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SUBSIDENCE RESULTING FROM MINING

BY

L. E. YOUNG

AND

H. H. STOEK

ILLINOIS COAL MINING INVESTIGATIONS
COOPERATIVE AGREEMENT

(This report was prepared under a Cooperative Agreement between the Engineering Experiment Station of the University of Illinois, the Illinois State Geological Survey and the U. S. Bureau of Mines.)



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BULLETIN No. 91

ENGINEERING EXPERIMENT STATION

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THE Engineering Experiment Station was established by act of the Board of Trustees, December 8, 1903. It is the purpose of the Station to carry on investigations along various lines of engineering and to study problems of importance to professional engineers and to the manufacturing, railway, mining, constructional, and industrial interests of the State.

The control of the Engineering Experiment Station is vested in the heads of the several departments of the College of Engineering. These constitute the Station Staff and, with the Director, determine the character of the investigations to be undertaken. The work is carried on under the supervision of the Staff, sometimes by research fellows as graduate work, sometimes by members of the instructional staff of the College of Engineering, but more frequently by investigators belonging to the Station corps.

The volume and number at the top of the title page of the cover are merely arbitrary numbers and refer to the general publications of the University of Illinois; *either above the title or below the seal is given the number of Engineering Experiment Station bulletin or circular, which should be used in referring to these publications.*

The present bulletin is issued under a cooperative agreement between the Engineering Experiment Station of the University of Illinois, the State Geological Survey and United States Bureau of Mines. The reports of this cooperative investigation are issued in the form of bulletins by the Engineering Experiment Station, State Geological Survey and the United States Bureau of Mines. For bulletins issued by the Engineering Experiment Station, address Engineering Experiment Station, Urbana, Illinois; for those issued by the State Geological Survey, address State Geological Survey, Urbana, Illinois; and for those issued by the United States Bureau of Mines, address the Director, United States Bureau of Mines, Washington, D. C.

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ENGINEERING EXPERIMENT STATION

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and

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SUBSIDENCE RESULTING FROM MINING

INTRODUCTION.

The subject of the subsidence of the earth's crust as a result of underground excavation due to mining has attracted widespread attention for some years past, but particularly during recent years. With the extension of mining and the increased value of the surface above the mines in many localities, the growth of towns in mining regions, and the extension of railroads over mining properties, the subject is one that will be of increasing interest as time goes on, not alone to those engaged in mining coal and ores, but to the railroads, municipalities, and other owners and users of the surface that may be affected by mining operations.

That the subject is not one of mere local interest is shown by the widespread distribution of surface subsidence as described in the following pages.

This bulletin has been prepared not with a view of bringing forward any new theories in regard to the subject, but it is in the nature of a reconnaissance and a statement of present knowledge of the subject, based upon the literature available up to the present time. It and a companion preliminary Cooperation bulletin on subsidence in Illinois by Dr. Young, which will be issued by the Illinois Geological Survey, are intended as studies upon which to base a detailed cooperative investigation of subsidence conditions in Illinois.

This bulletin represents the result of a study of the literature on the subject. Much of the text is an abstract of this literature, supplemented by extensive private correspondence by the writers, and by a study of conditions in western Pennsylvania, in West Virginia, and in Maryland as given by office data and by an intimate acquaintance with the subsidence problem in the anthracite fields of Pennsylvania.

The authors are particularly indebted to the several anthracite subsidence commissions for the use of unpublished reports, and to a number of engineers for private data, for some of which it has been possible to give due credit in the text, while other data of a confidential nature has had to be incorporated without due credit.

This preliminary study of subsidence literature and of the conditions in Illinois suggests the advisability of undertaking a detailed study of the problem in Illinois. This study may extend over a number of years

in the future. To begin such a study, several groups of mines should be selected; one group in northern Illinois, one in the central part of the state, and another in the southern part. At each mine selected monuments should be erected, and the elevation of these monuments taken at intervals. In connection with these surface observations the conditions in the mine should be noted as closely as possible, in the hope that gradually data will be collected upon which it will be possible to determine the probabilities of and the extent of subsidence upon the surface when underground conditions are known, to determine the size of pillars which will most effectively prevent loss of coal due to squeezes and will properly protect a given surface area.

For the preparation of the extensive bibliography, for the preparation of the abstracts of literature, and for the detailed presentation of the data collected, credit is due entirely to Dr. Young, the undersigned having acted mainly by assisting in the gathering of data and in an advisory capacity in the preparation of the manuscript.

H. H. STOEK.

CHAPTER I.

NATURE AND EXTENT OF SUBSIDENCE PROBLEM

The removal of solid minerals from the earth's crust produces cavities, and thus the equilibrium which has previously existed is disturbed. If the cavities caused by the mining operations are not of great extent, or, even if long, are narrow, this disturbance may be apparent only as a local movement and may cause only occasional falls of rock from the roof. If the excavation is wide as well as long, the unsupported strata above the excavation will tend to sag under their own weight and, if their texture will not permit the bending movement necessary for the strata to become adapted to the new conditions, cracks and fissures resulting in extensive falls of roof will occur. Successively, the overlying beds may break and fall until the disturbance extends to the surface.

If the overlying measures bend without breaking and sag until finally they are supported by the floor of the excavation, the strata at greater height may sag successively and in a corresponding manner. Eventually, this movement may extend to the surface, the disturbance generally being less extensive as the vertical distance from the excavation increases.

In estimating the weight upon any coal seam or other mineral deposit due to the overlying rock, it is customary to assume that this weight is distributed more or less uniformly over the entire deposit. When a portion of a bed of mineral is removed, the burden carried per unit of area by the unmined portion becomes greater than the burden carried before any portion of the deposit was mined, because the weight formerly distributed over the deposit is now concentrated upon the pillars. The extent of the increase of burden on the pillars depends upon the extent of removal of the material of the bed, assuming that the overlying rock does not break in such a way as to relieve the stress on the pillars. If the pillars are not strong enough to support the increased load, or if the underlying bed does not have sufficient bearing power to resist the increased pressure, a movement will begin which is commonly called a "squeeze"* or a "creep." Depending upon the depth of the mining operations and the geological conditions, the "squeeze" may cause an extensive vertical movement which may reach to the surface. The

*The Pennsylvania Mine Cave Commission gave the following definition: "A 'squeeze' is caused by the general subsidence of the strata overlying the coal bed, due to a partial failure of the pillars; when this subsidence radiates from origin it is called a 'creep.'" Another meaning of "creep" is movement of the floor, due to pressure of pillars.

removal of coal or other bedded minerals from any considerable area, therefore, at once develops the problem of the support of the surface which involves certain factors requiring careful attention by the mine operator before extensive excavations are made. If the operator, for commercial reasons, meets these problems in a manner that is not in harmony with the prevailing ideas of conservation, a remedy should be sought which will secure for the public the greatest continuing benefit.

Upon the opening of a new mine, the following questions may well be asked:

1. Is the owner of the surface, if other than the owner of the mine or mining rights, legally entitled to surface support?
2. Is the material to be mined at such a depth that mining of all of it will not disturb the surface?
3. If the removal of all the deposit will cause surface subsidence, what percentage of the deposit left in pillars will prevent subsidence?
4. What is the ratio between the value of the material in the pillars necessary to prevent surface subsidence and the value of the surface? What would be the charge per ton against this pillar material if the surface were bought outright?
5. What amount and what extent of subsidence may be expected under the conditions of operation most economical at the time?
6. Upon what basis will it be possible to adjust claims for damages?
7. What will it cost to restore the surface for agricultural uses after all the deposit has been removed?

There are certain questions which the public and the state should answer at an early date:

1. Shall the coal or other mineral now in the ground be brought to the surface and used or shall it be left in the ground, serving like worthless rock, only to support the surface?
2. Assuming that the removal of all the material will temporarily prevent the use of that part of the surface overlying the area being mined, will it be better policy for the state to see to it that all the merchantable material is mined and then have the surface restored, or will it be wiser to permit nearly one-half the material to be lost permanently in the effort to avoid temporary injury to the surface?
3. If the mine operator is required by law to protect the surface, shall anything be done to prevent his leaving a large percentage of the deposit in the ground, never to be recovered and simply to support the surface?

