Sinkholes and Subsidences in the Transvaal Dolomite of South Africa

Les Entonnoirs et les affaissements dans la dolomie du Transvaal, Afrique du Sud

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SUMMARY

Ground subsidence in dolomitic formations takes place in two ways: a gradual or *caving subsidence* or a rapid and catastrophic subsidence defined as a *sinkhole*. The frequency and severity of the problem is much increased in areas where the water table is lowered. Sinkholes are alarming and dangerous events. The mechanism is basically similar to the blockage of bins by arching during discharge and a five-concurrent-condition hypothesis is put forward to explain the occurrence of a sinkhole. Of the geophysical methods which aim at locating those voids likely to lead to sinkholes, the gravimeter has shown the best results but it suffers from shortcomings and cannot yet be considered adequate for the purpose. Further experimental work is in hand. In the meantime cover drilling associated with the provision of deep telescopic benchmarks is serving to provide warning of impending collapse into a sinkhole.

SOMMAIRE

L'effondrement du terrain dans les formations dolomitiques se produit de deux manières: *un effondrement graduel* ou affaisement, et *un effondrement rapide* et catastrophique qu'on appelle entonnoir. La fréquence et l'ampleur de ces effondrements augmentent dans les régions où la nappe phréatique a été rabattue. Les entonnoirs sont des phénomènes dangereux et effrayants. Leur mécanisme est essentiellement semblable au blocage des trémies par effet d'arc pendant leur déchargement. Les auteurs proposent une hypothèse à cinq conditions concourantes pour expliquer l'origine des entonnoirs. De toutes les méthodes géophysiques employées pour déceler les cavités qui sont la cause des entonnoirs, le gravimètre a produit les meilleurs résultats, bien qu'il souffre d'imperfections et ne peut encore être considéré comme pleinement satisfaisant à cette fin. De plus amples recherches expérimentales sont en cours. Entre temps, la reconnaissance par sondages associée à l'usage de repères télescopiques installés en profondeur servent à donner l'avertissement des effondrements imminents et de la formation possible d'entonnoirs.

THE COLLAPSE OF A THREE-STOREYED CRUSHER PLANT of a gold mine at Westdriefontein, about 50 miles west of Johannesburg, into a catastrophic sinkhole, in December, 1962, resulted in the loss of twenty-nine lives. The disaster is dramatically illustrated in Fig. 1. It will be noted that no trace of the collapsed section of the structure can be seen. It should also be observed that the rupture of the water pumping main was a consequence and not a cause of the collapse. There was practically no warning: the building had shown only very small movements and the collapse occurred suddenly. Certainly not more than one half-hour was involved, most of the time being taken up in the further falling-in of the sides of the sinkhole.

FIG. 1. Collapse of crushing plant into a sinkhole, Westdriefontein Mine, December, 1962. (Courtesy of the Johannesburg *Star*.)

Sinkholes of this type and magnitude are not uncommon in the dolomites of the Transvaal, the largest recorded being of the order of 300 feet in diameter and 120 feet deep. The Westdriefontein sinkhole is the only one which has caused loss of life, however. The frequency of the occurrence of sinkholes appears to have increased very greatly within the last five years, corresponding with a time period in which underground mine pumping has caused a substantial lowering of the water table—in places by as much as 400 feet.

In addition to the increased frequency of sinkhole formation, the lowering of the water table has resulted in surface subsidence, greater than 20 feet in some areas. This subsidence has taken place reasonably gradually and, except in a few important instances, has not been associated with the appearance of catastrophic sinkholes. Such conditions are generally not dangerous. Fig. 2 shows such an area of subsidence (the remnants of demolished dwellings can be

FIG. 2. A slow, caving subsidence of about 20-ft depth.

seen clearly). The photograph also illustrates the localized nature of the settlement, a result of the irregular subsurface topography of the dolomite, which consists of buried, steep-sided canyons and "avens" or chimneys.

There are thus two settlement problems in the dolomitic subsoils: (*a*) a gradual subsidence, defined as a *caving subsidence*, which gives rise to enclosed depressions in the ground surface; and (*b*) a catastrophic subsidence, defined as a *sinkhole*, which occurs suddenly, the hole having very steep sides and being of limited lateral extent. Both problems are serious economically, but the second is also dangerous because of its possible consequences to life. Concentrated attention is being given to this problem in an attempt to develop warning devices and forms of surface measurement (geophysical survey methods) which will disclose the potential conditions before collapse actually takes place.

