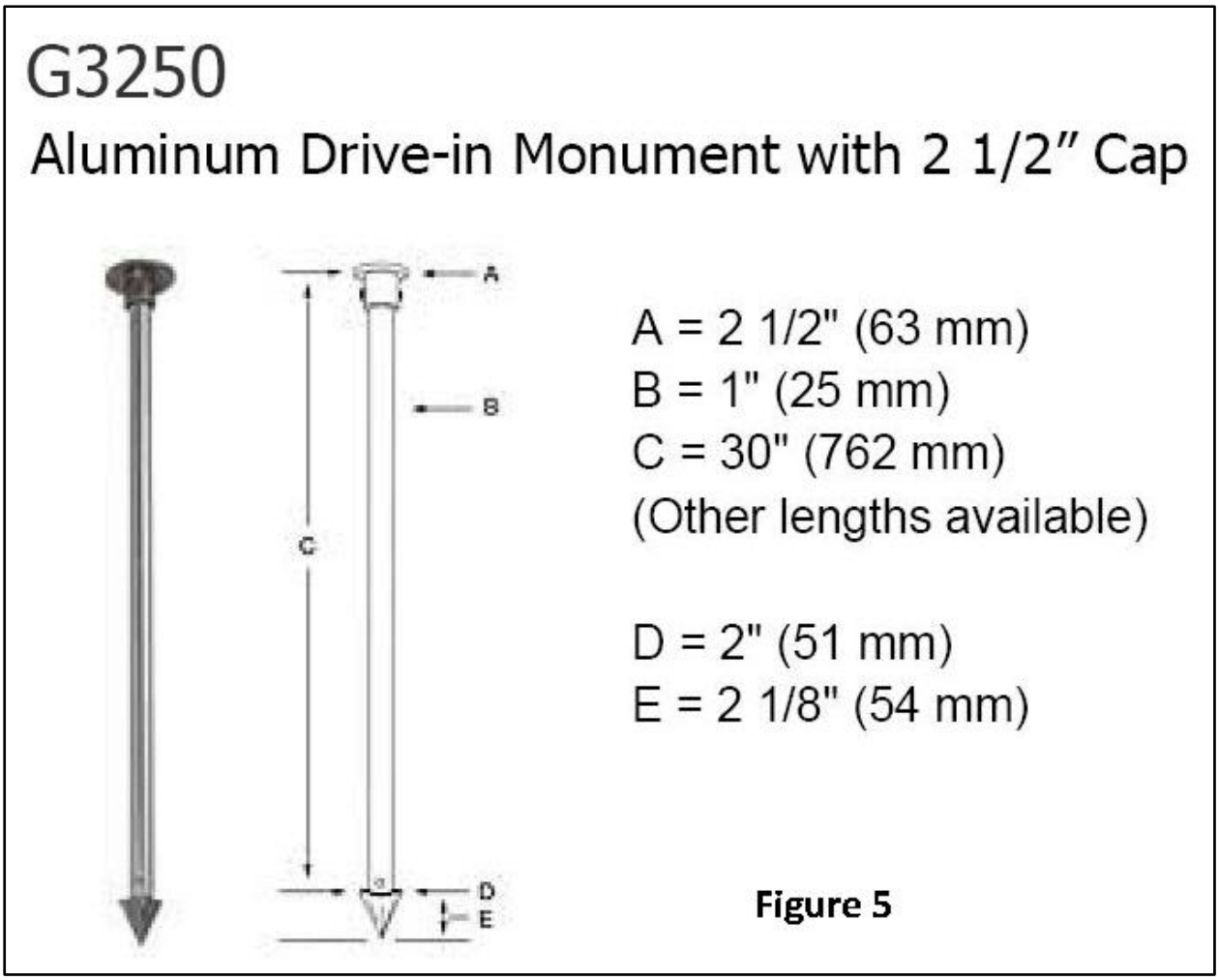
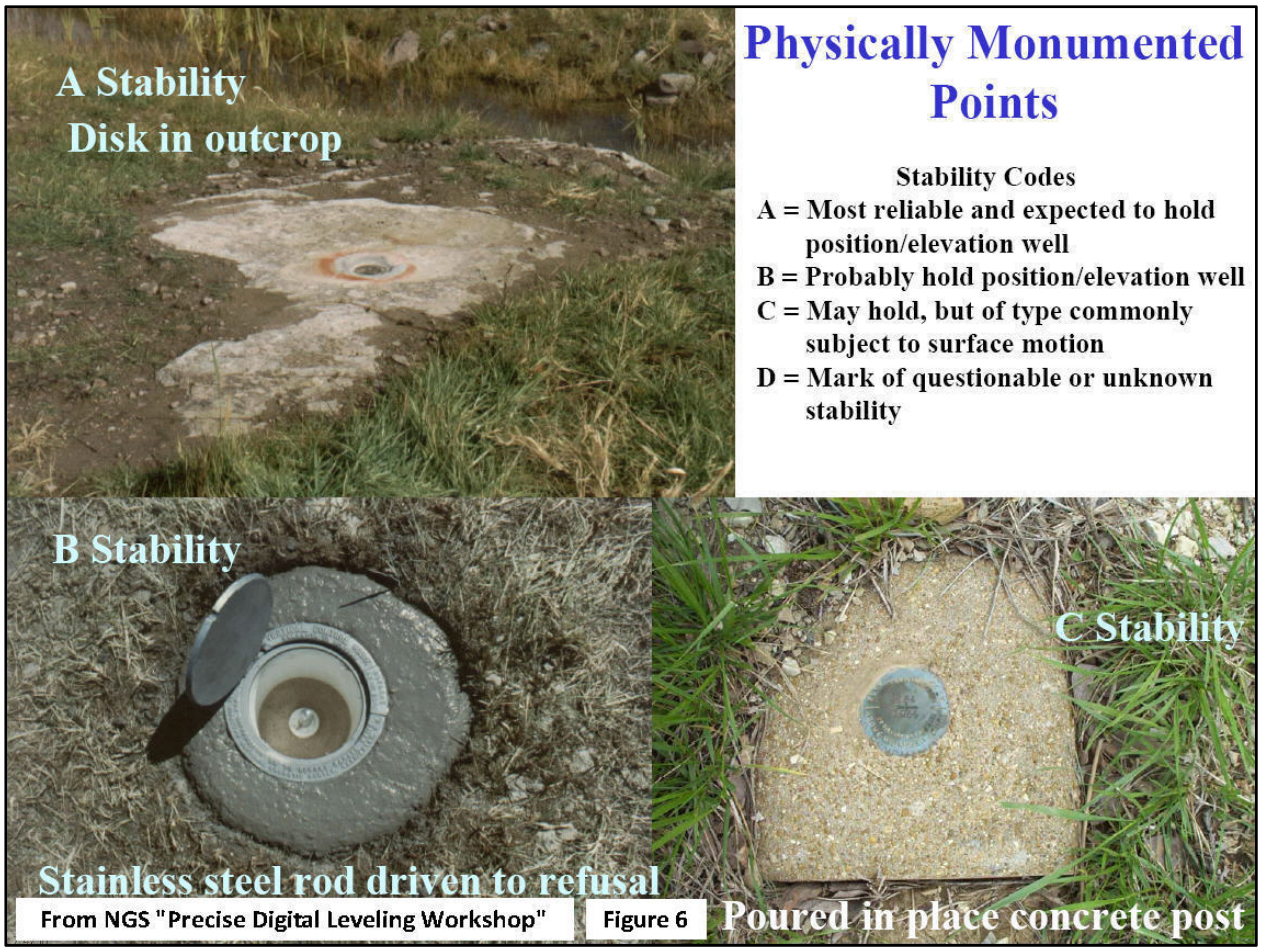


Figure 5

Ground Motions & Stability Defined

All survey marks are subject to the effects of geologic, soil and surface activity. The vertical component of survey control marks are affected more than the horizontal component because more often than not ground motions are in the vertical direction (aside from catastrophic tectonic activity like earth quakes). Ground motions can be classified into three groups: near surface; sub-surface; tectonic\isostatic. The stability classification of a monument in a soil (non-bedrock) installation is usually linked directly to the performance of the mark when related to the near surface motions only (Figure 6). NGS and US Army Corps of Engineer guidelines state that wherever possible, sound bedrock should be used for monuments installations. The guidelines also state that areas subject to sub-surface motion should be avoided. Current guidelines state that when areas with sub-surface motions cannot be avoided, deep driven rod monuments are recommended. Later in this paper, we will examine the performance of deep driven rods in areas of known sub-surface motion, and look at how they compare to adjacent marks of different construction. We will also discuss the necessity of building GPS/GNSS Continually Operating Reference Stations (CORS) sites predominantly in bedrock.



From NGS "Precise Digital Leveling Workshop" Figure 6

Near surface motions typically happen within the first 15 meters, or at the surface. These motions usually result from effects like frost heave, shrink and swell of soils and rock from moisture content, expansion and contraction from temperature variation, and soil consolidation from compaction\compression (as is the case under a large structure). Impacts to the mark itself can also be classified in a near surface motion. These can include being hit with a hammer or being run over by vehicular traffic. Impacts can also result in total destruction of a mark as would be the case with earth moving equipment.

Sub-surface motions can happen anywhere below the first 15 meters. Subsidence is a form of sub-surface motion that results from ground fluids mining. Subsidence motions happen within the soil layer, below the near surface events and above the bedrock. Subsidence will effect only those marks that are in the soil. A bedrock mark will not be effected by subsidence.

Tectonic and isostatic motions are those motions within the earth's crust (lithosphere) or below the crust and in the upper mantle (asthenosphere). Whereas these are also sub-surface motions like subsidence, these motions will have an equal effect on both a bedrock and non-bedrock monument within close proximity to each other (moving bedrock will also move the soil on top of the bedrock).

Glacial\isostatic rebound happens in the Midwest United States. It is occurring because of the reliction of ice sheets during the last ice age. During the ice age, the ice sheets weighted the earth's crust, depressing it. Now that the ice sheets are gone, the crust is seeking isostatic equilibrium, or in simple terms is floating upward because the mass of the ice is gone.

It is reasonable to deduce that a similar effect may happen in areas of large subsidence. Large quantities of water being removed from the substrata of soils will have a similar action on the earth's crust, as did the reliction of ice sheets. There are differences in magnitude, as the ice sheets of the last ice age were miles thick, and ground water levels have dropped hundreds of feet, with surface motions being in the tens of feet.