Scientists who have investigated the national resources have em-

phasized the fact that the supply of minerals is not inexhaustible and that at the present rate of increase in production the exhaustion of the supply of some of the most important ones is not far off, as time is measured in the life of a nation. In the case of coal, one of the means by which the life of our supply may be extended is by recovering all, or at least a much greater percentage than is recovered at present, of the coal in the ground. If the extent of the entire area underlaid with workable coal beds be compared with the extent of tillable land not underlaid with coal, it will be noted that the actual area that might be affected by surface subsidence is relatively small. When it is realized that land affected by subsidence may in most cases be restored to service for agriculture after all the deposit has been removed, it may be rightly urged that the mine operators remove much more of the coal than is taken under present conditions, when preservation of the surface is frequently the determining factor in deciding the amount to be mined. Since mineral once lost by improper mining or left in pillars in abandoned mines is lost forever, the maximum recovery consistent with safe mining is of prime importance and is fundamental. The problems, therefore, are to discover what effect mining under the existing physical conditions will have upon the surface, to anticipate and to reduce to a minimum possible surface subsidence and finally to discover the best means of harmonizing and coordinating the various industrial and commercial interests involved.

As will be noted in the discussion of the legal considerations involved in the problem* the legal rights of the several parties interested in the minerals, in the surface, and in the other forms of property in the community must be considered both relatively and absolutely. A study of the subsidence problem from various angles shows the complexity of "conservation" applied to mining, to agriculture, and to other interests at the same time. The complexity seems to increase when efforts are made to coordinate these various interests.

RECORDS OF DAMAGE TO SURFACE.

While the technical press contains many reports of surface subsidence attributed to mining operations there are in America only a few reliable records, available for study, showing the exact amount of subsidence of the surface after the mineral deposit has been mined. However, there are a number of instances in which European engineers have kept records of surface levels extending through long periods of years.

*See Ch. VI.

Surface movements have in many instances been disastrous; records of damage to property being available both in Europe and in America. In the following section a number of the most important instances of damage to property resulting from mining operations are presented. These instances show that the problem is of widespread interest and is not a local one.

Belgium.

Although serious subsidence adjacent to salt mines was noted in England in 1850* and instances of damage by coal mining are recorded in British technical literature, the problem of surface subsidence due to mining operations seems to have been studied first in Belgium. In the early part of the nineteenth century it was claimed that coal mining about Liege, Belgium, was causing damage to buildings, and in the year 1839 complaints were filed with the city officials on account of damages to property. As a direct result of these complaints, the city appointed a committee to report upon the problem and in filing its report the committee established the necessary restrictions required for the safety of the city and determined the size of adequate safety pillars.

The Belgian engineer, Gonot, formulated a theory of subsidence in 1839 and some years later published a pamphlet dealing with the damage to a row of houses adjacent to the mine of the D'Avroy Bovene Company, claiming the mining company was responsible for the damage done. The mining company published a reply to Gonot in 1858. The Provincial Government appointed two engineers to investigate the cause of the damage to the houses and they reported that the houses were not damaged by coal mining.

By a decree of May 31, 1858, the Minister of Public Works appointed a special committee to report on the influence of mining upon the surface and also to review the rules of the committee appointed in 1839. The committee of 1858 endorsed the recommendations of the committee of 1839.

The disturbance of the surface about Liege continued and G. Dumont was appointed to investigate the matter. In his report† he supported the fundamental principle of Gonot's theory but made certain reservations in its application. He placed the responsibility for the surface disturbances upon the mining companies. The Colliery Owners' Association

*Trans. I. M. E., Vol. 19, p. 249, 1899.

†"Des Affaissements Du Sol Produits par l'Exploitation houillère." Liege, 1871.

published a statement* pointing out the fallibility of Gonot's theory but admitted the applicability of the theory to relatively flat seams.

Since 1875 considerable attention has been given to the problem in Belgium, and the situation has been complicated by the mining of coal from superimposed beds.

England, Scotland, and Wales.

Considerable attention has been given to the subsidence problem in England, Scotland, and Wales, owing to the extent of the coal and salt measures, to the importance of the coal industry, and to the proximity of the mines to centers of population. In the early days of coal mining in Great Britain it was customary to leave pillars, but as mining practice improved a portion of the coal in the pillars was removed. In discussing early methods of working coal, Bulman and Redmayne† refer to surface subsidence resulting from the removal of pillar coal as follows: "The date at which it became customary to remove pillars formed by a previous working has been a point of some importance in determining claims for damage to the surface, and many such claims in which the point arose have led to legal proceedings. That damage of this kind was done at an early date is proved by the records of the Halmote Court for the County of Durham. Early in the fifteenth century there was an inquiry before that court about a case which had occurred in the parish of Whickham in which it is recorded: 'It is found by the jury that John de Penrith is injured by a coal mine of Rogers de Thorton so that the house of the said John is almost thrown down, to the damage of the said John of 200 pounds, assessed by the jury; therefore it is considered that the said Roger repair the said house to the value aforesaid, or satisfy the said sum.'"[‡]

Since the year 1860 a number of British mining engineers and operators have written upon the general subject of subsidence and support of excavations. Subsidence has resulted from salt mining operations, as well as from coal mining, and owing to the nature and extent of the salt deposits the effect upon the surface has been even more disastrous than the effect of coal mining. Salt mining has been carried on in the vicinity of Northwich, Cheshire, for many years. In a depth of 390 feet there is a total thickness of almost 200 feet of salt in four beds, the thinnest being 5 feet thick and two being each approximately 90 feet. The shallowest bed is covered by 32 feet of soil and by 92 feet of salt

*"Des Affaisements Du Sol Attribués a l'Exploitation houillère." Liege, 1875.

†Bulman, H. F., and Redmayne, R. A. S. "Colliery Working and Management," p. 9.

‡"History of Durham." Francis Whellan & Co.

marl. Shafts were sunk to the upper bed shortly after 1670 and the pillar-and-room system was used. Pillars from 12 to 21 feet square were left to support the surface, but these pillars were weakened in time by the dissolving action of the water which seeped through the roof and was pumped out as brine. Surface breaks occurred which were generally marked by brine pools. In 1750 the first serious breaks occurred near the main street of Northwich. These old breaks have been filled and buildings have been erected directly over them. Since 1750 numerous breaks have occurred throughout the salt district.* After 1781 all new shafts were sunk to the second bed, which is nearly 92 feet thick and is separated from the upper bed by about 28 feet of hard marl. The most serious subsidence occurred in 1880, and the locality is now covered by a lake about 30 acres in area and of considerable depth.

The drilling of brine wells has increased the rapidity with which the pillars have become weakened and has hastened subsidence in the vicinity of the old mines. Brine streams or channels have been formed underground between the wells and old shafts, and subsidence is greatest near these underground streams.

Owing to the seriousness of the subsidence over an area of 600 acres, frame buildings are used, as these may be blocked up and restored after the most serious surface movement has abated.

The local Board of Trade was asked by the Salt Chamber of Commerce in 1871 to have a report made upon the local situation. This request was referred by the Board of Trade to the Secretary of State, who directed Mr. Joseph Dickinson, Inspector of Mines, to make a report. In March, 1873, Mr. Dickinson presented to Parliament a report which was published under the heading, "Landslips in the Salt Districts."

In 1881 there was introduced in Parliament a bill which proposed to give relief to the owners of damaged property in the salt district. This bill failed to pass, but in 1891 a bill was passed providing for Compensation Boards to be formed in the salt districts. These boards were empowered to levy a tax, not exceeding 3d. on every 1,000 gallons of brine pumped, to form a fund to compensate owners of property damaged. This act was put into force, and in 1896 a provision was added, limiting such compensation to private holders of property and excluding all local authorities, gas and water companies, railway and canal companies, and all pumpers of brine, no compensation whatever being allowed them if any of their property were injured by subsidence.