GEOLOGICAL SETTING

The dolomitic formation of the Transvaal covers a total outcrop area of over 6,000 square miles, and varies in thickness from 120 to over 7,000 feet. The predominant rock type is dolomite ($CaCO_3.MgCO_3$), interbedded with bands of chert (SiO_2) and subsidiary bands of shale and banded ironstone. In the area where the worst trouble is being experienced, the dolomite formation is approximately 4,000 feet thick and is underlain by gold-bearing reefs. Chert bands are well developed in the upper horizons of the dolomite, making up as much as 30 per cent of the succession. The dolomite dips at an average angle of about 10° to the south, where it passes beneath younger strata of quartzite and shale. A number of igneous dykes strike north-south through the area, subdividing the dolomite into five separate groundwater compartments. The water table in each compartment is nearly horizontal. As a result of dewatering by mines in two of the compartments, however, the water table is locally drawn down into cones of depression at the pumping points.

SOLUTION OF DOLOMITE

Dolomite is soluble in water and the presence of CO_2 in groundwater (derived partly from the atmosphere but mainly from percolation through the soil) greatly increases its solvent ability. Although the rock is particularly compact and impervious, it possesses an intricate and closely spaced system of joints, and water can thus readily percolate through it.

Detailed examination of caves in the dolomite has revealed the presence of features which are characteristic of solution having taken place below the phreatic zone, i.e., below the water table. Movement of water in this zone is in the form of laminar flow from areas of higher to lower hydrostatic pressure. The flow follows ordinary flow net theory representing the course of seepage through the jointed rock, but the net tends to flatten out as solution enlarges the flow paths nearer the phreatic surface. The flow of the CO_2-charged water results in the development of a network of interconnected caverns in the zone immediately below a water table which has been static for any appreciable period of geological time. With the natural lowering of the water table as the trunk streams become more deeply incised, the network of caverns enters a new cycle in the vadose zone (i.e., above the water table) and the deposition of dripstone can take place. Major fissures in the roofs of the caverns, such as fault planes, now become widened by solution in percolating vadose waters; in this way the caverns develop avens into the overlying mantle of soil.

The soil cover consists of a residuum of insoluble chert and wad (manganese dioxide residual from the dolomite) and in places extends to depths of 400 feet or more. As the result of a long history of karst development, ancient sinkholes are now found to be filled with a variety of soil materials of different ages, from Carboniferous clays to Pleistocene aeolian sands. The caverns, too, have tended to become filled with transported materials which may vary from gravels to fine clay. The buried surface of the dolomite is very irregular, composed of pinnacles, valleys, and avens, and many large disconnected blocks of dolomite are present as "floaters" in the residuum.

MECHANISM OF SINKHOLE FORMATION

Considerable evidence shows that a sinkhole occurs by the collapse of an arch or dome which spans an air-filled void. The arch or dome lies wholly within the residuum above the

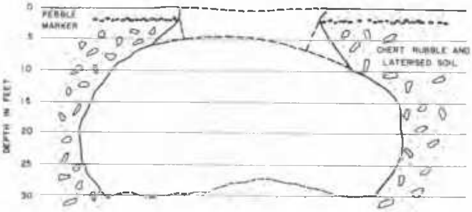

FIG. 3. Section through a sinkhole in which only the crown of the subsurface void has collapsed.

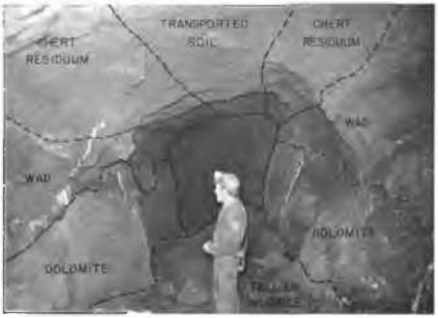

FIG. 4. An underground void of the type liable to cause a sinkhole.

highly irregular dolomite. Fig. 3 shows a section measured through a sinkhole in which only the crown of the dome has fallen in. It will be noted that the final intrados came very near to the surface. Fig. 4 shows the inside of a rubble-roofed void which is barrel-shaped, having about 30 feet of cover over the crown. The collapse of the roof takes place by an onion-skin peeling of the intrados. The material falls to the floor of the void and in this way the void moves upwards towards the ground surface. The collapse of the final arch or dome manifests itself as a sinkhole.

