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A VIEW OF SUBSIDENCE

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Figure 1. Giant earth fissure near Chandler Heights, Arizona. Earth fissures begin as tiny cracks, but become enlarged by water erosion and collapse of adjacent soils. This fissure is related to subsidence due to ground-water withdrawal. Photo taken on October 21, 1983 by Larry D. Fellows.

INTRODUCTION

Subsidence, the gradual settling or sinking of the earth's surface, is occurring in many areas of Arizona as a result of declining ground-water levels. Rates of subsidence have exceeded 0.6 foot per year and earth fissures, or cracks in the earth's surface, are proliferating (Figures 1, 2, and 3). In some areas, the total amount of subsidence has increased from 12.5 feet, measured in 1977, to about 16 feet.

Subsidence can be caused by natural geologic processes or by man's activities, such as the removal of subsurface fluids. In Arizona, subsidence is mostly due to large-scale withdrawal of ground water from subsurface reservoirs. The fluid pressure of ground water partially supports the material above. As the water is pumped out, that support is lost, causing compaction of the grains of earth material and lowering, or subsidence, of the earth's crust.

Earth fissures usually form around the margins of subsiding areas and may be related to distribution and thickness of basin-fill sands and gravels, buried bedrock topography, or other factors. It is not possible to predict specifically where fissures will form. It may be possible, however, to identify zones where fissures *might* form.

Land-elevation changes caused by subsidence can be determined by repeated, precise, survey leveling to fixed reference points or bench marks. Bench marks are usually brass caps encased in concrete and set a few inches above the ground surface. Precise surveys determine elevations of bench marks within the subsiding area by comparing them with stable bench marks set in bedrock *near* the subsiding area. Reference bench marks must remain stable to provide an accurate, common base for all measurements; therefore, they are located in bedrock.

Problems related to subsidence, especially differential subsidence and the formation of earth fissures, have been known for years. The issue itself is complex; numerous papers have been published to explain causes, identify problems, and offer solutions. A list of papers that describe specific subsidence areas and problems in Arizona is included at the end of this article.

It is not the purpose of this article to summarize or describe the extent of subsidence throughout Arizona, although a plan for monitoring subsidence in the State is discussed. This article does, however, describe the results of the National Geodetic Survey (NGS) precise leveling conducted in the Phoenix metropolitan area from 1980 through 1981 (Winikka, 1981). It also identifies subsidence areas and discusses uses of the NGS level datum.

THE PHOENIX AREA

The NGS Level Line

The 1980-81 NGS retracement of the 1967 NGS level line in Arizona was done as a segment of the current network of NGS transcontinental leveling, which extends through all States from coast to coast. In the Phoenix area, where several subsidence areas were crossed, numerous new bench marks were established in bedrock to preserve the precise leveling results. Consequently, more convenient stable elevations are now available to all users, particularly those who measure or monitor subsidence. The 1980-81 NGS leveling identified and measured subsidence that had occurred since 1967.