*Ward, T. "Subsidence In and Around the Town of Northwich in Cheshire." *Trans. Inst. Min. Engrs.*, Vol. 19, p. 241, 1889-1890.

The examples of surface subsidence due to coal mining in England and Wales are very numerous. Much agricultural land has been damaged and also various improvements, including buildings, railroads, bridges, railroad tunnels, canals, reservoirs, and streets and highways.

In one district the Great Western Railway had to fill 60,000 to 70,000 cubic yards annually. A canal in South Staffordshire has been raised 20 feet. Coal mining under the Merthyr tunnel, $1\frac{1}{2}$ miles long, produced a total subsidence of 10 feet in part of the tunnel. The settlement throughout the length of the tunnel was not uniform and part of the line had to be cut down to make the grade uniform.*

In the South Staffordshire district there has been considerable difficulty in securing suitable reservoir sites owing to the fact that coal mining has extended under most of the land and owing also to the fact that the bed is thick and nearly all the coal has been removed. A 3,500,000-gallon reservoir was built on a site which had been undermined thirty-four years before. When the reservoir was filled, the subsidence amounted to $1\frac{1}{4}$ to 2 inches. The cracks were filled with cement and the reservoir has since given no trouble. Another 43,000,000-gallon reservoir was constructed in the coal district in which there are three workable beds of coal, one being 8 feet 3 inches thick and lying at a depth of 1,200 feet, while 66 feet below it is a 6-foot 3-inch seam, and 80 feet above it is a 6-foot seam. These have been worked and one end of the reservoir has lowered 4 feet more than the other, the great difference in elevation between the ends being attributed to a fault.

In order to reduce the damage to water mains the practice in the English mining districts is to use lead joints instead of the "turned and bored" pipes.†

In the Midland and South Yorkshire coal fields the measures overlying the coal are principally shales, and mining at a depth as great as 2,000 feet has caused some subsidence.‡

In his address as President of the Institution of Mining Engineers, W. T. Lewis called attention to the seriousness of subsidence in Wales, stating that the surface sinks from 10 to 15 feet on account of mining at 1,800 to 2,400 feet.§ The removal of 4 feet 9 inches of coal and underclay, constituting a shaft pillar, at a depth of 2,108 feet is reported to have caused surface subsidence of 3 feet 6 inches at the South Kirby Col-

*Ingles, J. C. "Subsidence Due to Coal Workings." Proceedings, Inst. of Civ. Engineers, Vol. 135, p. 131, 1898.

†Proc. Inst. of Civil Engrs., Vol. 135, p. 156, 1898.

‡Eng. and Min. Jour., Vol. 84, p. 196, 1907.

§Trans. Inst. Min. Engrs., Vol. 22, p. 290, 1901.

liery.* This amount of subsidence is unusual in the district and was attributed to the crushing of a shaft pillar in the overlying Barnsley bed. A maximum subsidence of 1.74 feet resulted from longwall mining of 5 feet of coal at a depth of 1,595 feet in Derbyshire.† Mr. James Barrow cited an instance of mining coal 5 feet 6 inches to 6 feet 6 inches at a depth of 2,400 feet. The longwall method was used and the debris resulting from the working of the seam and the brushing of the roof was stowed underground.‡ Subsidence caused buildings on the surface to crack, water and gas mains to be broken, and bridges to be squeezed and distorted. Mr. J. Kirkup reported that the mining by longwall of a seam 22 inches thick produced cracks in walls and caused damage in pipes in workings in a seam 279 feet above. Moreover, a careful survey showed that the movement in the upper seam extended in advance of the workings in the lower seam.§ Mr. I. T. Rees has reported on subsidence resulting from longwall mining in the coal field in South Wales. The lower seam worked was from 3 to 4 feet thick and was well stowed. "Three hundred sixty feet above this seam, workings had been prosecuted in another seam in advance of the seam below, and although there were 360 feet of intervening strata, and the openings caused by working the seams were well stowed, yet the workings of the seam above were affected a distance of 150 feet in advance of the workings of the seam below."§ In 1912 the Wearmouth Coal Company, Ltd. (Sunderland), was forced to stop working the Hulton seam, which employed 400 men, on account of the heavy charges for surface damage resulting from subsidence. In one case the charge was \$500,000.**

France.

In France subsidence has been noted in the salt mining district as well as in the coal fields. In French-Lorraine, the salt measures extend under an area approximately 9 by 19 miles. The thickness of the beds varies from 33 to 230 feet and the beds lie at a depth of 300 feet or more. The salt has been removed in part by solution methods, which produce large chambers, and, owing to the great size of these chambers and to the character of the roof, extensive falls of roof rock have occurred. The subsidence has generally taken place slowly, but where the

*Snow, Charles "Removal of a Shaft Pillar at South Kirby Colliery." Trans. Inst. Min. Engrs., Vol. 46, p. 8, 1913.

†Hay, W. "Damage to Surface Buildings Caused by Underground Workings." Trans. Inst. Min. Engrs., Vol. 34, p. 427, 1908.

‡Proc. South Wales Inst. of Engrs., Vol. 20, p. 356, 1897.

§Kirkup, J. Discussion of paper on "The Absolute Roof of Mines." Trans. Inst. Min. Engrs., Vol. 31, p. 180, 1905.

§Proc. South Wales Inst. of Engrs., Vol. 20, p. 359, 1897.

**Trans. Inst. Min. Eng., Vol. 44, p. 533, 1912.

covering is limestone there have been sudden breaks which have caused extensive damage. Among the serious surface movements reported are one in 1879 at St. Nicholas and one at Ars-sur-Meurthe in 1876.*

Fayol made a number of observations of subsidence at the Comentry Mines, as well as laboratory experiments, and published the results of his observations, including the levels taken at these mines from August, 1879, to May, 1885.† He advanced a theory of subsidence which was essentially different from that formulated by the Belgian engineer, Gonot.

Germany.

Probably the first important German publication on surface subsidence in connection with mining was by A. Schulz, in 1867.‡ He investigated the dimensions of safety pillars and the angle of break in the Saarbruck field. The problem was considered so important that in 1868 the Prussian government appointed a commission of four engineers to investigate the effect upon the surface of mining operations in the coal fields of Belgium, England, France, and Rhenish Prussia. In 1869 von Dechen wrote upon the subsidence in and about the city of Essen. He had previously (in 1866) emphasized the importance of studying the part played by the heavy marl beds overlying the coal measures.

In 1867, von Sparre contributed a paper upon the "afterbreak."§ In 1894, the project of a canal between Herne and Ruhrort aroused a discussion in regard to the stability of the surface over which the proposed canal was to run. The Board of Mines of Dortmund conducted observations in the Dortmund district and the results were published in 1897.§

In the Dortmund district there have been a number of accidents** due to thrust movements, and in the Ruhr coal fields miniature earthquakes, supposed to have been due to coal mining, have caused considerable damage.

Methods of reducing surface subsidence by hydraulic stowing have received much attention from the mining operators of Upper Silesia and Westfalia.

The coal-beds under Zwickau, Saxony, are situated at a depth of

*Bailly, L. "Subsidence Due to Salt Workings in French-Lorraine." *Annales des Mines*, Ser. 10, Vol. 5, pp. 403-494, 1904.

†Bul. de la Société de l'Industrie Minérale, II^e série, Vol. 14, p. 818, 1885.

‡Zeit. für B., H., u. S.-W., 1867.

§Glückauf, 1867.

§Zeit. für B., H., u. S.-W., p. 372, 1897.

**Zeit. für B., H., u. S.-W., Vol. 51, p. 439, 1903.

600 to 2,500 feet. Beginning in 1885, observations were made at eighty-two points to determine the surface movement resulting from mining operations. After twelve years it was noted that subsidence amounted to 85.2 inches, due to mining at 600 to 900 feet. At 1,500 feet, the subsidence was only 9.17 inches.