Land Subsidence Defined

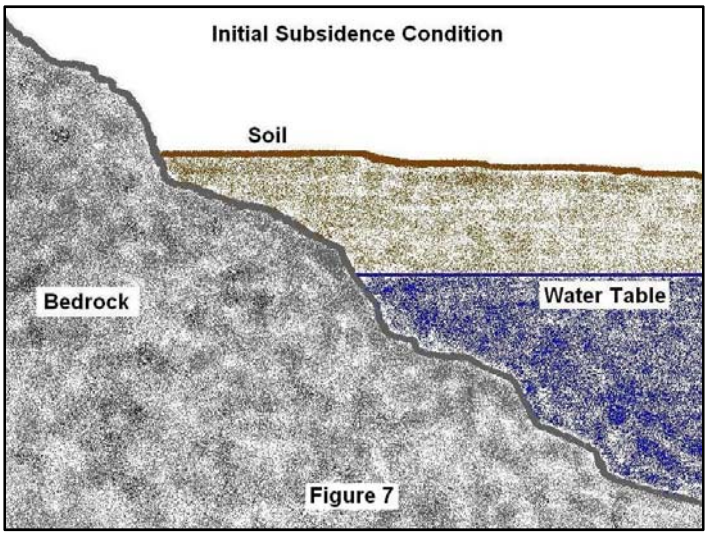


Figure 7

Subsidence can be caused as a result of ground fluids mining. Step one is the initial condition where subsurface fluids exist in the soil layer. Step two results when mining (pumping) removes the fluids, lowering the fluids level. This causes voids to exist in the subsurface soils. Steps three and four result when the voids collapse causing the effected zone to drop in height. The notable effect is twofold, first the subsurface holding capacity is reduced, and second the ground level drops. Step five, ground fissures, typically appear after subsidence has occurred, and will typically appear in areas of dissimilar subsurface activity (like at the edge of a zone where there is an inconsistent drop on either side of the fissure).