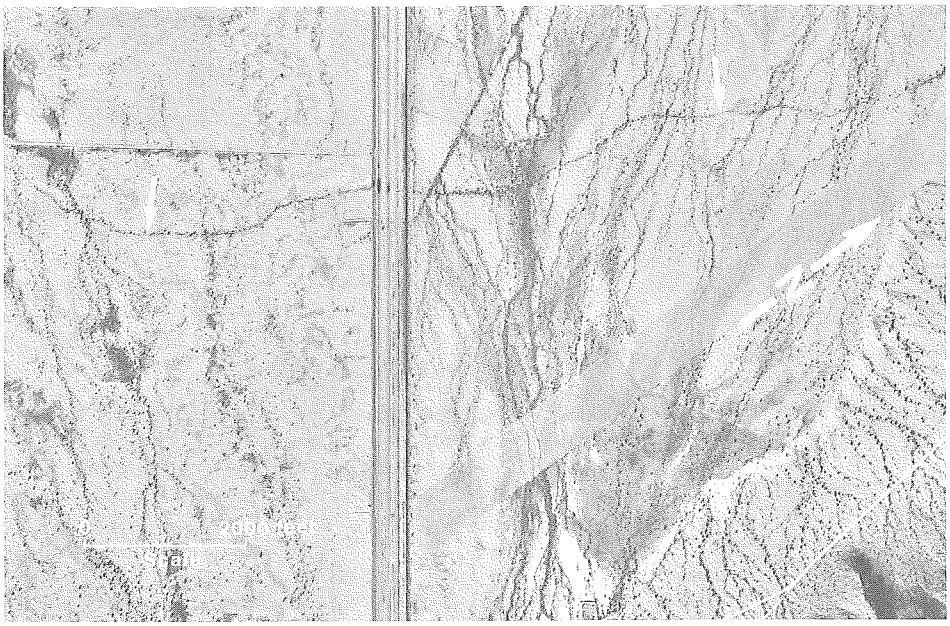

Figure 2. Aerial view of earth fissure crossing Interstate Highway 10 (I-10) between the town of Picacho and Picacho Peak. Photo taken on December 9, 1963 by the Arizona Department of Transportation.

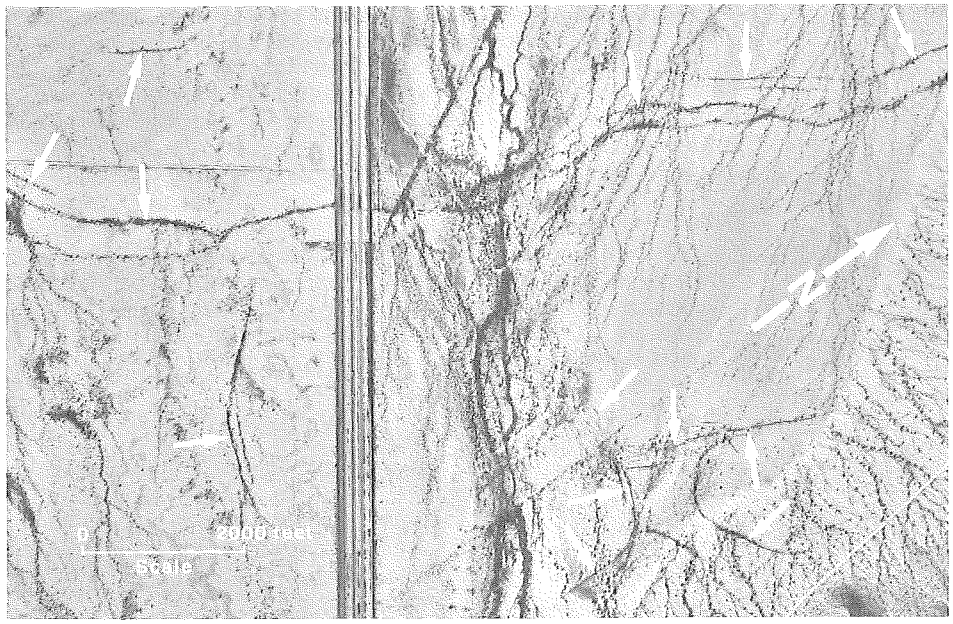

Figure 3. Aerial view of same area shown in Figure 2, taken 14 years later. Proliferation of earth fissures is indicated by arrows. Note that subsequent fissuring near the original fissure is all on the basin (west) side. Other fissuring, which may be due to buried bedrock topography, is evident to the east. Photo taken on January 9, 1978 by the Arizona Department of Transportation.

Final NGS elevations will not be available until the transcontinental leveling network is adjusted to account for numerous, influencing factors. The need to utilize the NGS leveling results, however, was great in the Phoenix area. To fill this need, the Arizona Department of Transportation (ADOT) used the NGS field information to make an accurate, preliminary, least-squares adjustment, which held NGS elevations previously established on bench marks in bedrock.

Because many bench marks set in 1967 and earlier years had been destroyed, new marks were set during 1980 and 1981 to establish a bench mark approximately every mile. Additional stable bench marks were established in rock to preserve ties to the NGS level datum for subsequent surveys. Enduring, subsiding bench marks, however, are equally important for continuity in subsidence monitoring. Figure 4 shows the location of the NGS level line through metropolitan Phoenix, the bench marks in bedrock, and the areas of measured subsidence.

Subsidence Areas

The greatest subsidence directly measured in the Phoenix area has occurred in the vicinity of U.S. Highway 60 and Bush Highway/Power Road. From 1948 to 1981, more than 5 feet of subsidence were measured just east of the junction, and several other points in the vicinity had subsided from 1 to 4 feet. The maximum subsidence rate in this area is approximately 0.2 foot per year. By indirect measurement, subsidence greater than 6 feet was determined to have occurred from 1943 to 1981 along Power Road, 1/2 mile south of U.S. Highway 60 at NGS bench mark W281. Because W281 was destroyed sometime between 1967 and 1970 and reset in 1970, a gap in information existed. The measured subsidence value was added to the projected value for the 1967-70 time period to obtain the total measure of subsidence.

