GROUND FAILURE CAUSED BY GROUNDWATER WITHDRAWAL FROM UNCONSOLIDATED SEDIMENTS--UNITED STATES

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Abstract

Aseismic ground failure is associated with regional land subsidence caused by ground-water withdrawal in at least 14 areas in 6 States in the United States. Two types of ground failure--tensile failures (causing earth fissures) and shear failures (causing surface faults)-are recognized. Fissures forming straight to arcuate patterns are caused by stretching related to bending of strata above a localized differentially compacting zone. Fissures forming complex polygonal patterns probably are caused by tension induced by capillary stresses in the zone above a declining water table. Surface faults occur along preexisting faults, many of which behave as partial ground-water barriers. Man-induced differential water-level declines across the preexisting faults have been sufficient to account for the heights of the historical offsets by a differential compaction mechanism. In the area most affected by surface faulting, Houston-Galveston, Texas, significant differential water-level declines across faults have not been observed and the specific mechanism of faulting has not been demonstrated.

Introduction

Aseismic ground failure, or ground rupture, is areally associated with most of the subsidence caused by aquifer compaction induced by groundwater withdrawal in the United States. Two general types of ground failure--tensile failures and shear failures--are recognized. Earth fissures result from tensile failures; opposing sides of the fissure move perpendicular to the plane of failure. Surface faults result from shear failures; opposing sides of the fault move parallel to the plane of failure. The principal hazard of ground failure is to engineered structures because deformation is localized. Accordingly, the principal economic effect has been in urban areas. In addition, earth fissures commonly are enlarged by erosion into steep-walled gullies and thus are a hazard to people or livestock. Earth fissures also can be detrimental to canals, levees, and dams because void space caused by extension during fissure formation creates the potential for catastropic release of water when fissures intersect these structures.

This paper summarizes the characteristics and the areal occurrence in the United States of ground failure associated with land subsidence and reviews current knowledge of the mechanisms that cause ground failure. For a more detailed and comprehensive summary, the reader is referred to Holzer (1984).

Ground-Failure Areas

Ground failure is both areally and temporally associated with groundwater withdrawal from unconsolidated sediment in at least 14 areas in 6



FIG. 1 Areas of ground failure associated with subsidence caused by ground-water withdrawal in the western United States.

States in the United States, all in the western part (Fig. 1). These areas are geographically widespread, and both the density of failures and the types of failure vary greatly from area to area; therefore, the generalized map (Fig. 1) does not show the local effect. For example, only single isolated failures have been reported in the Antelope, Santa Clara, and Yucaipa Valleys, California, and in the Raft River valley, Idaho. By contrast, ground failure is widespread in both south-central and southeastern Arizona, the Houston-Galveston area, Texas, and Fremont Valley, California. In the two combined areas in southern Arizona, for example, the total number of failures, producing predominantly earth fissures, is in the hundreds; in the Houston-Galveston area more than 86 historically active surface faults that have an aggregate scarp length of 240 km have been documented. Of the three largest subsidence areas in the United States, the San Joaquin Valley, California, south-central Arizona, and Houston-Galveston, Texas, only the latter two areas have significant numbers of recognized ground failure. Only four ground failures, resulting in one surface fault and three earth fissures, have been reported in the 13,500 km² San Joaquin Valley subsidence area.

Earth Fissures

Earth fissures are the most spectacular type of surface deformation associated with ground-water withdrawal (Fig. 2) because of their length



FIG. 2 Earth fissure, approximately 1 m across, in south-central Arizona that has been enlarged by erosion.

and the enlargement of the original tension crack by erosion. The longest fissure zone of those studied in the United States is 3.5 km long (Holzer, 1980b), and lengths of hundreds of meters are typical. Fissures commonly are enlarged by erosion into gullies 1 to 2 m wide and 2 to 3 m deep. Fissures usually are first noticed after erosion along them has begun as a result of heavy rainstorms. Measurements of separations in caliche, trees, and engineered structures indicate that fissure separations do not exceed a few centimeters; the maximum separation reported is 6.4 cm (Holzer, 1977).

Calculations of crack volume, based on the size of gullies formed along fissures, on small fissure separation, and on the field observation that most of the eroded sediment washes downward and is deposited in the tension crack, suggest that tensile failure may extend to depths measured in dekameters (Holzer, 1977). The greatest measured depth is 25 m (Johnson, 1980).

Earth fissures form two general types of patterns: 1) straight to arcuate and 2) polygonal. The former patterns are predominant in the United States. Locally, straight to arcuate patterns may be complex (Fig. 3), but they can still be distinguished from those formed by networks of closed polygons. The polygonal patterns are similar in map view to those formed by desiccation cracks in fine-grained sediment. Diameters of polygons commonly range from 15 to more than 100 m (e.g., Holzer, 1980b).