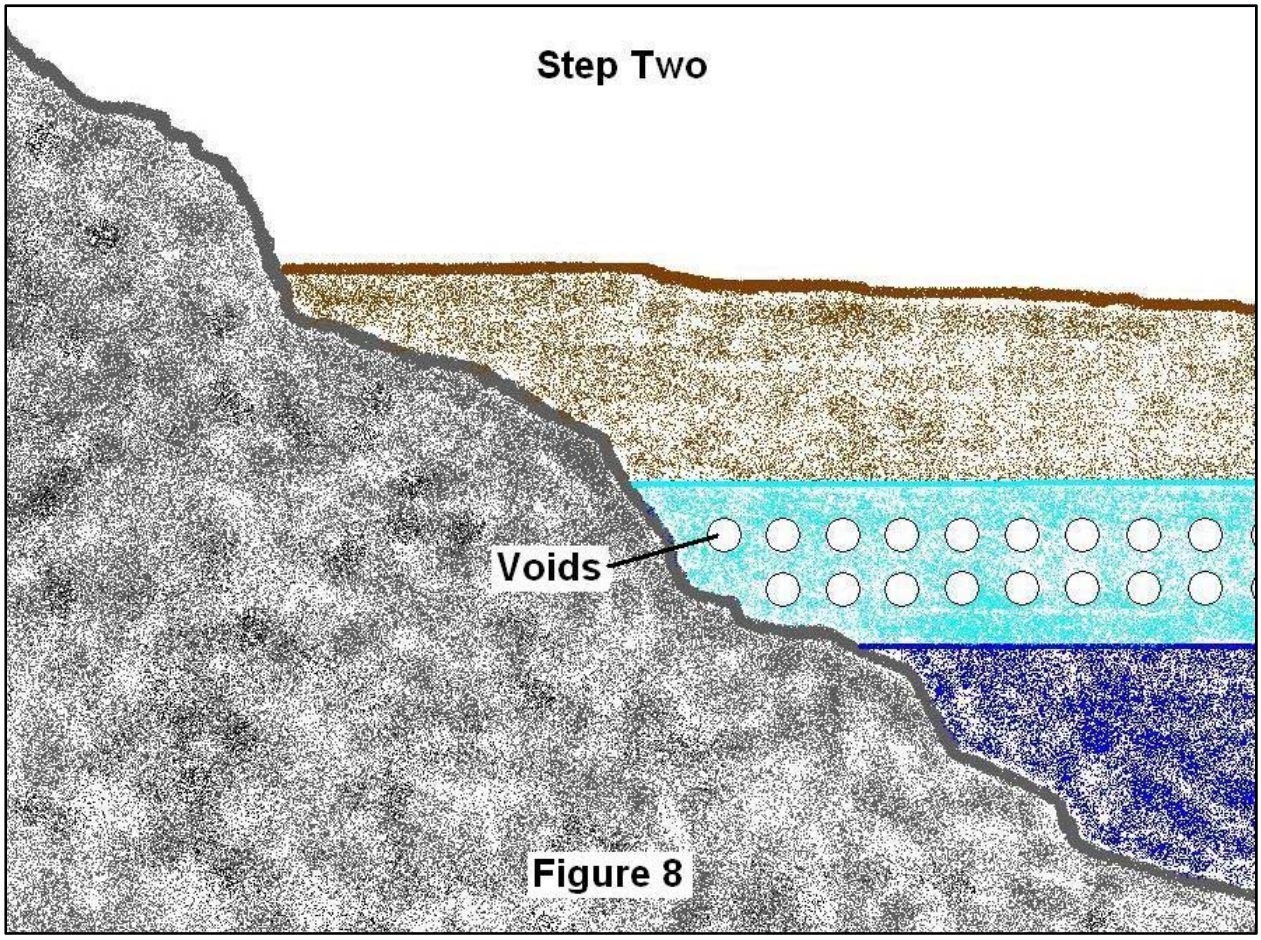


Figure 8

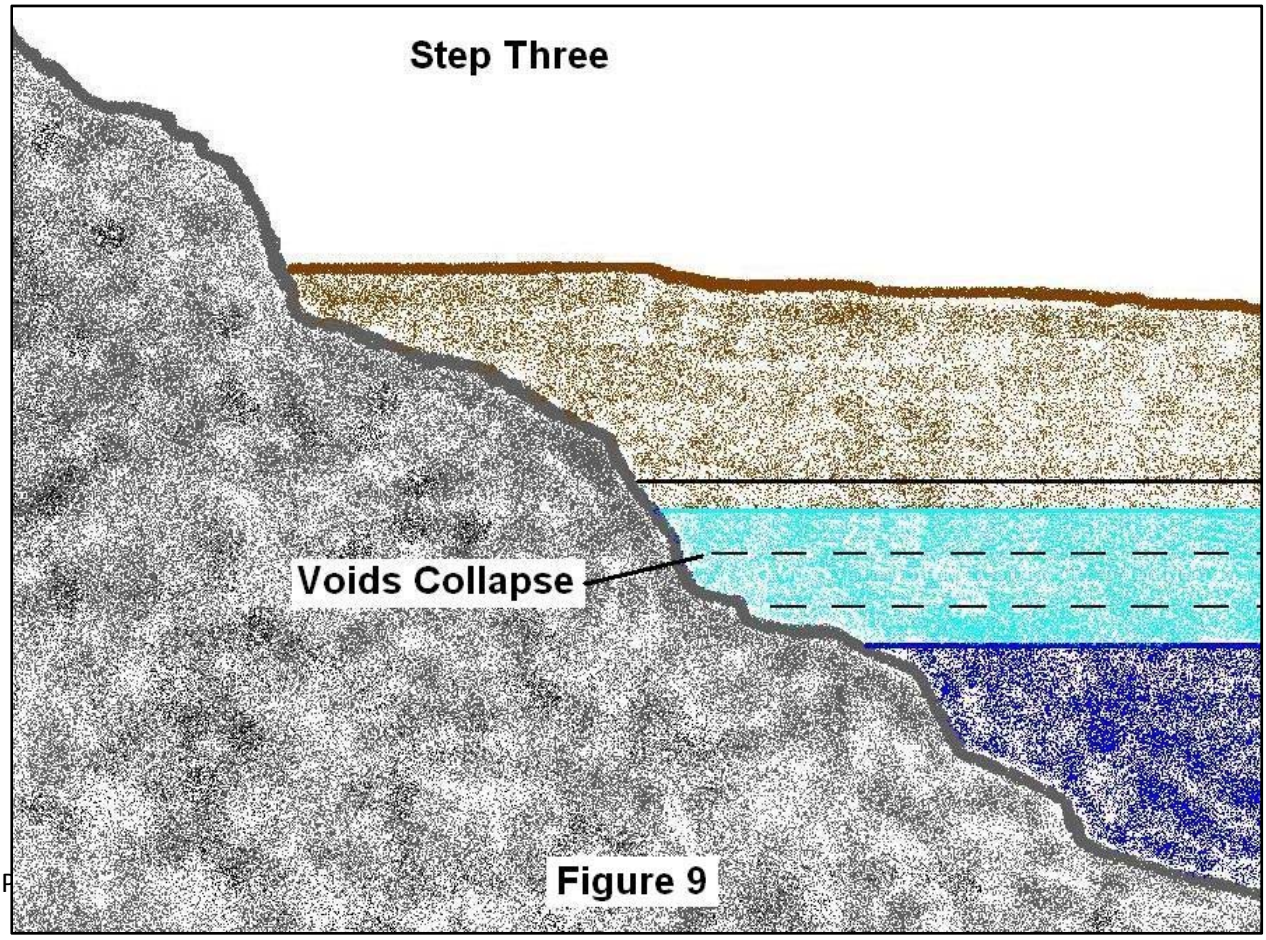


Figure 9

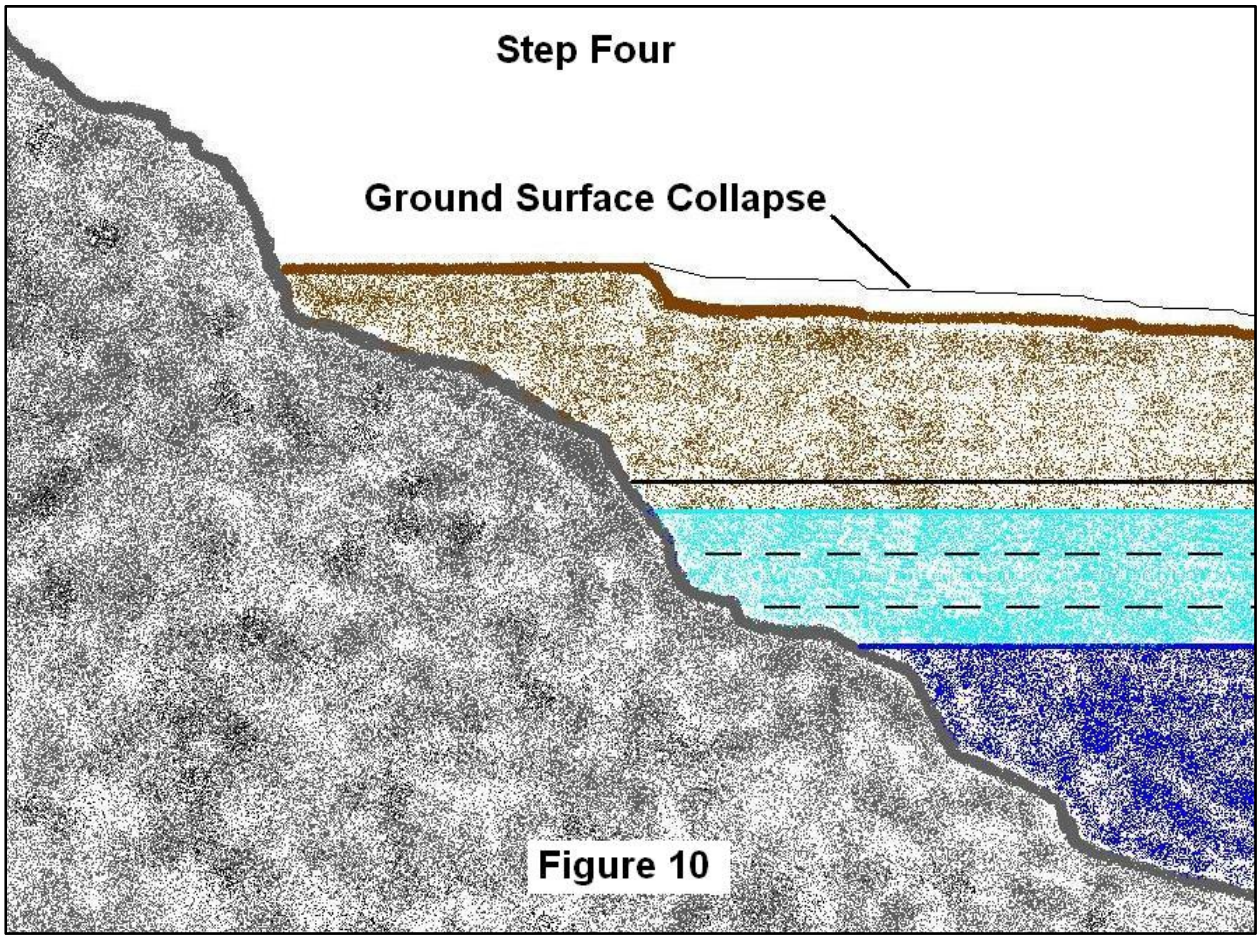


Figure 10

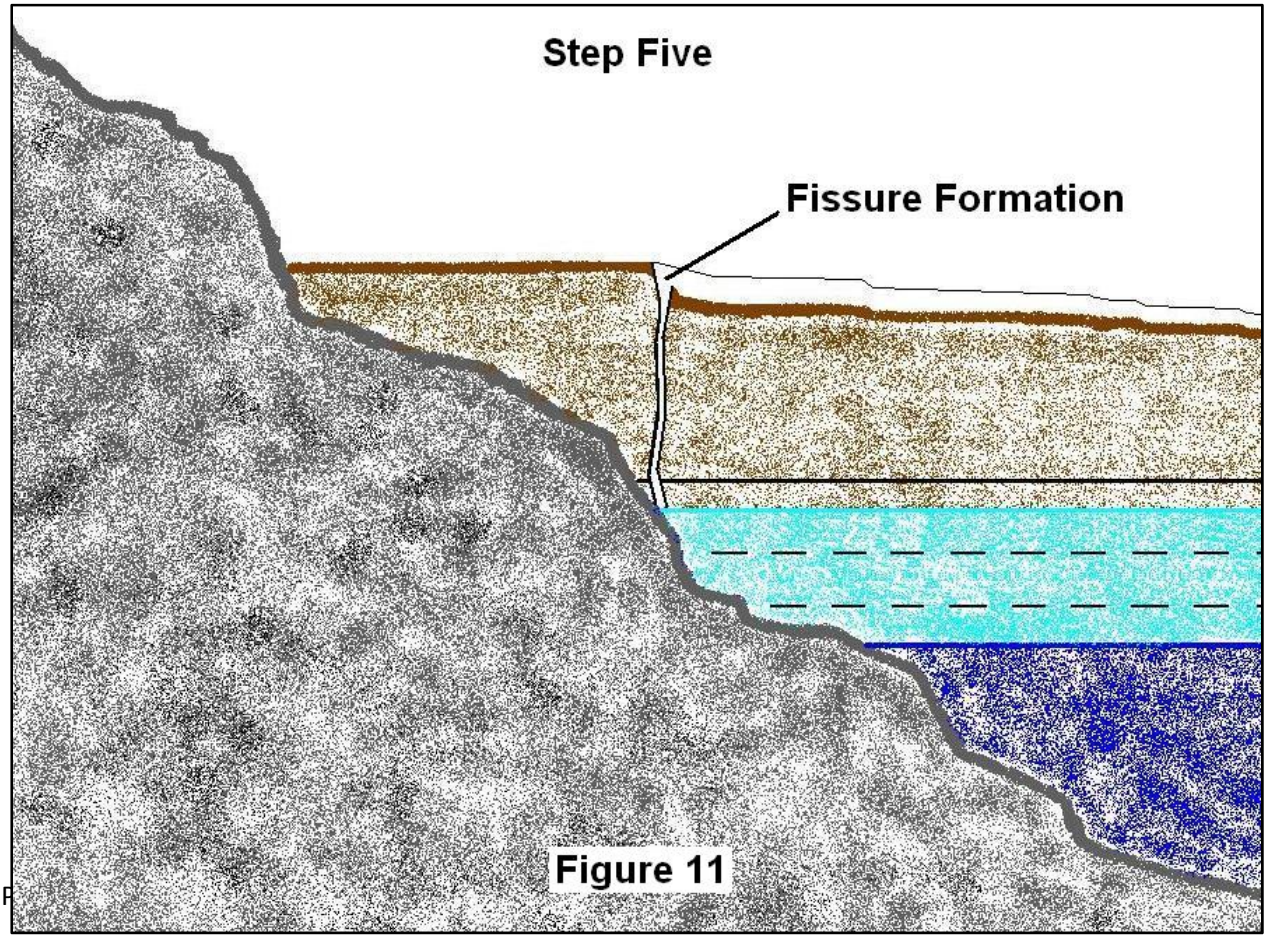


Figure 11

Methods for Quantifying Land Subsidence

Traditional Ground Surveys to Benchmarks (Leveling)

Traditionally the only method for quantifying\observing land subsidence was to run precise geodetic leveling starting and ending on a bedrock benchmark and crossing over a subsidence area. In Figures 12 NGS level runs are compared over a known subsidence area. Figure 13 shows a close up of three adjacent monuments within a 1 kilometer radius. The three monuments have different stability classifications, but all perform identically within the subsidence feature.

Depth to bedrock in Figure 13 is about 450 meters. Groundwater levels have been historically between 30 and 100 meters in this area. The source of the motion from subsidence originates where the change in the water table occurs. This means that the traditional NGS stability codes will not apply when the source of the motion is so deep.