The next highest measure of subsidence was obtained west of Phoenix along the Beardsley Canal, from U.S. Highway 60 south to the junction of Perryville Road and McDowell Road. Total subsidence from 1948 to 1981 exceeded 4 feet at the Beardsley Canal near both Bell Road and Peoria Avenue. Analysis of subsidence rates along the Beardsley Canal shows an increase in the annual rate at each of six bench marks north of Glendale Avenue. The approximate annual rate of 0.08 foot from 1948 to 1967 increased by 50 percent to 0.12 foot from 1967 to 1981. From Glendale Avenue south, on the other hand, the subsidence rate *decreased* at each of four bench marks. The approximate annual rate of 0.10 foot decreased by 50 percent to 0.05 foot during the corresponding time periods (Table 1). Although the definite cause of this variation in subsidence rates is currently unknown, the difference is most likely due to a change in ground-water pumping influenced by dewatered alluvial material.

Other areas in which subsidence was measured include the following:

(1) Along the Arizona Canal where it crosses the Salt River Indian Reservation (maximum 1948-81 measurement is 0.9 foot at Dobson Road and at Mesa Drive);
(2) Along portions of Beardsley Road from I-17 west (maximum 1967-81 measurement is 0.45 foot at 83rd Avenue); and
(3) Along I-17 from the Arizona Canal north to Beardsley Road (maximum 1967-81 measurement is 0.28 foot at Thunderbird Road).

Although subsidence measurements are given for the specific areas listed above, subsidence was measurable only where reliable bench marks were recovered. Many bench marks had been destroyed during the rapid growth and development in the Phoenix area; thus, a tie to past leveling information was lost. To either side of the level line, subsidence exceeding the values listed above is very probable.

Uses of the NGS Datum

In the Phoenix area, the establishment of NGS bench marks, especially those set in