The town of Eisleben in the Mansfeld mining district was seriously damaged by earth shocks, fissures, and subsidence during the years from 1892 to 1896. Various theories were advanced concerning the cause of these disturbances. Some held that they were due to the dissolving of various salt deposits by underground water thus producing caverns, and that as these caverns became of great extent, large falls of overlying rock caused the shocks and the subsidence. Others held that in addition to the solution of the salt, carbonated waters were leaching the deeper lying dolomitic formations, and when these became honeycombed, they were unable to support the load concentrated on the natural pillars resulting from the solution of part of the overlying salt beds. At the Mansfeld Copper Mine copper bearing shale from 12 to 20 inches thick was being mined by a longwall method at a depth of from 900 to 1,800 feet. Public opinion blamed the mining company and, as a result of arbitration, the company paid \$125,000 damages.*

Potash mining at Stassfurt in beds 50 feet thick and dipping 40 degrees has caused serious subsidence. Stone buildings have sunk as much as 20 feet, rows of houses have been removed to firm ground, and chimneys and towers are standing 5 degrees from the vertical.†

On June 10, 1910, surface subsidence, described as a local earthquake, occurred at the Consolidation Mine. "The part of the coal measures most affected formed part of an undulation or 'saddle.' The forces at work were of such intensity, and so irregular in their action, that steel rails were twisted into corkscrew like shapes, and in a section of the saddle 10 feet in length, two lines of rails, water-pipes, signal-wires, and rope-way were found crushed together into a bundle of about 12 to 16 inches thick."‡

Austria.

The review of the theories of subsidence presented by Austrian engineers, as given by Goldreich,§ indicates that as early as 1859 there

*Lang, Otto "Subsidences at Eisleben." *Bul. de la Societe Belge de Geologie*, Vol. 11, p. 190, 1898.

†Private correspondence.

‡Zeit. f. B., H., u. S.-W., Vol. 59, p. 68, 1911. Abstracted in *Trans. Inst. Min. Eng.*, Vol. 41, p. 587, 1910.

§Goldreich, A. H. "Die Theorie der Bodensenkungen in Kohlengebieten." Berlin, 1913.

were regulations controlling the mining of coal under railways in Austria. Director W. Jicinsky published a treatise on "The Subsidence and Breaks of the Surface in Consequence of Coal Mining."* The publication by Rziha† was the first contribution by an Austrian engineer to the theories of subsidence. Most of the Austrian writings on subsidence have been on the problems of the Ostrau-Karwin coal district. Goldreich has studied the problem principally through years of observation in railway engineering.

One of the most serious disasters in Austria resulting from surface subsidence occurred July 19, 1895, at Brux, Bohemia,‡ where the brown-coal seams lie nearly horizontal at a depth of 325 feet, covered by clay-shale interspersed with quicksand from 10 to 65 feet thick. There are in all four seams having an average total thickness of 80 feet. Some filling had been used, but sand broke into the mine, and it is estimated that two million cubic feet of sand entered the workings. Numerous holes were formed on the surface, rendering sixty-six houses uninhabitable and making 2,000 people homeless.

Another serious disaster occurred at Raibi, Bohemia, at a lead mine, where an attempt was being made to secure an adequate water supply through underground workings. Two short drifts were being driven through the rock toward water-bearing sands, and though a borehole was kept ahead of each drift, a blast so weakened the cover that the roof broke and a rush of sand followed. A large hole was made on the surface and without warning a small municipal hospital dropped forty feet, causing the death of seven of the inmates.§

India.

Coal mining in the Bengal field has caused disturbance of the surface along the outcrop. At the Khoira Colliery the mining of 10 feet 6 inches of coal dipping 30 degrees has caused complete subsidence of the surface where the workings are shallow. At the Barrea Colliery, owing to the value of the rice land, stowing has been used to reduce the amount of subsidence.§ In the same field mining of thick coal overlaid by thick beds of sandstone has been attended by extensive falls of roof which have produced fatal air-blasts.**

*Oestrr. Zeit. für B., u. H.-W., p. 457, 1876.

†Oestrr. Zeit. für B., u. H.-W., 1882.

‡Helmhacker, R. "Land Subsidence at Brux, Bohemia." Trans. Inst. Min. Engrs., Vol. 10, p. 583, 1895-96.

§Oestrr. Zeit. für B., u. H.-W., Vol. 58, p. 31, 1910.

§Stonier, G. A. "Bengal Coal Fields." Trans. Inst. Min. Engrs., Vol. 28, p. 537, 1904.

**Adamson, T. Trans. Inst. Min. Engrs., Vol. 29, p. 425, 1905.

South Africa.

In the diamond mines of South Africa there have been rushes of mud into the mines. These have been due to water softening the steep walls of the open pits which then give way and fill the mine openings.*

In connection with the Rand gold mines there has been surface subsidence similar to that caused by deep longwall coal mining.† The maximum depth from which mining has affected the surface has been 710 feet on the Champ d'Or. Other depths from which subsidence has extended to the surface are 566 feet at the Bonanza mine, 650 feet at the May Consolidated, 480 feet at the Treasury, 340 feet at the New Kleinfontein, 490 feet at the New Heriot, and 425 feet at the Windsor. At the Gueldenhuis Deep an area 1,000 feet on the strike by 620 feet on the dip, at depths of from 650 to 924 feet, with an average stopping width of 15 feet caved suddenly but no sinking of the surface resulted. Similar results at other mines have led South African engineers to conclude that cavings of stopes below 1,000 feet in depth will not affect the surface.

UNITED STATES.

Alabama.

In Alabama little attention has been given to the subsidence problem, owing to the fact that many of the coal mining companies have been operating under land to which they hold the title and of which the surface has relatively little value in comparison with the coal. At least 90 per cent of the mining is at a depth of less than 400 feet. Some cracks have extended to the surface and when damage has been caused to property not owned by the mining companies, it has usually been possible for the mining companies to make settlements not greatly out of proportion to the damage done.‡ At the present time some mining is being carried on where the cover is as much as from 800 to 1,200 feet and very little trouble is being experienced.

Idaho.

In the metal mines of the Coeur d'Alene district, disturbances have been noted which apparently are due to causes similar to those

*Williams, G. F. "Diamond Mines of South Africa," pp 400-404.

†Richardson, A. "Subsidence in Underground Mines," Jour. of the Chem. Met. and Min. Soc. of S. A., Mar., 1907; Eng. and Min. Jour., Vol. 84, p. 196, 1907.

‡Private correspondence.

which have produced air-blasts in other ore mines.* Recently at an Idaho ore mine two men were killed and four seriously injured by an air-blast.

Illinois.

Subsidence of the surface due to coal mining has attracted attention in Illinois for a number of years. In the early days of coal mining, when only the shallow beds were mined, the surface was seriously damaged, but in those days the price of farm lands was low and most of the mining was conducted in sections not thickly populated. The first important suit for damages that was appealed to the higher courts in Illinois was in Sangamon county in 1880 (Wilms vs. Jess, 94 Ill. 464). Since that date but few subsidence cases have been tried in the higher courts in Illinois, most of the claims for damages being settled by arbitration or by decisions of the lower court.

An investigation in 1914 showed that there had been surface subsidence in the most important coal producing counties of the state. Twenty-four of the total of fifty-two counties in which coal is mined produced 94 per cent of the coal mined in the state in 1913, and in twenty-one of these counties, subsidence, in various stages and degrees of intensity, was noted.

The reported damages include injury to farm lands and buildings, to city buildings and streets, to railroads and highways, and to domestic and municipal water supplies. Large tracts of farm land in northern Illinois are reported to be damaged by disturbance of surface drainage due to subsidence. There has been litigation to determine the extent to which mining is responsible for the inundation of lands adjacent to waterways and streams.