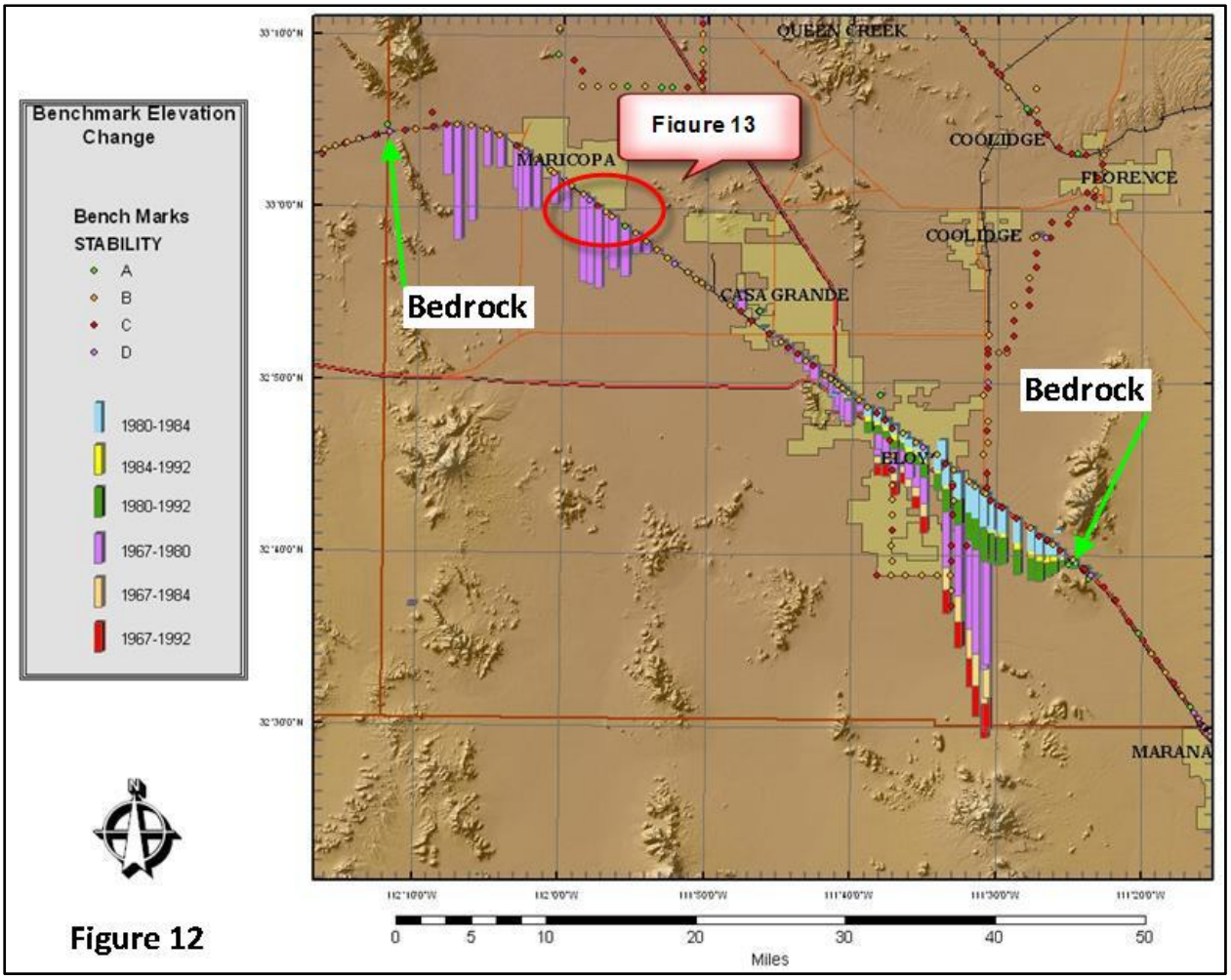
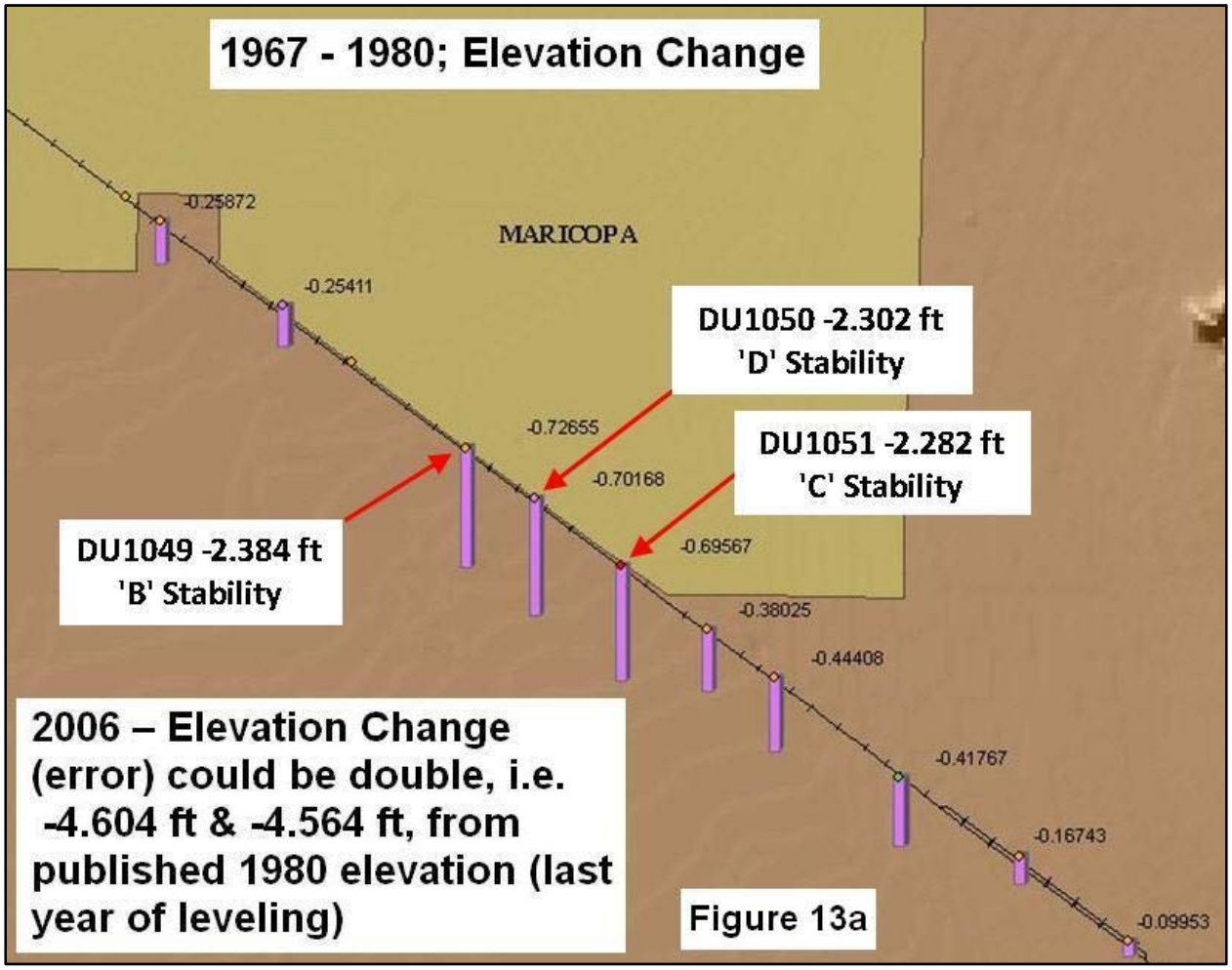
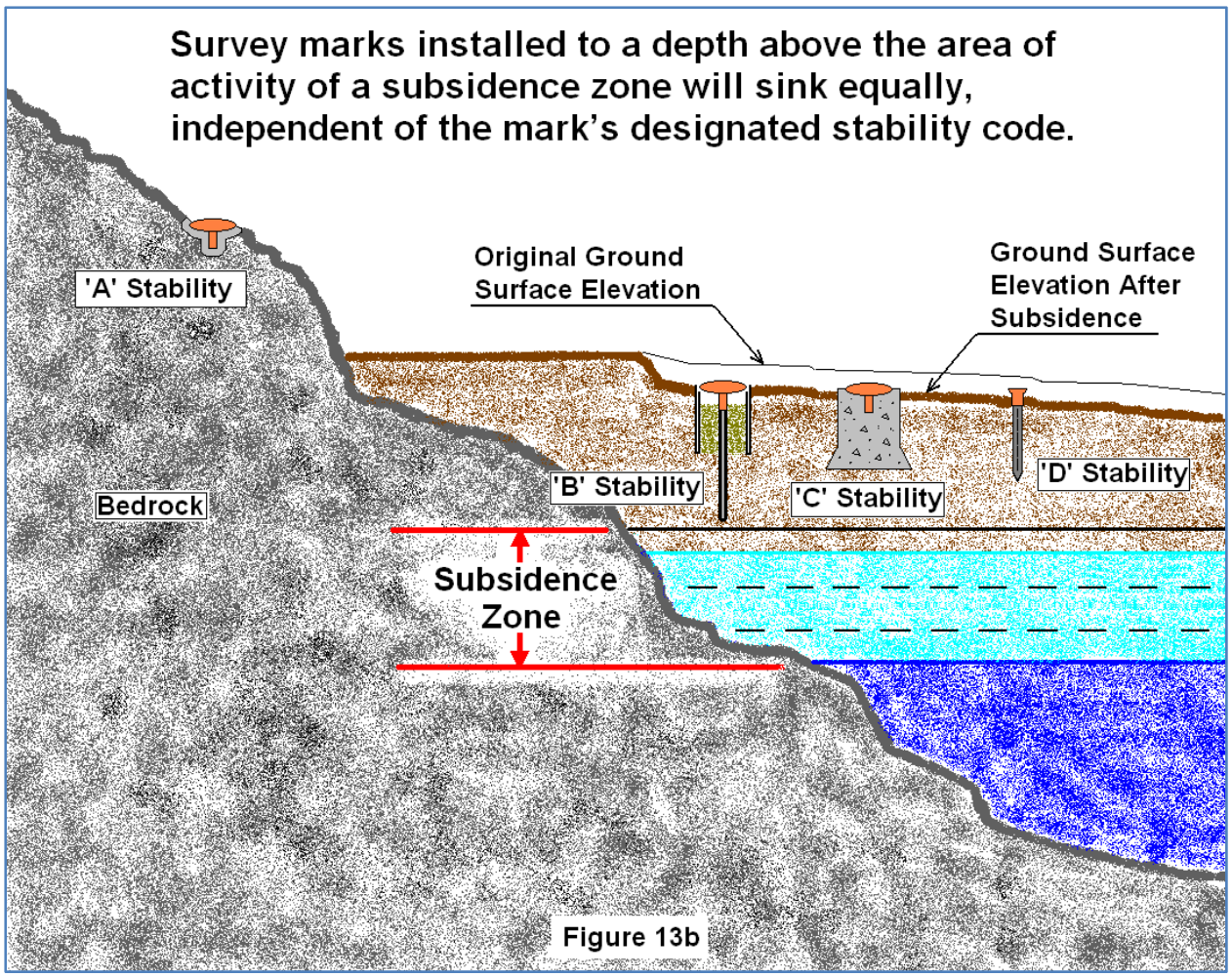


Figure 12



NGS datasheet stability designations for the points illustrated in Figure 13a.

DU1049 **********
DU1049 DESIGNATION - T 360
DU1049_MARKER: DB = BENCH MARK DISK
DU1049_SETTING: 46 = COPPER-CLAD STEEL ROD W/O SLEEVE (10 FT.+)
DU1049_SP_SET: 16 FT
DU1049_STAMPING: T 360 1967
DU1049_STABILITY: B = PROBABLY HOLD POSITION/ELEVATION WELL
DU1050 **********
DU1050 DESIGNATION - 1226
DU1050_MARKER: P = PIPE CAP
DU1050_SETTING: 17 = SET INTO TOP OF METAL PIPE DRIVEN INTO GROUND
DU1050_SP_SET: METAL PIPE DRIVEN INTO GROUND
DU1050_STABILITY: D = MARK OF QUESTIONABLE OR UNKNOWN STABILITY
DU1051 **********
DU1051 DESIGNATION - U 360
DU1051_MARKER: DB = BENCH MARK DISK
DU1051_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT
DU1051_SP_SET: SET IN TOP OF CONCRETE MONUMENT
DU1051_STAMPING: U 360 1967
DU1051_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO SURFACE MOTION



Note on mark stability, cost, and monitoring programs.

As mentioned previously, current guidelines state that when areas with sub-surface motions cannot be avoided for survey mark placement, deep driven rod monuments are recommended. A finding from this study is that this may not be the most prudent course of action any longer. The cost of a deep driven mark (Figure 3) is about $1,000 - $2,000. The cost of a concrete mark (Figures 4a & 4b) is about $100 - $200. Lastly the cost of a drive in mark (Figure 5) can be as little as $20 - $50. When leveling was the only option for determining the vertical position of a mark, the cost to locate a mark was a major deciding factor in determining the style of construction. A modern approach to mark location, like the use of GPS/GNSS, changes this equation significantly. Cost savings from mark construction can be used for a monitoring program instead, and will result in better data in the long run within the subsidence area.

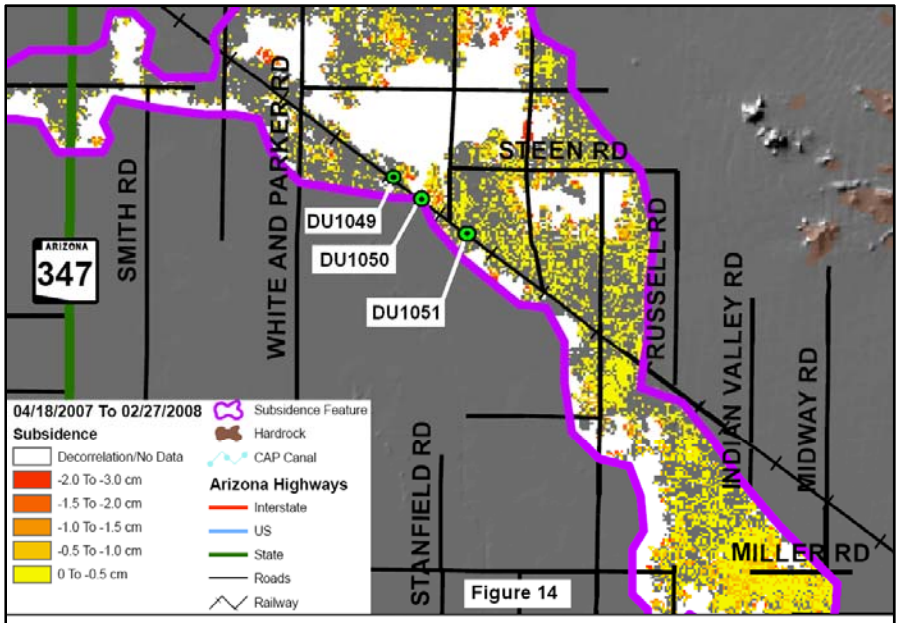
In summary, spend less money on the individual survey marks within the subsidence area, and divert these funds into the construction of bedrock mounted CORS sites. This will be detailed in a later section of this paper.