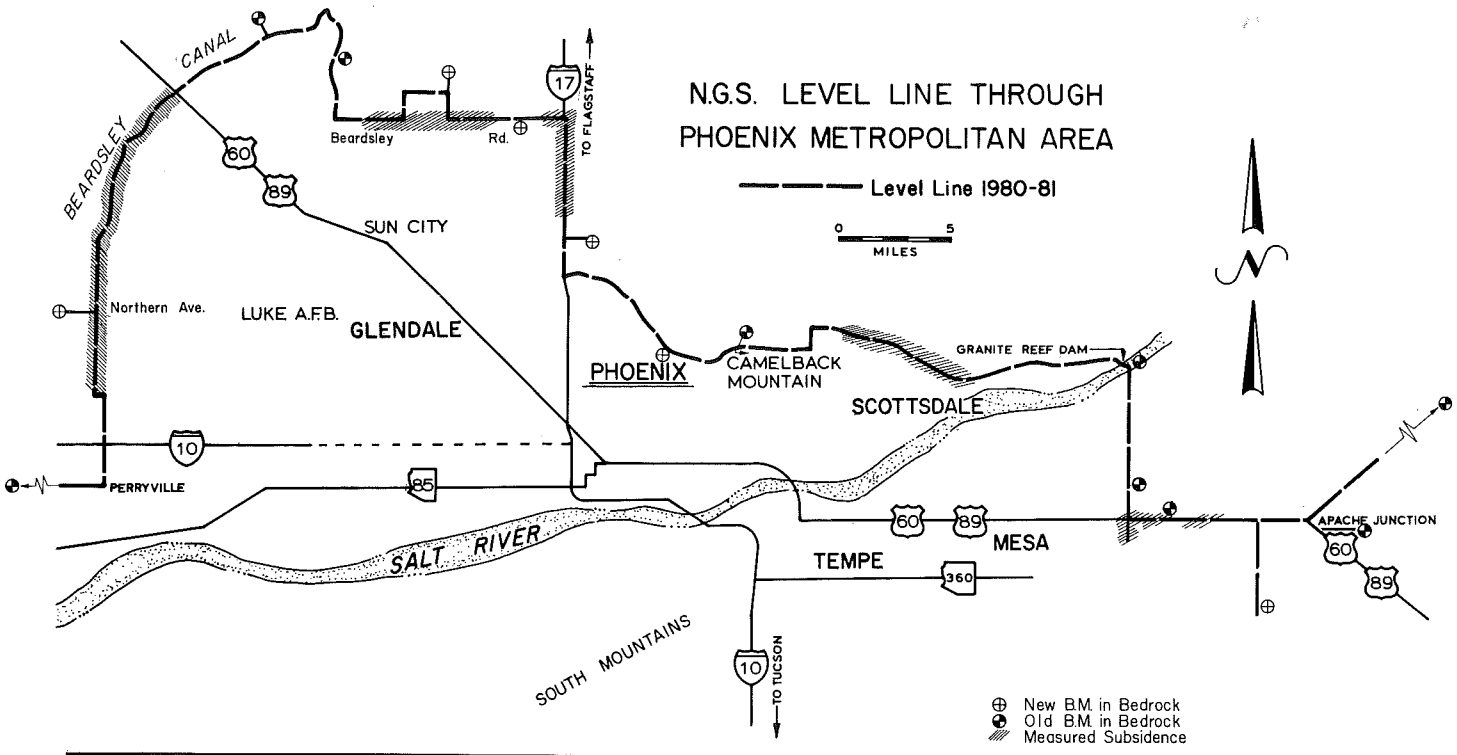

Figure 4. Location of the NGS level line run through Phoenix area during 1980-81. Old and new bench marks established in bedrock are shown, as well as areas of measured subsidence.

stable rock, has enabled the ADOT and others to detect and monitor subsidence for various purposes.

The U.S. Bureau of Reclamation (USBR) annually runs control levels along the Central Arizona Project (CAP) aqueduct to detect and monitor subsidence. West of Apache Junction, the design of the aqueduct accommodates subsidence in areas crossed by the structure. Monitoring provided essential information used in the design and will continue after the aqueduct becomes operational.

The Arizona Department of Transportation periodically runs a level circuit that includes the future extension of the Superstition Freeway east of Power Road. The freeway and its extension cross several areas of subsidence, including one that is also crossed by the CAP aqueduct. In this instance, common bench marks are used by the ADOT and USBR to obtain more frequent data from this critical area.

The city of Phoenix is experiencing subsidence-related problems with several sewer lines in Paradise Valley, where more than 3 feet of subsidence were measured and monitored from 1965 to 1982 (Harmon, 1982). Phoenix has recently engaged a geotechnical engineering consultant to analyze the problems and suggest solutions in this area, where the annual subsidence rate has reached 0.35 foot. All leveling to monitor subsidence is tied to NGS bedrock bench marks. Use of this consistent datum is particularly important because elevations and grades affect the capacity of the sewer system, which presently drains by gravity.

The city of Gilbert is planning to extend its sewer system considerably east of present development to accommodate future needs. A consulting firm on the project has used recent, precise, ADOT levels that rely upon NGS bench marks. These levels, which extend from the Superstition Freeway south along Power Road to Germann Road, have confirmed that approximately 3 feet of subsidence have occurred. Because this amount of subsidence, as well as the projected subsidence rate, was significant, city officials decided to alter the plan for the wastewater collection system.

Without question, the new NGS datum in the Phoenix area is becoming the base accepted by all levels of government and several private firms. The older level datums will still be used indefinitely, even though their inadequacy for subsidence monitoring is evident. Lines begun and ended within a subsiding area are of questionable value because they are not tied to stable, nonsubsiding bedrock. Measurements become even more inaccurate if the lines are tied to bench marks that have subsided at different rates. A precise level line with bedrock ties, such as the NGS line through the Phoenix region, is invaluable for conducting surveys in subsiding areas.

Table 1. Subsidence along the Beardsley Canal.

Bench mark	Crossroad	Total Subsidence (ft) 1948–67	1967–81	1948–81	Rate (ft/yr) 1948–67	1967–81
R265	Union Hills	1.171	1.237	2.408	0.0616	0.0884
Q265	Bell Road	1.887	2.186	4.073	0.0993	0.1561
P265	Greenway Road	1.932	(bench mark destroyed)		0.1017	—
N265	Waddell Road	1.919	(bench mark destroyed)		0.1010	—
M265	Cactus	1.706	1.598	3.304	0.0898	0.1141
L265	Peoria	1.578	2.513	4.091	0.0830	0.1795
K265	Olive	1.207	1.081	2.288	0.0635	0.0772
J265	Northern	1.244	1.304	2.548	0.0655	0.0931
H265	Glendale	2.067	1.189	3.256	0.1088	0.0849
G265	Bethany Home	1.433	0.469	1.902	0.0754	0.0335
F265	Camelback	2.152	0.633	2.785	0.1133	0.0452
E265	Indian School	1.866	0.581	2.447	0.0982	0.0411