Few instances of injury to persons by subsidence of the surface have been reported. Mining at shallow depths has permitted the movement of large bodies of surficial material, at time resulting in a rush of sand, clay, and water into the mine, causing serious damage to the mine. Fortunately there have been but few such instances of personal injury to miners from such rushes. This may be due largely to the precautionary steps which have been taken since the accident in the long-wall field in 1883 at Braidwood. The disaster at Mine No. 2 of the Diamond Coal Company near Braidwood, Illinois, was due to the inrush of water through surface breaks caused by subsidence.†

*Sizer, F. L. "An Air-Blast or Earth Movement." *Mines and Minerals*, Vol. 33, p. 87, 1912.

†Coal Report of Illinois, p. 97, 1883. Roy, A. "History of the Coal Mines of the U. S." Columbus, pp. 190-194, 3d Ed., 1907.

A horizontal bed, 3 feet thick, was being mined at a depth of about 100 feet. The overlying strata are largely shale and clay. Longwall mining had permitted the surface to sink and, at various points at which the rock cover was thin, cracks and breaks extended for some distance up into the surficial material. In February, 1883, there had been a heavy fall of snow followed by a thaw and rain. On February 15, vast sheets of water were standing on the prairie and on the following day a number of the miners did not go to work, as they feared that the water would break through into the mine. At 11 a. m. on February 16 there occurred a cave which permitted a great inrush of water from the surface. The flow of water cut out a larger inlet to the mine and in a short time all of the low points on the roadways were filled with water so that escape was impossible. In three hours the entire mine was filled and the water rose to the surface. Sixty-one men and boys failed to escape before the mine was flooded.

A comprehensive report upon subsidence in Illinois has been prepared by L. E. Young and will appear as a contribution of the Cooperative Investigation by the Illinois Geological Survey.

Indiana.

The following data regarding subsidence in Indiana have been furnished by H. I. Smith, mining engineer, U. S. Bureau of Mines:

A few squeezes have been reported in the mines near Evansville. At one mine operated under the Ohio River at a depth of 260 feet below the river bottom no trouble from the overlying river was reported and at another mine operated at a depth of about 300 feet no loss of coal due to squeezes was reported when about 55 per cent of the coal was removed. Local squeezes occurred but were stopped by a barrier pillar and the coal was reached from the next set of parallel entries.

Probably the greatest damage from subsidence in Indiana has been in Clay county over the upper and lower block coal beds. In one instance in which there was from 20 to 40 feet of cover, consisting of shale with 2 to 6 feet of clay and soil on top, the overlying material was so yielding that an outline of each pillar or stump could be traced on the surface. After a period of twenty years these sinks are said to have evened up, leaving little or no trace upon the surface. Over recent workings succeeding rooms can be traced on the surface by pit-holes or sinks. In some cases the strata have broken through to the surface and the depth of the hole is the same as the thickness of the coal, that is, about five feet. Local residents state that within five years farm land again be-

comes tillable and in twenty years the depressions have disappeared. This does not apply to large swags which cover a number of adjacent rooms and which in some cases must be drained. A good example of these swags is found at West Seeleyville in the field north of the interurban stop and between the interurban stop and the Vandalia Railroad. These swags are said to have occurred one year before the mine was abandoned, and the coal is said to lie at a depth of 110 feet.

In Vigo county, about $1\frac{1}{2}$ miles north of Miami, a number of small sinks were observed in a cultivated field. On the opposite side of the road, in Clay county, one of the sinks has broken through and is about five feet deep. Other depressions were observed in the line of these workings, but were not broken through.

A private correspondent reports that in Linton, about six years ago, one side of a concrete block house dropped from $2\frac{1}{2}$ to 3 feet. The break extended from top to bottom and passed through the blocks instead of following the joints. Two or three years ago one section of an L-shaped school house was badly damaged and the front end of a store fell in. The court records show five or six suits at Linton for recovery of damages due to mining. The coal is worked on the room-and-pillar system.

Kansas.

Longwall mining at shallow depths in Kansas in the vicinity of Osage City has caused some subsidence, but no damage has been done to sidewalks, brick buildings, etc. The coal is from 12 to 18 inches thick, and lies at a depth of 70 to 80 feet.* Above the coal is a light limestone and upon it rest the upper Pennsylvania strata of alternating shale and limestone.†

It is reported that subsidence of surface has resulted from the removal of salt by brine-pumping. The salt measures are about 400 feet thick and are covered by a total thickness of 600 feet of beds of shale, limestone, and sandstone.

In the southeastern part of the state mining is conducted on the room-and-pillar system in coal dipping gently toward the west. There have been subsidences, especially near the outcrop, but no extensive damage has been done.

Near Leavenworth longwall mining is carried on at a depth of about 700 feet in a bed 19 to 24 inches thick. There are no published records of subsidence. The surface is rolling and no damage would be likely

*Private correspondence.

†Kansas State Geol. Survey, Vol. 3, p. 70.

except to buildings, paving, pipes or sewers. The numerous stone and brick buildings of the State Penitentiary at Lansing have been undermined by the State Mine, but show no evidences of subsidence. Mines extended under the Missouri River show no seepage of river water.

Maryland.

In the George's Creek Region, Maryland, the coal seam varies from 6 feet 6 inches to 9 feet 10 inches in thickness and, when the pillar coal is removed, falls occur which extend to the surface.* Fig. 1 indicates the supposed effect of the removal of the pillars under the overlying strata where the surface is 250 feet above the coal seam. Subsidence extends

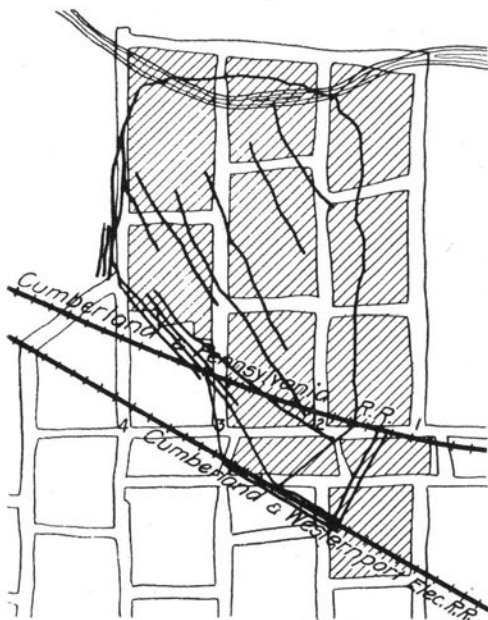


FIG. 2. RELATION OF SURFACE CRACKS TO UNDERGROUND WORKINGS.

to the surface in such a case after the pillars have been drawn back 220 feet. After the first break occurs at *B* due to drawing the pillar at *A*, the entire block of roof sinks and causes the cavity *C*. The distance from *A* to *B* horizontally is 40 feet, or 40 feet of pillar have been taken out when the first fall occurs. The second fall occurs at *D* and the fracture line extends to the space *E* at the Redstone seam. This break occurs

*Reppert, A. E. "Pillar Falls and the Economical Recovering of Coal from Pillars." Proc. West. Va. Coal Mining Institute, p. 110, 1911.

after 60 feet of pillar has been taken out and the break extends almost 40 feet above the floor of the Pittsburgh seam. The third fall extends to *F* and the fourth to *G*, the line of fracture in the latter case extending to the space *H* in the Lower Sewickley seam, 85 feet above the floor of the Pittsburgh seam, the total length of pillars drawn up to this stage being 100 feet. The next break occurs when pillars have been drawn for 160 feet to *K* and the break extends to *L*. When the pillars are drawn back a distance of 220 feet to *M* the fracture extends to the surface at *N*, a height of 250 feet above the bottom of the Pittsburgh seam. This fracture line is approximately correct as shown in Fig. 1 and is based on actual survey and observation of a large number of surface breaks in relation to the mine workings. Fig. 2 indicates the position of surface breaks due to the removal of pillars at a depth of 170 feet over an area 300 feet by 350 feet, the thickness of coal averaging 8 feet. The first surface break occurred between rooms No. 1 and 2 and was about 70 feet from the barrier pillar. The average angle of fracture from the vertical is $22^{\circ} 30'$. The break along the barrier pillar at the top of the rooms was at an angle of 14° from the vertical, while the break along the left hand pillar of No. 4 room was nearly vertical. The conclusion has been drawn that "until a pillar fall extends to the surface, the fracture is conical in shape, but as the pillar line extends down the rooms beyond the first surface break, the strata fracture on a nearly vertical line."*

Michigan.