Clearly a number of interdependent conditions are necessary before a sinkhole can form.

1. There must be adjacent rigid material to form abutments for the roof of the void. These are provided by the dolomite pinnacles or sides of the steep-sided subsurface canyons as illustrated in Fig. 4. The span must be appropriate to the strength of the bridging material since, with a span which is too large, the arch cannot form.
2. A condition of arching must develop in the residuum, i.e., a part or all of the vertically acting selfweight must be carried by arching thrusts to the abutments. Complete arching will have occurred when the vertical stress along the intrados is zero.
3. A void must develop below the arch in the residuum. This void may be small, for example, a horizontal crack which may not be disclosed by boring.
4. A reservoir must exist below the arch to accept the material which is removed to enlarge the void in (3) above to substantial size. Some means of transportation for the material, such as flowing water, is also essential.
5. When a void of appropriate size has been established in the residuum, some disturbing agency must arise to cause the roof to collapse. The void will move progressively upwards towards the surface. A common agency causing collapse is water in the arched material which leads to loss of strength or washing out of critical binding or keying material. This provides the trigger which initiates the collapse leading ultimately to the sinkhole.

These five conditions must occur successively and if any one is absent, the sinkhole will not form. For example, if the span is too large in relation to the strength of the residuum material, any removal of material, as in (4), will be accompanied by surface settlement; this is the condition leading to caving subsidence. There is also nothing to prevent caving subsidence proceeding until blockage is caused at the point of subsurface draw-off. The surface movement will then slow down, and separation, forming a void, will occur below the point of blockage. Similarly, if there is no mechanism for transportation or deep consolidation, the enlarged void cannot develop and the sinkhole will not form. This provides a new viewpoint on the part played by caverns and other strongly roofed cavities in the solid dolomite. These only contribute indirectly to the sinkhole by providing the reservoir for the removed material. In general, sinkholes do not form by collapse into such caves. There is also a distinct parallel between sinkhole development and the blockage of a discharging bin.

The five concurrent conditions necessary for sinkhole development are illustrated on the left-hand side of Fig. 5; on the right-hand side of the figure are shown the conditions leading to caving subsidence in a case where the span is too great for the development of an arch.

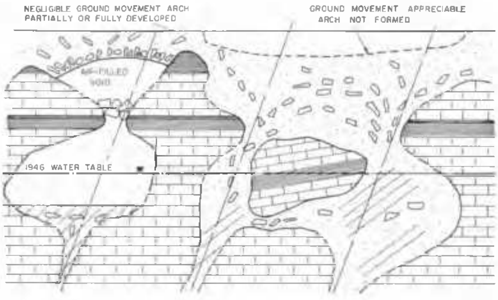

FIG. 5. Section through ground showing: (left) conditions leading to a void liable to cause a sinkhole and (right) conditions leading to caving subsidence.

GEOPHYSICAL METHODS

The various geophysical methods for locating the presence of subsurface conditions likely to lead to the development of a sinkhole should be considered in relation to the five necessarily concurrent conditions already listed. Until now the gravimeter has proved the most useful instrument and, with slight modification in interpretation, the results can be used to estimate the depth to the mean surface of the dolomite, thus providing a picture of the average topography of the subsurface. The picture is only a general one, since the gravimeter cannot distinguish between the various causes for change in gravity. The highly irregular surface of the dolomite and the existence of large floaters are details which are obscured. The method has unfortunately failed to show correlation with sinkholes which have developed in areas over which such surveys had already been carried out: the sinkholes generally occurred either at positions of lowest gravity or in situations where the gravity gradient was greatest. The areas involved are so large that the method lacks sensitivity.

Resistivity surveys have been undertaken with the potential electrodes placed both between and outside the current electrodes. The results are interesting but difficult to interpret and up to the present have failed to disclose the presence of the conditions likely to lead to sinkholes.

A limited amount of seismic work has also been undertaken, but the results to date have not been hopeful. A more recently developed procedure is to observe the harmonic response of the ground surface. Using a large, truck-mounted variable-speed vibrator, the natural frequency and the harmonics of the ground surface are observed. A theory is being developed which relates these observations to the depth to an open cavity.