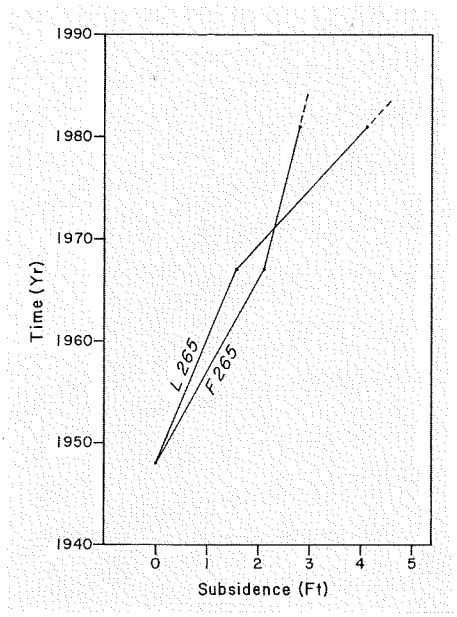

Figure 5. Total subsidence and subsidence rate changes for bench marks L265 (Peoria) and F265 (Camelback), listed in Table 1. Note that the subsidence rate for each bench mark increases until 1967, after which the rate for L265 accelerates, whereas the rate for F265 *decreases*. This graph illustrates that subsidence rates are not static.

THE TUCSON AREA

Within the Tucson metropolitan area, subsidence due to ground-water declines has begun (Strange, 1983). In some sections, the water table has been lowered by more than 100 feet, the magnitude at which subsidence can be expected to commence. The U.S. Geological Survey is conducting a study of aquifer compaction in the Tucson area. Survey geologists have installed seven compaction recorders in wells to detect subsidence in the upper 1,000 feet of the earth's surface. To date, the highest subsidence rate that has been measured is approximately 0.02 foot per year.

Results of NGS leveling through the area show a maximum subsidence of 0.4 foot, a measurement that was obtained by comparing the 1951 results with the 1980 results. This subsidence occurred at a bench mark between Davis Monthan Air Force Base and Interstate 10.

SUBSIDENCE RATES

As the above examples suggest, for the planning and design of civil-works projects, the subsidence rate is at least as important as the total amount of subsidence. Subsidence in Arizona is not static, but changes both in rate and locus. Continued subsidence, particularly at increasing rates, proves that the problem cannot be ignored. Until recently, subsidence was a phenomenon that lacked impact. As subsidence increases in developed areas, however, its importance will also increase.

As bench marks in subsiding areas are identified and subsidence rates are recorded, the dynamics of continuing movement are conveyed to users. By knowing locations, amounts, and rates of subsidence, users will have a rational basis for decisions to use or reject the use of subsiding bench marks.

Total subsidence and the subsidence rate are well illustrated by simply plotting subsidence against time at an appropriate scale (Figure 5).

A SUBSIDENCE-MONITORING PLAN

Spurred by the NGS leveling results in the Phoenix area and the realization that severe subsidence and earth fissures are occurring in Arizona, the Arizona Mapping Advisory Committee and its member agencies recognized the need for a statewide plan to monitor subsidence. At the request of Governor Bruce Babbitt, the National Geodetic Survey prepared the plan, which was completed in 1983 (Strange, 1983). The plan was the result of a comprehensive effort by the NGS and the interagency Ad Hoc Land-Subsidence Committee of the State. The committee, which was chaired by a representative of the Arizona Department of Water Resources, included members from State, Federal, and local government groups, universities, and private industry. Although the plan still lacks operational funds, copies are available for purchase from the NGS.

The NGS Global Positioning System (GPS), which utilizes satellites and geodetic receivers, was recommended in the subsidence plan. The system was recently tested to evaluate its possible use in Arizona. Numerous bench marks, subsiding as well as stable, were measured. Leveling to most of these bench marks to determine present elevations was done for comparison. If the GPS results yield elevations accurate to within 0.2 foot, as expected, this system may prove to be an efficient monitor of subsidence.

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