Remote Sensing (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) Data is another method of monitoring surface motions. Figure 14 shows a close up of the three benchmarks mentioned above. The time series for the NGS levels and the InSAR data is different, but the two studies show active subsidence in the same region over an extended period of time (1967 to present). The next example of InSAR data will be compared to the same time sequence of data collected at a NGS CORS site, AZPE.

There are two major advantage of using InSAR data verses point positioning. First, the InSAR data covers an area, whereas point positioning only produces data at discrete locations. Second, InSAR data is far more cost effective to investigate large areas.

ADWR has been using InSAR to look for areas that may have subsidence for about ten years. Additional work has also been performed in the identified areas to confirm the findings. Gravity data and static GPS/GNSS surveys have been performed to verify the InSAR findings.



Land Subsidence in the Maricopa-Stanfield Sub-Basin, Pinal County
Based on ADWR EnviSat Time-Series InSAR Data
Time Period of Analysis: 0.8 Years 04/18/2007 To 02/27/2008

Decorrelation (white areas) are areas where the phase of the received satellite signal changed between satellite passes, causing the data to be unusable. This occurs in areas where the land surface has been disturbed (i.e. bodies of water, snow, agriculture areas, areas of development, etc).

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In the next section, a deep driven rod within a known subsidence area, Maricopa County's Geodetic and Cadastral Survey (GDACS) control station 4FB1, will be examined. The station was originally set in 1999, and subsequent surveys tying this point to bedrock control by both ADWR and the County have confirmed that the station has changed in the vertical direction by about 3 centimeters downward.

Synthetic Aperture Radar (SAR) is a side-looking, active (produces its own illumination) radar imaging system that transmits a pulsed microwave signal towards the earth and records both the amplitude and phase of the back-scattered signal that returns to the antenna. Figure 15 shows an ERS-1 Satellite. Interferometric Synthetic Aperture Radar (InSAR) is a technique that utilizes interferometric processing that compares the amplitude and phase signals received during one pass of the SAR platform over a specific geographic area with the amplitude and phase signals received during a second pass of the platform over the same area but at a different time. InSAR techniques, using satellite based SAR platform data, can be used to produce land surface deformation products with centimeter scale vertical resolution, 50 meter pixel resolution, and covering areas of 100 square kilometers.

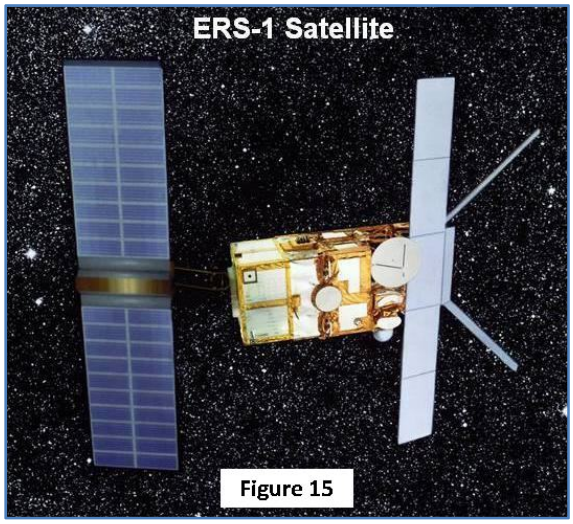


Figure 15

ADWR has used SAR data from the European Space Agency's ERS-1 ERS-2, and EnviSat satellites and the Canadian Space Agency's RadarSat 1 satellite. All of these satellites utilize the C band which has a wavelength of approximately 5.6 centimeters. One downfall of the C band is that areas where the land surface has been disturbed (i.e. bodies of water, snow, agriculture areas, areas of development, etc.) tend to decorrelate. Decorrelation occurs when the phase of the received satellite signal changed between satellite passes, causing the data to be unusable.

The Japanese Space Agency recently launched an L-Band SAR satellite that greatly decreases the amount of decorrelation in those same areas where the C-band data would have decorrelated. The L-Band has a wavelength of approximately 20 centimeters, more than three times the wavelength of the C band, which will improve land subsidence monitoring in those areas of active agriculture and development. ADWR has recently started analyzing L-Band data in certain areas of Arizona.

ADWR's InSAR program started in 2002 with the awarding of a three year NASA Earth Science grant in cooperation with the University of Texas at Austin Center for Space Research and the Vexcel Corporation. ADWR and its cooperators developed the InSAR program during the three years of the grant. In 2005, ADWR began collecting and processing monthly level 0 raw SAR data from the European and Canadian Space Agency SAR satellites, producing time-series interferograms for the greater Phoenix and Tucson metropolitan areas. The InSAR coverage has been greatly enhanced around Central and Southern Arizona, collecting monthly SAR data for Maricopa, Pinal, Pima, La Paz, and Cochise counties. Through these efforts, ADWR has identified and now monitors more than fifteen active subsidence features around Arizona. Numerous State, County, and Local government entities understand the importance of InSAR and utilize the data as an important resource into their own monitoring efforts. As a result, these groups have entered into agreements with ADWR, providing annual contributions to the

InSAR program, ensuring that SAR data is collected, processed, and analyzed for those areas critical to each group's monitoring efforts.

ADWR has been using InSAR to determine the spatial extent, deformation rates, and time-series history of those land subsidence features identified around the State. InSAR is very cost effective due to its resolution and the large area covered by each satellite frame. Engineers, hydrologists, geologists, and scientists greatly benefit from the InSAR data to identify and evaluate areas of subsidence, uplift, earth fissures, faults, and many other geologic features. InSAR data is used by those involved in the fields of: water resources, structural engineering, geological engineering, hydrological engineering, land planning, and surveying.

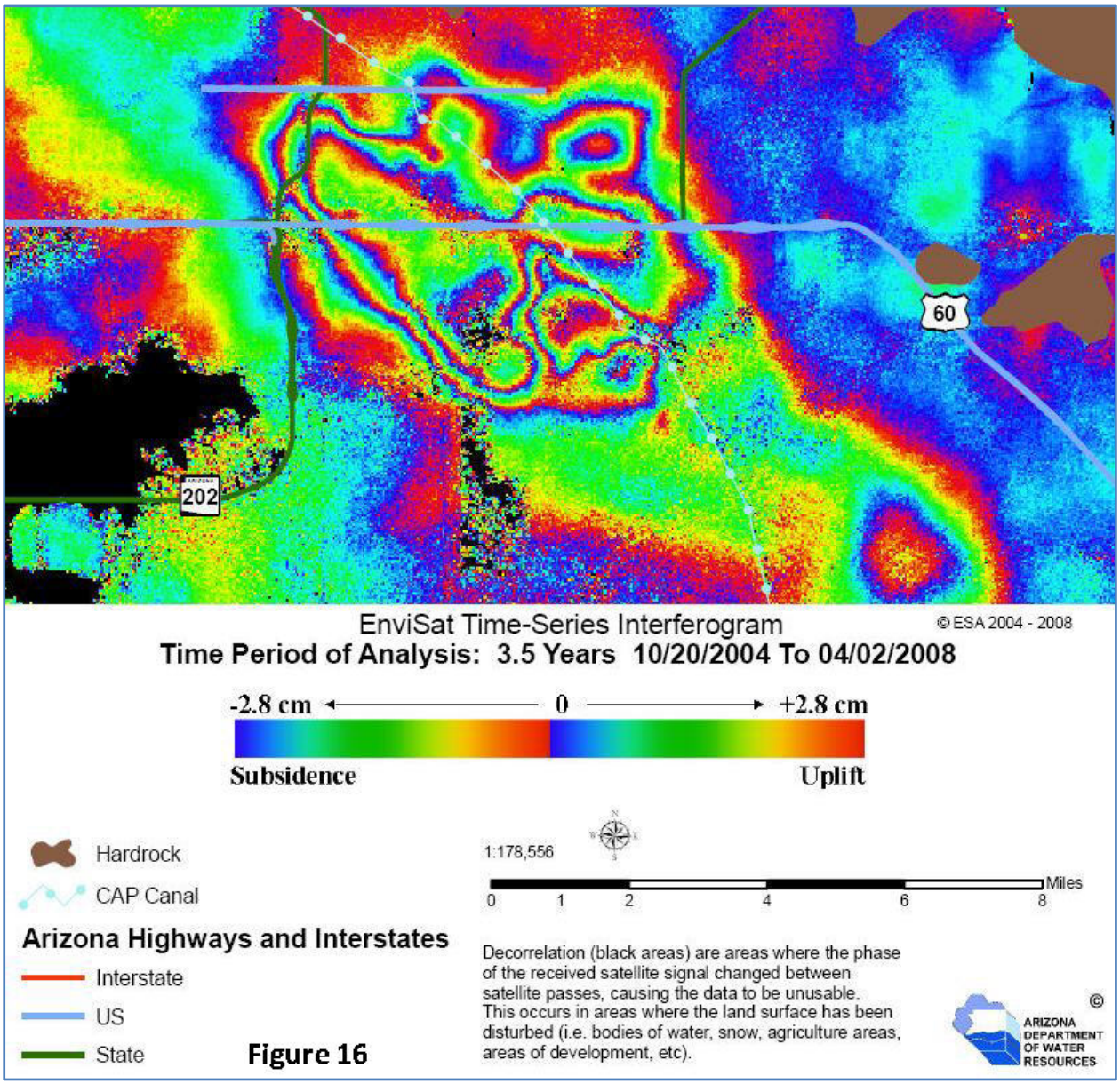


Figure 16

GPS/GNSS Ground Surveys to Benchmarks

GPS/GNSS ground surveys offer advantages over traditional leveling for monitoring subsidence, Figure 17. The station below, 4FB1 can be tied to two bedrock marks, FRIA RM4 and BEDROCK 1, with a 2 – 4 hour observation to determine 2cm level position. This survey requires two to three field technicians. A comparable ground leveling campaign would run 33 miles, use the same number of field technicians, and would take weeks. In fairness the leveling campaign would also be able to tie many more points along the way, but the cost savings of the GPS/GNSS survey are twofold. First, control can be picked individually if desired, and only the target area is observed. Leveling has to run its entire length, and cannot pick up and leave off in the middle like a GPS/GNSS survey can. This can be looked at like an 'as needed' and 'on demand' capability that a GPS/GNSS survey has over leveling. Secondly, GPS/GNSS surveys, even with multiple stations covering an area, cost about 45% - 75% that of leveling.