Most of the geophysical methods aim at measuring the influences of the open void and the important aspect of arching stresses has not yet received any geophysical attention.

PROTECTION OF VITAL BUILDINGS

A catastrophic sinkhole is an alarming event which can cause loss of life and destruction of property. However, human activity in these areas must continue, and, to provide some warning of impending disaster, several measures based upon the five-condition hypothesis for sinkhole formation have been devised.

1. *Control of surface water.* In order to reduce the most common triggering mechanism, a careful survey must be made of all sources of uncontrolled surface water.

2. *Precise surface levelling.* Points are established on all vital buildings and installations and these are levelled at regular intervals to a precision of 0.01 cm. The fixed benchmarks are difficult to establish. The reduced levels are plotted against time: a linear relationship is taken as normal, but acceleration or slowing down of the movements with time are taken as abnormal and must be further investigated.

3. *Drilling to explore for voids.* The area of the vital building or installation is straddled with deep drill holes, the minimum spacing between holes being taken as a function of the sinkhole diameter against which protection is required, e.g., a 75-ft spacing has been selected for protection against a sinkhole with a 100-ft diameter. The drilling observations must provide a good geological log and also disclose air-filled cavities.

4. *Drilling resistance as a measure of arching stress.* The time to penetrate each five feet of advance of the jumper drills is recorded, a note also being kept of diameter, weight, and drop of the string of tools. From these data a curve of drilling resistance with depth is obtained. If a mean curve shows an increasing resistance with depth, then it is concluded that there is no arching in the subsoil; but if the resistance increases and then decreases it is concluded that arching stresses are present. The disclosed cavities generally occur just below such arches, as shown on Fig. 6.

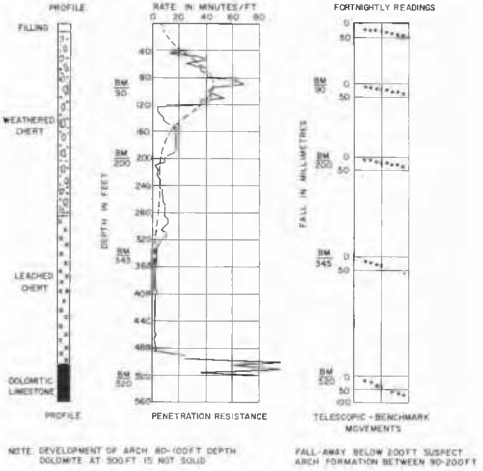

FIG. 6. Vertical profiles: geology, drilling resistance, and movements of deep level stations.

5. *Deep, level references in telescopic benchmarks.* In the borehole, at various levels decided from the geological profile, level stations are established by concrete plugs into which pipes are grouted. The pipes telescope into each other and are brought to the surface, as shown in Fig. 7. In this way a very accurate record is obtained, showing either a consolidating condition (lowest points move at the slowest rates) or an arching condition (lowest points move at the fastest rates). The latter behaviour is also shown in Fig. 6. The telescopic benchmark is also designed to indicate the onion-skin collapse of a void during its passage upwards to the surface.

FIG. 7. Surface points in a deep telescopic benchmark.

6. *Lateral movement indicators.* In some boreholes adjacent to ground where a potential sinkhole is suspected, special provisions have been made to measure lateral movements.

All of the measures given above are applied against a background of information provided by geological and gravimetric surveys. The whole picture as disclosed by all of the information is used for judgment of the safety of the ground. As in all new engineering undertakings where the background scientific information is still sparse, engineering judgment plays a dominant role.

CURRENT RESEARCH

In the laboratory, models which attempt to simulate the field conditions are being used to study the mechanism of arching. The tests resemble studies of bin behaviour with the emphasis on the properties of materials in which arching can be developed, and on the influence of the geometry of the draw-off orifices.

In the field a search is being made for those types of caves or voids which are liable to lead to sinkholes and Fig. 4 shows the interior of one such cave. It is proposed to collapse artificially a number of caves to form sinkholes to test the five-condition hypothesis. Ideas on the behaviour of surface levels, telescopic benchmarks, and lateral movements will be examined experimentally and repeated geophysical observations will be made in an attempt to find those procedures which will disclose in advance the presence of such dangerous subsurface conditions.