Copper Mines.—In the deep copper mines of northern Michigan extensive falls of roof have produced air-blasts. At great depths the pillars left to support the roof, or at times masses of poor rock left unmined, show the effect of the tremendous weight upon them. The edges of these pillars fail first and large slabs may burst off and fly some distance. The pillars fail suddenly and the fall of rock may be extensive enough to cause a jar that will be felt on the surface.†

Beginning in 1904 there were a number of caves at the Atlantic mine. The stopes averaged 15 feet in width and extended for a mile along the strike of the lode and for one-half mile down the dip. These falls became so extensive and the pressure on the pillars became so great that the shafts were ruined and the mine was put out of commission, May, 1906.‡

*Op. Cit., p. 113.

†McNair, F. W. "Deep Mining in the Lake Superior District." Eng. and Min. Jour., Vol. 83, p. 322.

‡Stevens, H. J. Copper Handbook, Vol. 10, p. 377.

Extensive falls of the hanging-wall or roof have caused trouble at the Quincy mine. Stopping averages 20 feet in width and in parts of the mine has been carried on to a depth of more than 6,000 feet on the dip of the lode. The sudden and violent compression of air by falls in the mine has caused damage to the levels and shafts and has produced miniature earthquakes.* The general manager of the Quincy mine, in his report for the year 1914, writes as follows:

“On March 25 air-blasts occurred throughout the mine and continued intermittently for a week or ten days. As a consequence, various cross-cuts and drifts were crushed and closed up. No. 6 shaft timbers were seriously crushed between the 51st and 58th levels, and No. 2 shaft was crushed and closed between the 40th and 50th levels. About 500 feet of the crushed section of No. 2 shaft had to be entirely recovered and retimbered at an expense nearly as great as that of sinking a new shaft. In the remaining portion of the damaged shaft about half of the timbers were replaced.

“Below the 50th level the shaft was not damaged by the air-blasts, though the cross-cuts at the 57th, 64th, 65th and 66th levels were entirely closed, and the levels north were badly crushed.

“In earlier days, when air-blasts were little understood, it was the custom to stope out the lode without reference to the shaft. Going through the upper portions of No. 2 and No. 6 shafts is like going down through open stopes, with practically no pillars left to protect the shafts. It was in the lower part of these sections that the caving and crushing took place with such serious results.

“At the present bottom of the mine, pillars are being left 200 feet on each side of the shaft. The air-blasts have never caused any damage to these sections of the shaft.

“Air-blasts have continued with more or less frequency since July, though they have not damaged or retarded the work to any great extent. In order to meet the air-blasts and prevent as far as possible the damages caused by them, as fast as the mining in each stope is finished, the bottom of the stope along the back of the level is filled with poor rock, constituting what is termed ‘rib work.’ Experience has taught that these rock-packs are the most effective means yet employed to lessen the damages caused by air-blasts. In order, however, that the highest effectiveness possible may be secured within the limits of profitable mining at greater depth, this rib work should be still further strengthened. It is

*Ibid., Vol. 10, p. 1444.

estimated that the voids in the rock give it a shrinkage of about 20 per cent at the present depth of the mine. In order to lessen this shrinkage and strengthen the rib work, the question of filling the voids with bank sand, stamp sand, or crushed rock is receiving serious attention, inasmuch as provision must be made for better and stronger supports to the back of each level, as fast as stoping is finished. During the year \$57,190 was spent for the recovery of the shafts and levels that were damaged by the air-blasts, and \$21,487 has been expended in the fight toward preventing damages by air-blasts."

These rock movements appear to be confined to the deeper portions of the mines and no effect is noted at the surface except a vibration, giving the effect of an earthquake. No subsidence is reported.

Iron Mines.—At a number of points on the Lake Superior iron ranges, in Michigan and in Minnesota, the mining of extensive bodies of ore close to the surface has caused the subsidence of large areas. A considerable portion of the iron ranges is covered with glacial deposits and when the bedrock is shattered by mining rushes of sand into the mine may follow.

At several important mines large caves have occurred under important railway lines. Owing to the inclination, volume, and extent of the ore body it was thought that it would be more practical to bring the track to grade by filling than to construct a new line entirely outside the subsiding area. The continued development of the ore body and deeper mining have caused the subsidence to continue from year to year so that now the problem of filling has become a very expensive one for the railroad company.

Missouri.

At Lexington, Missouri, the mining of 20 inches of coal at a depth of 160 feet has caused subsidence amounting in places to the full thickness of the coal. No serious damage has resulted.*

In the Joplin district extensive caves of the surface have resulted from the mining of large bodies of zinc ore at shallow depths, but no detailed study of subsidence has been made.

During the year 1915 a number of mills were damaged through the tailings piles falling into the excavations. One cave-in resulted in the death of several men in the mine by drowning and it seems inevitable that there will be many more caves in the district, particularly in the sheet deposits where small pillars are left.

*Private correspondence.

In the Flat River district large areas have been mined at depths up to 700 feet. The beds are practically horizontal and have good roofs. "In some mined-out areas where the pillars have been removed and slabbed the back has come in, extended over an area of from one to three acres. In two such caved areas that have been examined it has been found that in each case a natural arch has been formed and the caved material has nearly filled the opening to the back. The largest of the caves of this type has run up about 100 feet into the back, which leaves about 400 feet of undisturbed formation above it."*

Oklahoma.

Coal mining in Oklahoma has caused surface disturbance at a number of places. On September 4, 1914, a serious squeeze occurred in Mine No. 1 of the Union Coal Company at Adamson, which resulted in the death of thirteen miners, complete loss of the mine, and minor surface damage. The mine was opened on the pillar-and-room system. Fig. 3 shows a cross-section through the two thin seams that were worked. The lower seam is 4 feet thick and 45 feet above it is a seam

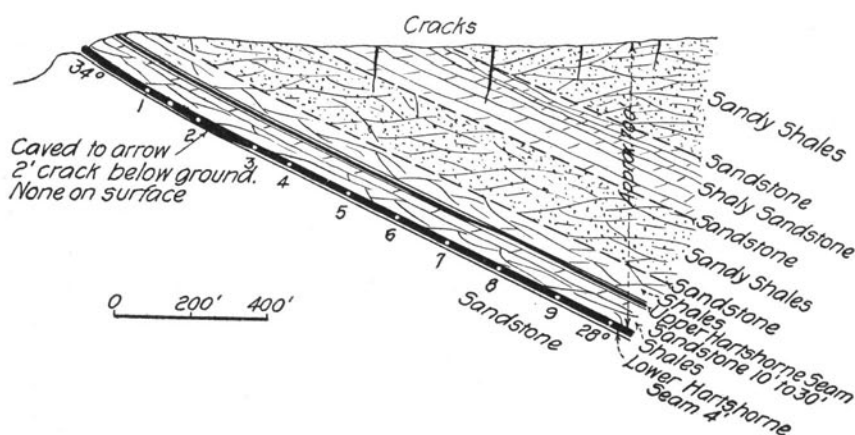


FIG. 3. SECTION THROUGH ADAMSON MINE, OKLAHOMA.