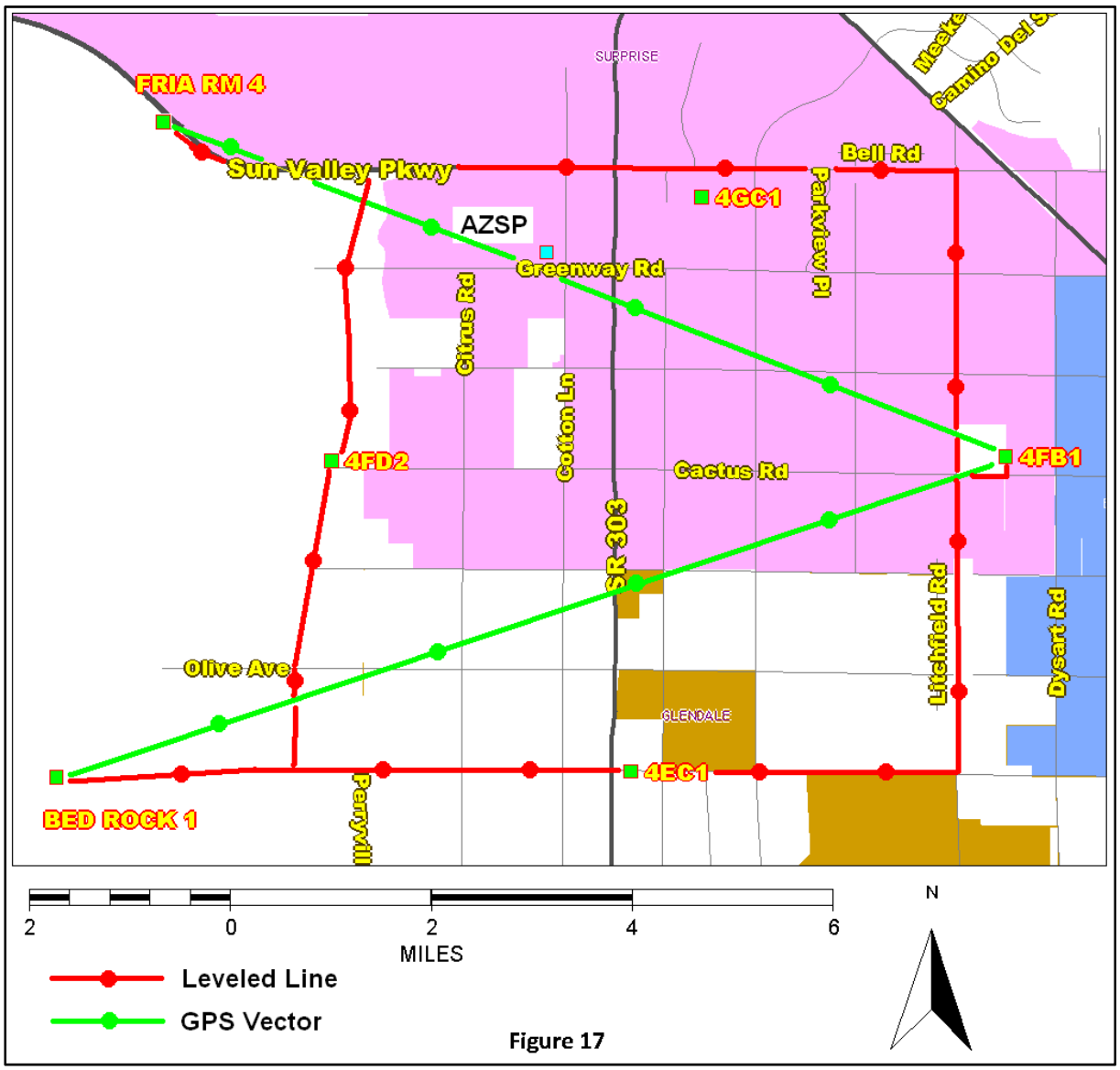


Figure 17

GPS/GNSS CORS Surveys

CORS sites offer several advantages over traditional terrestrial survey marks for monitoring subsidence. First, the data is continuous (active) verses discrete (passive). Second, there are cost savings for collecting the data, as the CORS is always set up and a field technician is not required to attend the station as it collects data. Lastly, random setup errors are eliminated as a CORS is hard mounted to the survey mark. With the traditional survey mark, additional equipment is needed to connect the GPS/GNSS antenna to the reference mark (tripod, etc.). Consistency in measurements is sacrificed for portability of the equipment.

Figure 18 shows 4FB1 being tied to two CORS sites. The cost for locating this point is almost a third of the cost when compared to the GPS/GNSS ground survey as shown in Figure 17. Only one field technician is needed for the field observation. CORS sites cost more to construct than ground stations, but the cost is offset in the long run from every survey that is able to tie to them with only minimal effort, and cost savings that can be had in constructing less expensive monuments within the subsidence area.

The example in Figure 18, though sound in theory, is at present not practical. Both AZSP (not a national CORS) and AZPE, are within the same subsidence feature. If the published positions for the two CORS are used to check the published position of 4FB1, virtually no change will be measured. All three stations have subsided almost equally, so in a relative sense, their positions are stable. AZPE will be examined more closely in the next section.

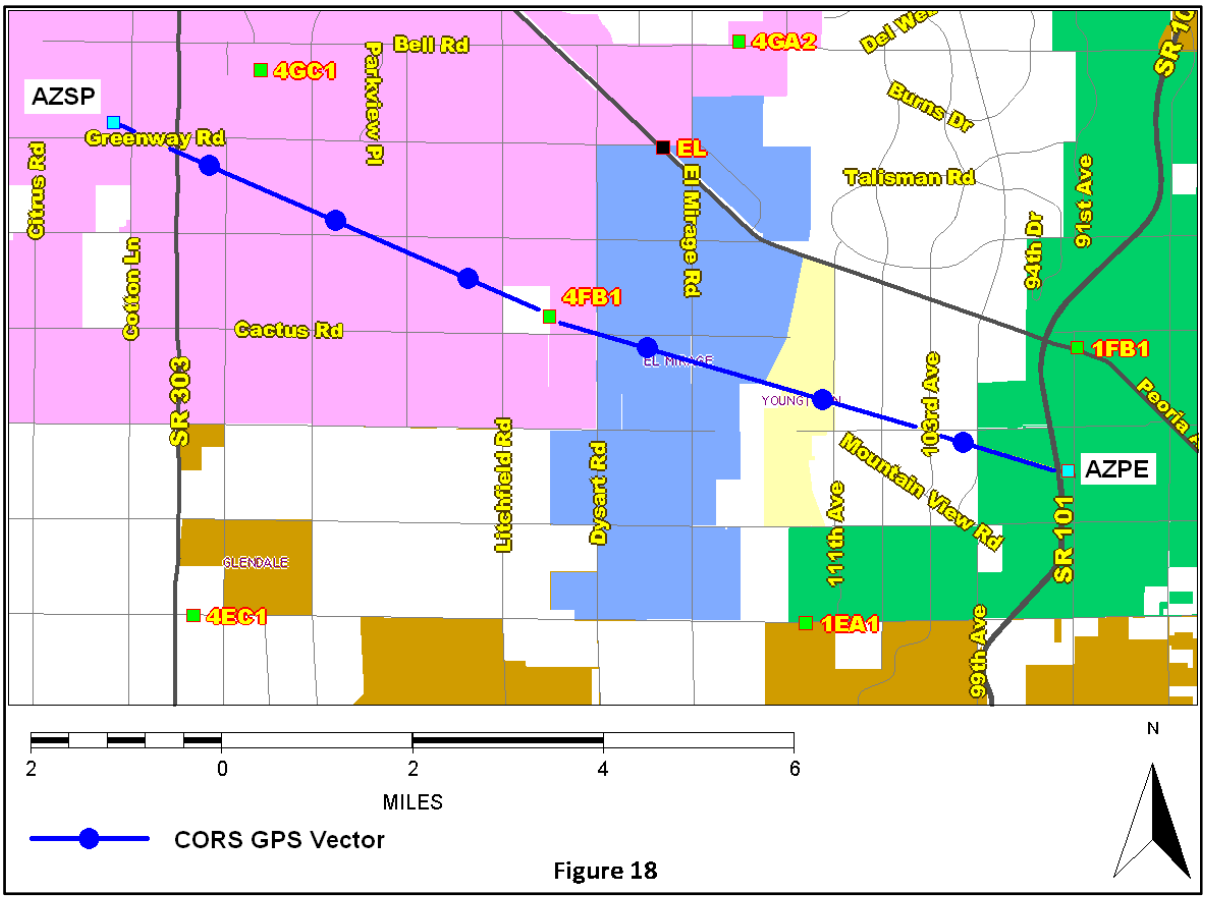


Figure 18

CORS Site Stability

CORS sites (a survey mark with a GPS/GNSS antenna permanently mounted to it), are essentially identical to traditional ground survey marks when it comes to stability. If they are constructed in a soil area they are subject to subsidence. An illustration of an UNAVCO deep drilled station is shown in Figure 19. If this style of station is not connected to bedrock (like case 3 or 5 in Figure 2) it will still be effected by deep soil motions (those below the 15 meter depth).

CORS site P003 is a UNAVCO deep drill braced monument, and is in an area most probably effected by subsidence. The InSAR data in the area is mostly inconclusive because the farm activity is very heavy, but the depth to bedrock is over 120 meters. P003 is in a known heavy groundwater pumping area. The station is also about a centimeter lower now than two years ago, Figure 20. The most likely cause is subsidence.