On the basis of contouring of regional geodetic data, i.e., the leveling of bench marks that have a spacing greater than 1 km, earth



FIG. 3 Isopach map of unconsolidated alluvium beneath complex fissure area in south-central Arizona. Contour interval is 50 m. Hachures on contours point toward increasing sediment thickness. Fissures shown by dark heavy lines. From Jachens and Holzer (1982).

fissures occupy all positions and orientations within subsidence bowls. Analysis of surface deformation based on closely spaced bench marks near straight to arcuate earth fissures, however, indicates that these fissures are forming along zones of localized differential subsidence (Holzer and Pampeyan, 1981). In subsidence profiles oriented perpendicular to fissures, the fissures occur at the point of maximum convex-upward curvature (Fig. 4). Computations of horizontal strain from horizontal displacements of these closely spaced bench marks also indicate that horizontal tensile strains occur near the fissure and attain maximum tension at the point of the maximum convex-upward curvature (Holzer and Pampeyan, 1981; T.L. Holzer, unpublished data). Precise monitoring of the horizontal distance between bench marks spaced 20 to 30 m apart across fissures indicates that horizontal displacements continue as long as differential subsidence continues (T.L. Holzer, unpublished data). Jachens and Holzer (1982) described fissures in south-central Arizona that continued to open and accept sediment more than 25 years after their formation.

Although detailed studies of subsurface conditions beneath earth fissures have not been made in all the areas in which fissures have been reported, two types of subsurface conditions have been recognized in



FIG. 4 Profiles of changes of elevations across earth fissures in Arizona, California, and Nevada. Decrease in elevation is positive.

In south-central Arizona, most straight to arcuate areas studied. fissures overlie zones of convex-upward curvature on the upper surface of the consolidated or crystalline bedrock that underlies the base of the unconsolidated aquifer system (Anderson, 1973; Jennings, 1977; Pankratz and others, 1978b; Jachens and Holzer, 1979, 1982). zones range from ridges to "steps" in the bedrock surface. These Figure 3 shows an example of bedrock control of a complex fissure system. In Las Vegas Valley, Nevada, and Fremont and San Jacinto Valleys, California, some fissures are coincident with preexisting faults. Subsurface characteristics of the fault zones, however, have not been investigated in detail. Gravity and magnetic surveys in Lucerne Valley, California, and southeastern Arizona, areas that have earth fissures in polygonal patterns, did not indicate special subsurface conditions beneath the fissures (R.C. Jachens, 1982, written communication). Fissures in both areas are underlain by fine-grained lacustrine and playa sediments.

Surface Faults

Scarps formed by faulting related to ground-water withdrawal generally resemble fault scarps of natural origin and can be confused with them. Faults suspected to be related to ground-water withdrawal commonly have





scarps more than 1 km long and more than 0.2 m high. The longest scarp measured to date is 16.7 km long (Verbeek and others, 1979) and the highest scarp is 1 m (Reid, 1973). Both measurements were made in the Houston-Galveston area, Texas. Scarps range from discrete shear failures to narrow, visually detectable flexures, commonly along individual faults.

Surface faults generally grow in height by dip-slip creep along normal failure planes. Measured rates of vertical offset in the United States range from 4 to 60 mm year⁻¹. Neither abrupt movement nor seismicity has been reported in association with these faults. Monitored differential vertical displacements across these faults indicate that rates of offset vary over time. Although some short-term episodic movement has been reported (Reid, 1973), seasonal variations of offset that correlate both in magnitude and timing with seasonal fluctuations of water level are remarkably widespread (Reid, 1973; Holzer, 1978, 1980a; Holzer and others, 1983). Figure 5 shows examples of seasonal variation of fault offset. In addition, changes in longterm creep rates have been reported for a few faults (Van Siclen, 1967; Holzer and others, 1979, 1983). A striking example of these changes is in the Houston-Galveston area, Texas, where fault offset has ceased in an area where regional water-level declines have been reversed by reductions in ground-water withdrawal (Holzer and others, 1983).

Surface faults, like earth fissures, form at all positions and orientations within subsidence bowls (e.g., Holzer and others, 1983). Geodetic monitoring of closely spaced bench marks indicates that the land surface near the scarp may tilt above both the footwall and hanging wall blocks (Holzer and Thatcher, 1979; T.L. Holzer, unpublished data). Tilting is greatest near the scarp and has been observed to extend as far as 500 m from the scarp.