2 feet 3 inches thick, not worked. The beds dip about 30 degrees. Rooms were turned on 33-foot centers, the room pillars being not more than 9 to 12 feet wide and in places much less. The roof was a sandy shale, 28 feet thick, and above it an equal thickness of hard sandstone and a little fireclay. The squeeze came comparatively quickly, completely

*Private correspondence.

closing the slope. A number of cracks appeared on the surface, but no serious surface damage was done.*

There are no records available showing the amount of surface subsidence, but the surface cracks have been located fairly accurately. Assuming that the underground break extended to the tenth level, there was about 700 feet of cover, and the angle of break may be calculated for the cracks farthest from the mouth of the slope. It has been assumed that the large crack over the east side resulted when the 7th East entry was lost. Similarly cracks on the west may be correlated with the underground movement on the 6th West and 9th West entries.

George S. Rice, Chief Mining Engineer, U. S. Bureau of Mines, says in regard to this accident:

"What happened was almost inevitable with a strong roof and increasing depth, where so large a percentage of the coal had been extracted in the advance work and the pillars left standing. Estimating from the map, about 75 per cent of the coal had been taken out by the entries and rooms. As a result, in the lowest level of the mine there was a load of over 3,000 pounds per square inch on the 25 per cent of coal which remained in the entry and room pillars. This is more than bituminous coal can sustain. Therefore, I am inclined to think that the main support of the overlying strata had been carried by arch stresses, the arch being buttressed on one side by the strata near the outcrop and on the other by the dipping strata. Then when the fracture occurred at the latter buttress, it threw the entire weight on the mine pillars, causing them to be crushed. The surface cracks, reported by reliable witnesses to have occurred prior to the collapse, running parallel but in advance (horizontally) of the lowest level, indicated that a shear fracture had occurred in a plane roughly at right angles to the plane of the dipping beds, and when this fracture extended laterally to a sufficient distance, it formed a slip plane which permitted the entire weight or the overlying strata less friction to be thrown upon the pillars, resulting in the collapse of the mine."

Pennsylvania.

Pennsylvania Anthracite Field.—In the United States surface subsidence due to mining operations has received most attention in the anthracite field of Pennsylvania, and notably in the city of Scranton. Of the total area of 176 square miles in the Wyoming region, incorporated boroughs and cities cover 101 square miles.† The city of Scranton ex-

*Brown, G. M. "A Sudden Squeeze in an Oklahoma Mine." *Coal Age*, Vol. 6, p. 533, 1914.

†Report of Pa. State Anthracite Mine Cave Commission, 1913.

tends entirely across the coal field, a distance of five miles, and for the same distance along the valley. Beneath a portion of the city are eleven important coal beds having an average aggregate thickness of 58 feet. It has been estimated that during the seventy-five years of active mining under the city 177,000,000 tons of coal have been produced. This output represents a volume of 198,000,000 cubic yards, an amount in excess of the total estimated excavation in connection with the Panama Canal.* In the early years of mining accurate maps of the mines were not made and preserved and a number of the coal companies made little effort to columnize the pillars in the various coal beds that were worked. These conditions have made it difficult to study the problem and to provide adequate and practical remedies.

While subsidence has occurred in many parts of the city, it was estimated in 1912 that not more than 15 per cent of the area of the city was threatened.

Although surface subsidence had damaged property within the city limits prior to August 29, 1909, the public in general gave the matter little connected attention. This was due largely to the fact that the mining companies hold deeds which permit them to remove the coal without liability for damage to the surface. On the date mentioned, surface subsidence caused serious damage to a school building, which fortunately was not in use at that season of the year.

Following this cave Honorable J. B. Dimmick, then Mayor of Scranton, by approval of the City Council and the Board of Control of the Scranton School District, created a Commission to investigate the physical causes of mine caves and the legal responsibility therefor. The report of this Commission, submitted March 20, 1911, was published in 1912 as Bulletin No. 25, U. S. Bureau of Mines. It was the result largely of the investigations of Eli T. Conner and William Griffith and reviews the existing mining conditions and discusses at length methods for supporting the surface. Considerable attention was given to "flushing" methods of filling and the report contains a chapter by N. H. Darton, entitled "Notes on Sand for Mine Flushing in the Scranton Region." An appendix includes the results of tests to determine the compressive strength of anthracite† and of tests of various kinds of materials for supporting the roof in mine workings.‡

*Bul. 25, U. S. Bureau of Mines, Washington, 1912.

†These tests were made for a committee of the Scranton Engineers' Club in 1900 in the engineering laboratories at Cornell University, Lehigh University, and the Pennsylvania State College.

‡Fifteen tests on the compressive strength of materials for supporting roof were made for this investigation at the Engineering Laboratory of Lehigh University.

The U. S. Bureau of Mines continued investigations along several lines which were discussed in the report by Conner and Griffith and subsequently published the results as bulletins. Bulletin No. 60 contains the investigation by Charles Enzian entitled "Hydraulic Mine Filling; Its Use in the Pennsylvania Anthracite Fields." Bulletin No. 45 by N. H. Darton is a report upon "Sand Available for Filling Mine Workings in the Northern Anthracite Basin of Pennsylvania."

In 1911 Governor Tener appointed the Pennsylvania State Anthracite Mine Cave Commission to investigate the physical conditions and legal rights of surface support. This Commission consisted of:

W. J. Richards, Vice-President and General Manager, Philadelphia and Reading Coal and Iron Co.

G. M. Davies, Mining Contractor.

J. Benjamin Dimmick, Mayor of Scranton.

E. G. Lynett, Editor, Scranton Truth.

W. L. Connell, Coal Operator, Ex-Mayor of Scranton.

R. A. Phillips, General Manager, Coal Department, Delaware, Lackawanna and Western Railroad.

W. H. Lewis, Retired Coal Operator.

Charles Enzian, Mining Engineer, U. S. Bureau of Mines.

W. A. Lathrop, President, Lehigh Coal and Navigation Co.

(Owing to the death of W. A. Lathrop, he was succeeded by S. D. Warriner, President, Lehigh Coal and Navigation Company.)

The investigation of this Commission covered the period from June 12, 1911, to March 1, 1913, when the report was submitted to the Governor and Legislature, the text of the report being printed in the Journal of the Pennsylvania Legislature for 1913, Volume 5, page 5947. This Journal report contains none of the maps or illustrations essential to an understanding of the report, which is available, therefore, only in typewritten form. In addition to the field investigations, the Commission conducted a series of thirty-four tests upon supporting materials, the tests being made at the Bureau of Mines Laboratory in Pittsburgh, in cooperation with the U. S. Bureau of Standards, under the supervision of Charles Enzian.

The 1913 session of the Pennsylvania General Assembly enacted the Davis Mine Cave Law,* which provides for the protection of public highways, streets, etc., and also provides for the creation by municipalities of a Bureau of Mine Inspection and Surface Support, the duties of which are to investigate the mine workings in their relation to the

*Act No. 857. Approved July 26, 1913.

support of public highways. Thus far the City of Scranton is the only municipality in Pennsylvania that has passed an ordinance for the creation of such a bureau. The City of Scranton Bureau of Mine Inspection and Surface Support has been in existence since August 5, 1913, and has investigated a number of mines and made reports upon such investigations. The reports of this Bureau are not in print.

The City Council of Scranton on October 24, 1913, appointed H. D. Johnson and D. T. Williams to prepare a report upon the mine of the Peoples Coal Company, and in their work they were assisted by Chas. Enzian, Mining Engineer of the U. S. Bureau of Mines. The report of these gentlemen, submitted December 12, 1913, was made under the provisions of the Davis Mine Cave Act. It comprises ninety-three typewritten pages and, in addition to reviewing the mining conditions in three city wards, contains much concise information of general application in the study of the problem of surface subsidence.

The subsidence problem in the Pennsylvania anthracite field has been further complicated by the glacial deposits which occasionally are localized in "pot-holes." These pot-holes may extend to a considerable depth below the glacial sheet, making it dangerous to carry on any mining operations near them. When the subsidence of the coal measures extends to a pot-hole filled with sand and water, the water and some of the sand may seep into the mine, and if the subsidence has shattered the intervening strata or if the roof has been thin and weak, a rush of sand may fill the mine workings. The difficulties of mining under such glacial deposits have been recently presented* to the mining profession and fourteen accidents have been noted.