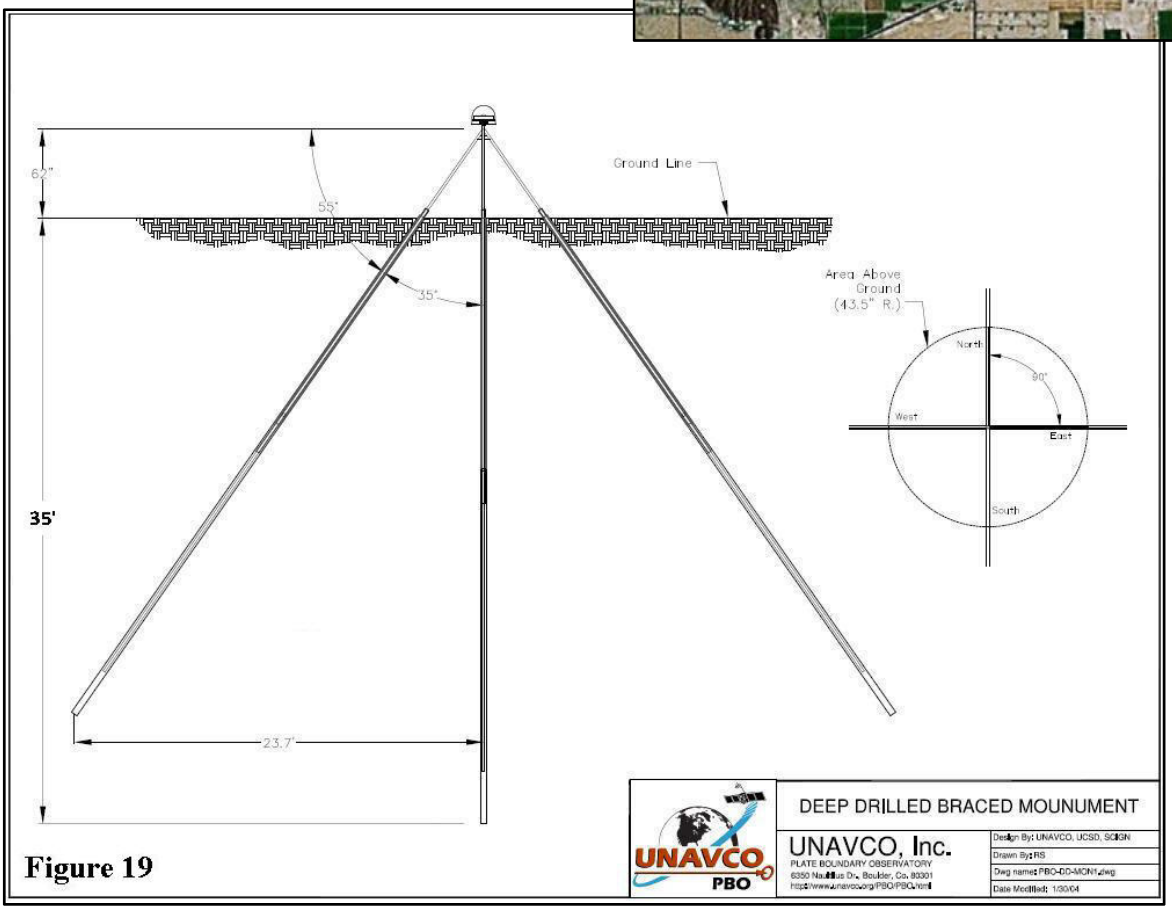
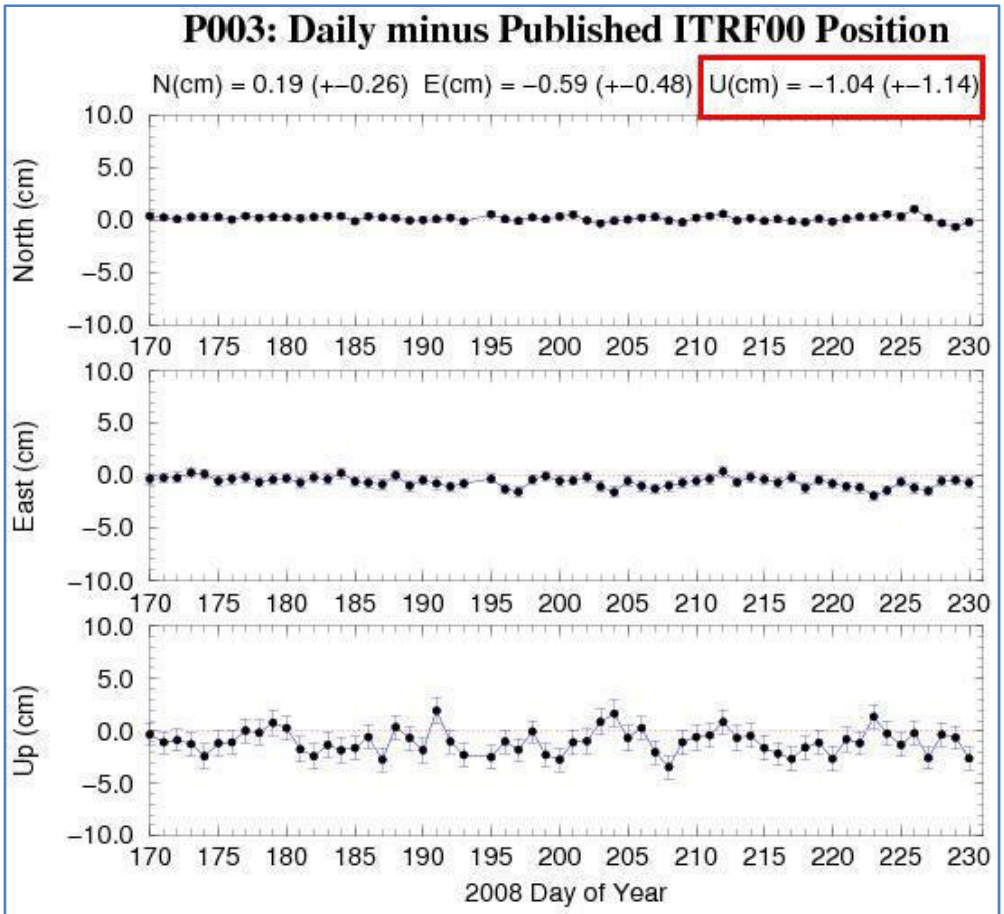


Figure 19

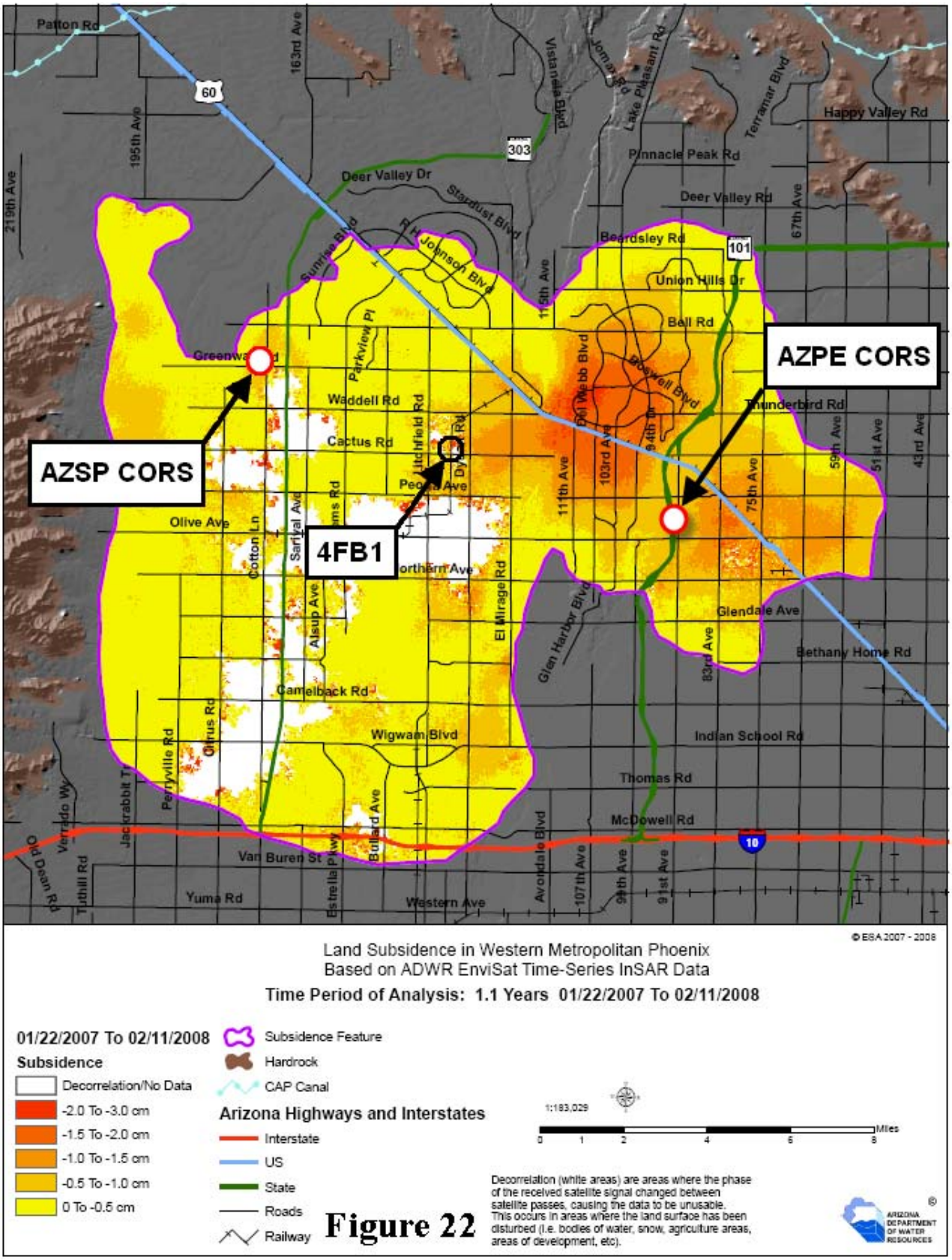


Four Character ID : P003
Monument Description : DEEP-DRILLED BRACED
Agency : UNAVCO

Figure 20

CORS mounted to building tops will be effected in the same way, Figure 21. If the area is in a subsidence zone, the building and surrounding area will sink.

Figure 22 shows an ADWR InSAR map of the Western Metro Phoenix subsidence feature. Within this feature is a NGS CORS site, AZPE. The map covers a time sequence from 1-22-2007 thru 2-11-2008. Data from this CORS was sampled every ten days and processed to bedrock CORS using OPUS. The results were graphed, and are shown in Figure 23. InSAR data shows the station to have lowered in the vertical between 0.5 cm and 1.0 cm. This was confirmed in Figure 23, showing the station has lowered 0.4 cm in the same time period. Figure 24 shows the NGS 60 day plot for the same station. From the start of the station in 2005, the station has lowered by about 3 cm, or at an average rate of 1.0 cm per year.


AZPE CORS
AZSP CORS
4FB1
Patton Rd
Happy Valley Rd
Pinnacle Peak Rd
Deer Valley Dr
Deer Valley Rd
Beardsley Rd
Union Hills Dr
Bell Rd
Thunderbird Rd
Waddell Rd
Cactus Rd
Olive Ave
Glendale Ave
Bethany Home Rd
Camelback Rd
Wigwam Blvd
Indian School Rd
Thomas Rd
McDowell Rd
Van Buren St
Yuma Rd
Western Ave
Stardust Blvd
Sunrise Blvd
R H Johnson Blvd
Parkview Pl
Litchfield Rd
Dysart Rd
Peoria Ave
Northern Ave
Sarival Ave
Cotton Ln
Alsup Ave
El Mirage Rd
Glen Harbor Blvd
Del Webb Blvd
Boswell Blvd
Vistanela Blvd
Jomax Rd
Lake Pleasant Rd
Terramar Blvd
Citrus Rd
Perryville Rd
Jackrabbit Tr
Verrado Wy
Old Dean Rd
Tuthill Rd
Estrella Pkwy
Bullard Ave
Avondale Blvd
Old Webb Blvd
Boswell Blvd
Lake Pleasant Rd
Jomax Rd
Vistanela Blvd
Sunrise Blvd
Stardust Blvd
Deer Valley Rd
Pinnacle Peak Rd
Happy Valley Rd
Terramar Blvd
Glendale Ave
Bethany Home Rd
Indian School Rd
Thomas Rd
McDowell Rd
Western Ave
Yuma Rd
Van Buren St
Olive Ave
Cactus Rd
Waddell Rd
Thunderbird Rd
Bell Rd
Union Hills Dr
Beardsley Rd
Deer Valley Dr
Patton Rd
60
303
101
10
219th Ave
195th Ave
163rd Ave
115th Ave
111th Ave
103rd Ave
94th Dr
75th Ave
67th Ave
59th Ave
51st Ave
43rd Ave
83rd Ave
107th Ave
99th Ave
91st Ave
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Land Subsidence in Western Metropolitan Phoenix
Based on ADWR EnviSat Time-Series InSAR Data
Time Period of Analysis: 1.1 Years 01/22/2007 To 02/11/2008
01/22/2007 To 02/11/2008
Subsidence
Decorrelation/No Data
-2.0 To -3.0 cm
-1.5 To -2.0 cm
-1.0 To -1.5 cm
-0.5 To -1.0 cm
0 To -0.5 cm
Subsidence Feature
Hardrock
CAP Canal
Arizona Highways and Interstates
Interstate
US
State
Roads
Railway
1:183,029
0 1 2 4 6 8 Miles
Decorrelation (white areas) are areas where the phase of the received satellite signal changed between satellite passes, causing the data to be unusable. This occurs in areas where the land surface has been disturbed (i.e. bodies of water, snow, agriculture areas, areas of development, etc).
ARIZONA DEPARTMENT OF WATER RESOURCES