Surface faulting caused by ground-water withdrawal takes place along preexisting faults (Van Siclen, 1967; Holzer, 1978, 1980a; Elsbury and Van Siclen, 1983). Hydrogeologic studies of subsurface conditions beneath surface faults in Arizona (Holzer, 1978; Pankratz and others, 1978a) and California (Holzer, 1980a) have indicated that the preexisting faults are partial ground-water barriers across which water levels have declined differentially in conjunction with ground-water pumping. The water-level differences are in the same sense as the historical fault offset. In the Houston-Galveston area, Texas, evidence for differential water-level declines across faults is equivocal (see Kreitler (1977) and Gabrysch and Holzer (1978) for discussion).

Mechanisms

Subsurface conditions and surface deformation measured near straight to arcuate earth fissures, as well as theoretical considerations, indicate that these ground failures are caused by localized differential compaction. The fissures result from horizontal tensile strains produced by bending of the overburden. The strains attain maximum tension at the point of maximum convex-upward curvature in the subsidence profile (Lee and Shen, 1969). By modeling the bending process within a small area in south-central Arizona, Jachens and Holzer (1982) estimated that tensile strains at failure ranged approximately from 0.02% to 0.2%. These values agree with strain at failure inferred from average annual strain rates measured across earth fissures at other locations (Holzer and Pampeyan, 1981).

The complex polygonal network pattern of some fissures suggest that these fissures are caused by a horizontally isotropic tensile stress field. By analogy to desiccation cracks, the probable source of such tension is the large negative capillary stress in the dewatered zone above a declining water table. Such a mechanism was proposed by Neal and others (1968) to explain naturally occurring fissures that form giant polygons on playas.

Investigations of subsurface conditions and surface deformation near two faults in Arizona and California suggest that localized differential compaction can also cause modern surface faulting. Both the surface faults coincide with preexisting faults that are partial ground-water barriers. Man-induced water-level differences across the faults and inferred specific compaction of the sediment were sufficient to cause localized differential compaction across the preexisting faults equal to the observed scarp heights (Holzer, 1978, 1980a). Reid (1973) and Kreitler (1977) have proposed that such a mechanism may also apply to surface faulting in the Houston-Galveston area, Texas, although the magnitude of water-level difference required to cause the offsets observed there does not appear to be compatible with available waterlevel data (Gabrysch and Holzer, 1978). This result does not preclude possible localized differential compaction. Many faults in the Gulf Coast commonly were active during deposition of the sediment that they offset because they affected sedimentation. Therefore, different thicknesses of compressible material may exist across these faults. If present, such localized lateral changes of thickness across preexisting faults might be sufficient to cause discrete differential compaction. In any case, the specific mechanism of faulting in the Houston-Galveston area has not been demonstrated despite strong circumstantial evidence linking historical faulting to water-level declines (Holzer and others, 1983).

Discussion

Ground failure takes place in most of the areas of land subsidence caused by ground-water withdrawal in the United States. Only a few subsidence areas do not have ground failure. The first failures in each area took place after subsidence began, and in those areas that now have large numbers of failures, the number gradually increased as subsidence continued. Thus, in a sense, ground failure may be considered as a secondary, although relatively common, condition caused by ground-water withdrawal from unconsolidated sediments.

Variations in the density of failures from area to area are conspicuous and are obviously determined by more than just areal differences of water-level decline and compressibility of sediments. For example, the areal extent and magnitude of subsidence in the San Joaquin Valley of California is the greatest of any area in the United States, but ground failure is rare. Part of the explanation for these density variations probably lies in differences in the subsurface conditions among the areas. Surface faults and straight to arcuate earth fissures are associated with preexisting faults and subsurface zones conducive to localized differential compaction, respectively. In areas like the San Joaquin Valley, these special subsurface conditions are rare (e.g., Miller and others, 1971).

Prediction of locations of potential ground failure on the basis of subsurface conditions appears to be feasible. However, it may not be economically feasible to acquire the detailed subsurface information for all applications. In some areas, inexpensive geophysical techniques may be satisfactory. For example, precise gravity surveys in south-central Arizona have been a practical means of delineating zones underlain by convex-upward curvature in the underlying bedrock surface (Jachens and Holzer, 1979, 1982). These surveys can delineate the potential fissure zones within a few dekameters. Jachens and Holzer (1982) also have shown that if sufficient data on tensile strength and the configuration and compressibility of subsurface materials are available, the finiteelement method satisfactorily predicts the approximate magnitude of water-level decline at which fissuring will take place.

Finally, although no efforts to control ground failure have been attempted, investigations of relations between rate of fault movement and water-level change indicate control may be possible. In the Houston-Galveston area, Texas, and the San Joaquin Valley, California, fault movement stopped when water-level declines were reversed.

754

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756