Figure 22

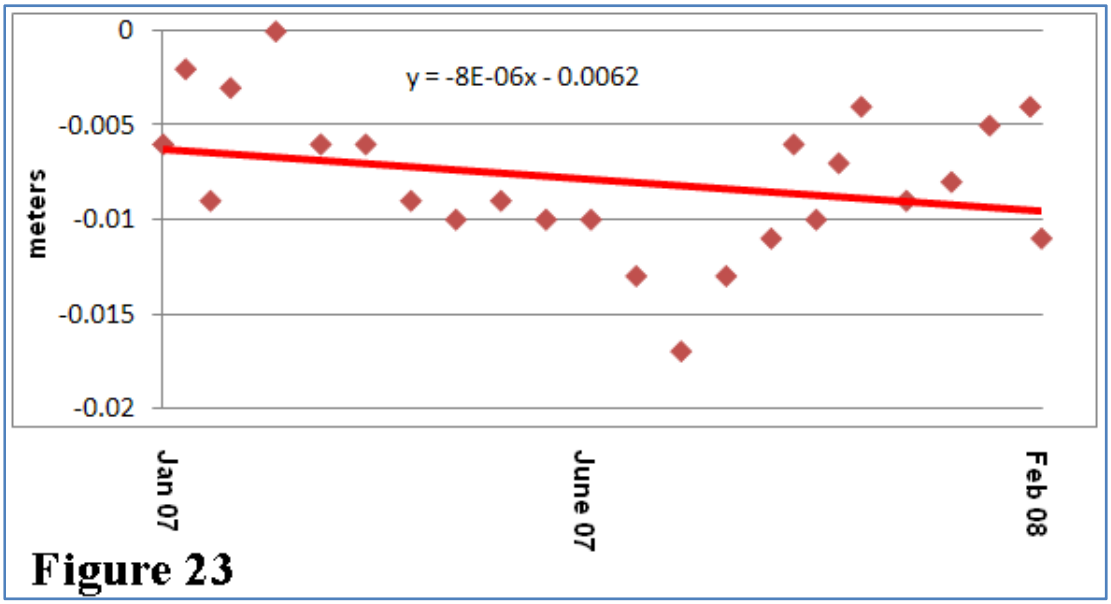

Figure 23

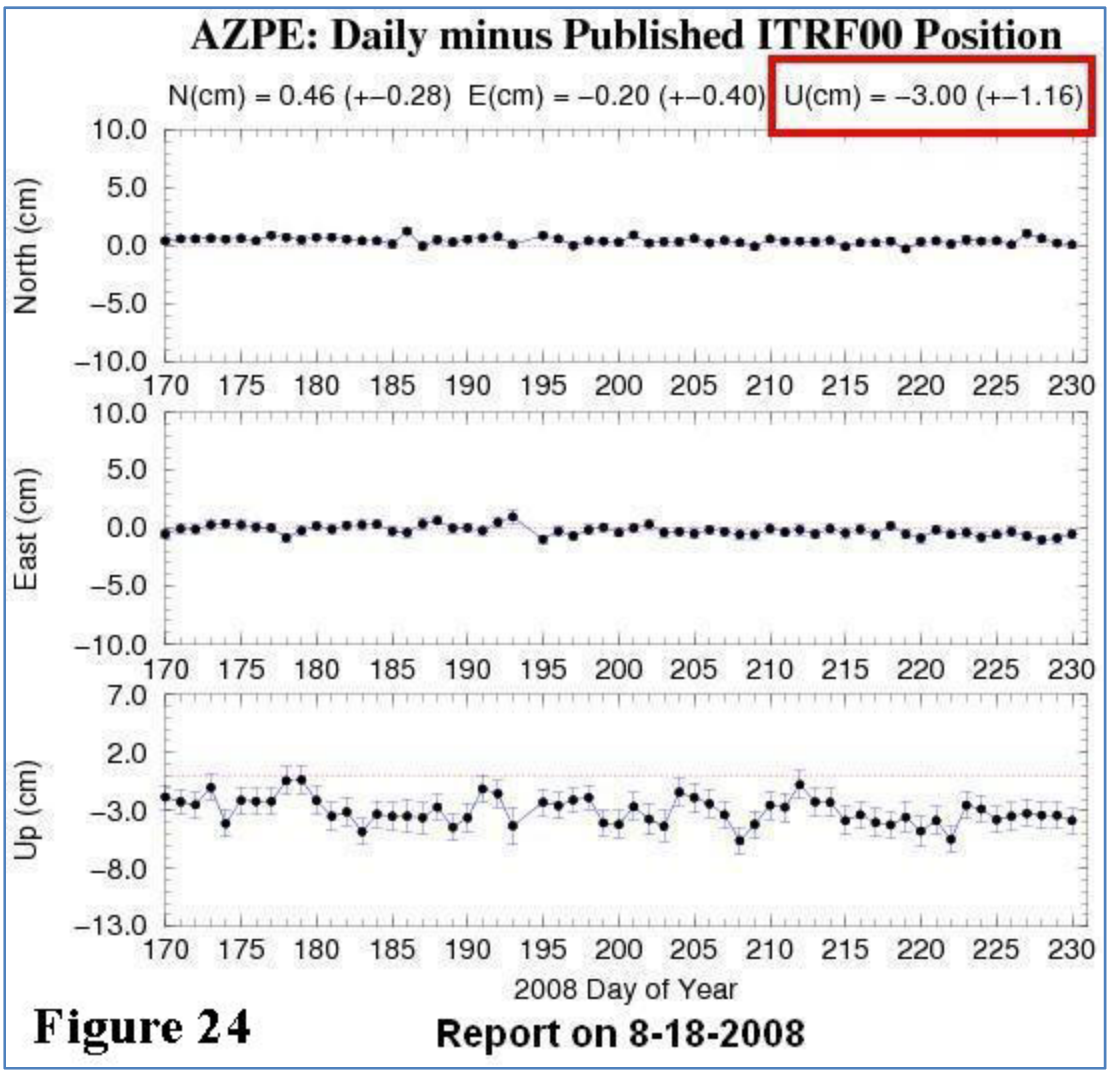

Figure 24 **Report on 8-18-2008**

Proposed Approach to Managing Survey Control Within a Subsidence Area

It has been shown that the NGS stability codes apply only to near surface motions, and do not apply to total survey mark performance when motion happens below the first 15 meters. To manage this inevitable movement within a subsidence area, positioning of survey control will need to be continually reobserved. Any survey, to a great extent, is only as accurate as the control it is tied to. This being said, subsequent observations have to be tied to stable (bedrock) control each time. Tying adjacent control within a subsidence area cannot isolate the vertical motion caused by subsidence and can produce erroneous results. As in Figure 13a, if DU1050 were to be reset by leveling from the two adjacent marks DU1049 and DU1051, the measurement between DU1049 and DU1051 would show potentially adequate closure (0.03 meters) when in reality the vertical position could be some fifty times worse (compared to the 1980 published value).

This can also be seen in Figure 16 & Figure 19. If 4FB1 were to be reset using GPS/GNSS from the published positions of AZSP and AZPE, a bias in the resulting vertical position would occur.

The most cost effective method to manage survey control within a subsidence zone is to first monitor the area using InSAR data. Once subsidence zones are identified, observations can be planned where necessary. Traditional leveling shall not be used to establish heights within the subsidence area, as they are too costly and only provide a 1D position. GPS/GNSS surveys tied directly to active bedrock control (bedrock mounted CORS) shall be used to position all marks within the subsidence zone.

Initially, bedrock CORS will be tied to the National Spatial Reference System as accurately and precisely as possible. Doing so will allow their positions to be held fixed when additional control is tied to them. The potential of updating their position will still be an option to manage other smaller magnitude motions (tectonic deformations, expansive bedrock, etc.) but the frequency of adjustments on the bedrock CORS will be very low (ideally years between adjustments). Having high stability CORS sites helps minimize adjustments of the total network, and makes managing all points and subsequent data much easier.

Positions of supplemental marks (both CORS and classical terrestrial marks) within the subsidence feature need to be updated at a high frequency (weeks, months or years depending on precisions required) from the bedrock CORS.

Incidental ground control (points used to control ground surveys, photo control, total station work, etc.) shall have a scheduled re-observation procedure to, at a minimum, monitor their motions. All survey efforts will have a direct and active geometric link to the underlying geodetic datum as realized by the bedrock CORS. This will be done every time the survey control is to be referenced too (start, during, and at the end of projects). In essence, ground control within the subsidence area, after initially observed, will have a shelf life. This shelf life will depend on the velocity of the subsidence and the precision required. To be able to take full advantage of the GPS/GNSS observations of benchmarks, a new approach to the definition of a vertical datum is also required.

Fully integrated 3D geodetic datum definitions

3D Geodetic Datum

The Geodetic datum shall be defined to be NAD83(CORS96-2002.0000)as it is the current adjustment of the CORS network. The Principle defining points shall be bedrock mounted CORS. These sites shall be held 'fixed' in all subsequent observations. Their initial positions shall be the most precise relative to themselves as is possible. Their positions and physical installations shall be the most stable, and as such will be the underlying foundation for the definition of all control within an area. All positions shall be tied directly to these stations. This will maximize homogeneity of subsequent data. Where real time positioning is required, and the geometric distribution of the bedrock CORS is insufficient, supplemental non-bedrock CORS or traditional terrestrial marks shall be constructed. The position of these supplemental marks shall be fluid and deterministically constrained back to the bedrock CORS. Where a station is subject to motion, the position will be actively observed to the bedrock CORS, and updated. The frequency of the updates shall depend on the precisions required, and the rate of the motion of the station. Current NGS guidelines for the republishing of CORS positions states 4cm in the vertical. This is too great if the CORS is to be used for a vertical datum definition, as described in the next section.

Vertical Datum defined by Geoid model and the ellipsoid height component of the geometric geodetic datum.

Heights with some form of relation to gravity are required for engineering work. As such the vertical datum definition shall still make provisions to emulate the current vertical datum NAVD88 (helmert orthometric heights). Heights shall be a product of the GPS/GNSS observations and resulting geodetic positions (latitude, longitude and ellipsoid height). A geoid model (probably Geoid03) shall be defined along with an interpolation method (probably biquadratic). This two step process (observing geodetic position, and applying a geoid model) shall be the principle realization method for determining a vertical reference datum within the subsidence area.

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