In most of these a large area of the workings has been filled by the rush of glacial material and water, and in several instances extensive surface subsidence resulted.

On June 10, 1914, at the Sugar Notch Mine, a breast in the Kidney bed broke into the wash. The material entering the mine was largely sand and clay in a semi-fluid state, and its volume was estimated at 20,000 cubic yards. This filled several thousand feet of gangways and tunnels, but no lives were lost. The accompanying illustrations show the important data in connection with this accident. Fig. 4 shows the mine workings, the contours of the top of the rock, the location of drill holes, and the important surface features previous to the accident. The cave occurred at the face of breast 15. Fig. 5 shows the conditions

*Bunting, D. "The Limits of Mining Under Heavy Wash." Amer. Inst. of Min. Engineers, Bul. No. 97, p. 1, 1915.

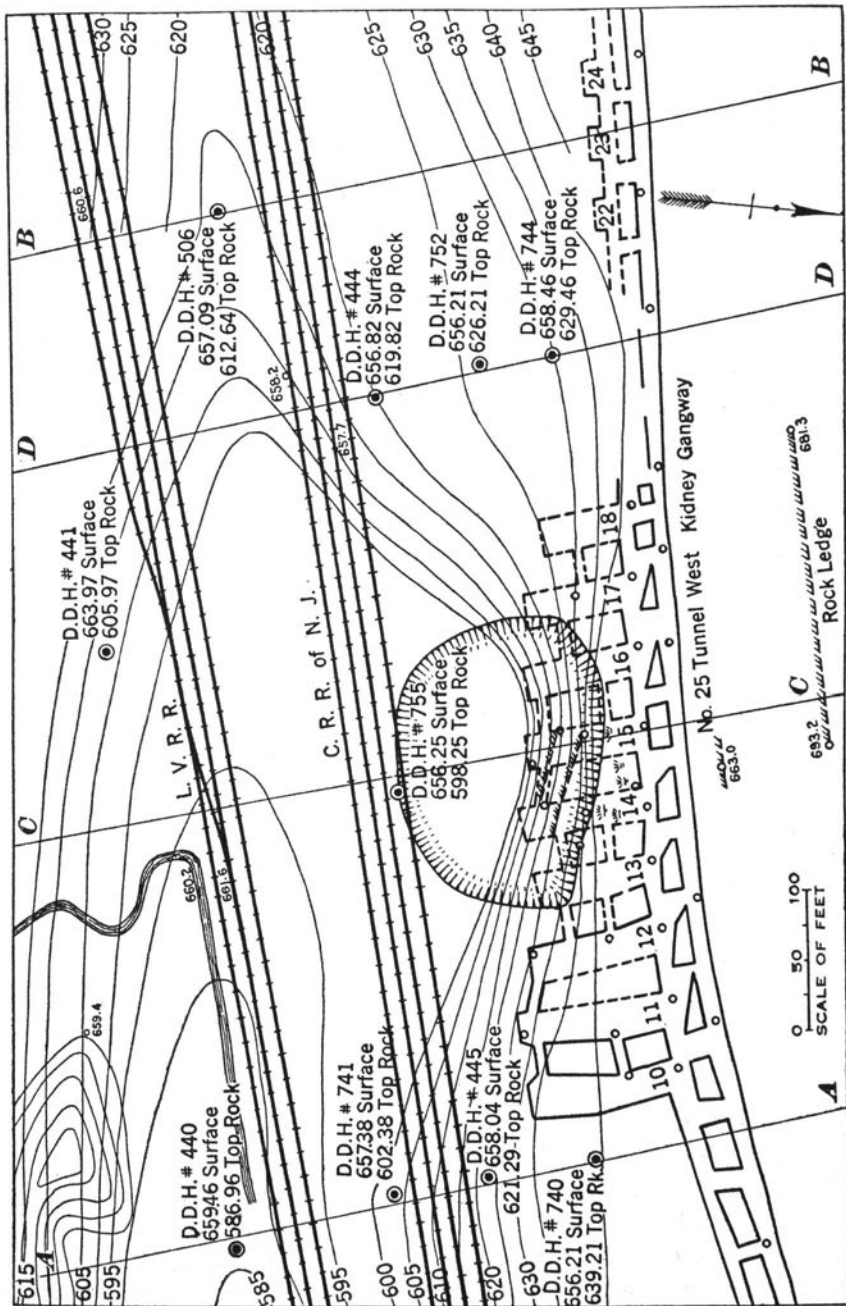


FIG. 5. SURFACE AND UNDERGROUND FEATURES AFTER ACCIDENT.

TABLE 1.

ACCIDENTS IN WYOMING FIELD DUE TO INRUSHES OF SAND AND WATER.

Accident, No.	Date	Mine	Location	Vein	Tapped by	Result
1	July 4, 1872	Burroughs	Plainville	Hillman	Breast	An inrush of sand and water. A pumpman, the only man in the mine at the time, easily escaped.
2	June 30, 1874	Wanamie No. 18	Wanamie	Red Ash	Breast	Gangway and workings in the vicinity were filled for some distance from the break.
3	Jan., 1882	Maltby	Swoyersville	.....	Rock Plane	Gangways were filled; also the shaft for a vertical height of 90 ft.
4	Apr. 23, 1884	Fuller	Swoyersville	Six Foot	Slope	Slope filled to the top for a distance of 900 ft.
5	....., 1884	Ridge	Archbald	Archbald	.....	.....
6	May, 1885	Ridge	Archbald	Archbald	.....	.....
7	Dec. 18, 1885	No. 1 Slope	Nanticoke	Rosa	Breast	Gangways in the vicinity were completely filled in less than an hour.
8	Aug., 1889	Fuller	Swoyersville	.....	Rock Plane	The planes and all workings tributary to it were filled with sand or water.
9	Mar. 1, 1897	Mt. Lookout	Wyoming	Pittston	Breast	A large area of the workings was filled; no men at work at the time.
10	Dec. 30, 1898	Wanamie No. 18	Wanamie	Copper	Breast	Gangway on lower level filled to a height of 2 ft. for a distance of 300 ft. Depression on the surface 100 ft. east and west and 75 ft. north and south.
11	Feb. 2, 1899	Franklin	Wilkes-Barre	Kidney	Breast	Filled gangway to a height of 3 or 4 ft. for a long distance.
12	Apr. 13, 1899	No. 2 slope	Nanticoke	Hillman	Breast	Gangways were filled for several thousand feet. Breasts had been worked 26 years previous; no men at work in the vicinity. Surface depression was 70 to 80 ft. deep.
13	Apr. 25, 1899	Bliss	Hanover	Hillman	Breast	Gangways and tunnel in the vicinity were filled tight to roof. Conical depression on surface 60 ft. in diameter and 40 ft. deep.
14	June 10, 1914	Sugar Notch No. 9	Sugar Notch	Kidney	Breast	Gangways and tunnels were filled tight to the roof. Depression on surface 150 ft. wide, 210 ft. long and 60 ft. deep.

after the cave and indicates the points where additional drill-holes were put down. Fig. 6 shows the conditions which existed in section C-C, before the accident and indicates the supposed limit of the wash. Fig. 7 shows the conditions after the accident and shows the limits of the wash as proven by the additional drill-holes. The face of breast 15 was at an elevation of +590.0 when the break occurred. The elevation of the surface directly above was +657.0 and it was thought that the bot-

tom of the wash was at +630.0. It was planned to carry the breast to +600.0. The bottom of the wash was actually at +600.0 instead of +630.0.

One of the most serious of the accidents noted was the so-called "Nanticoke disaster" of December 18, 1885, which resulted in the loss of 26 men.* The mine workings tapped a pot-hole which was subsequently found to be over 200 feet deep. The hole was 400 feet away from the present stream and was covered by a culm-bank. The thickness of the rock where the cave occurred has been estimated at from 22

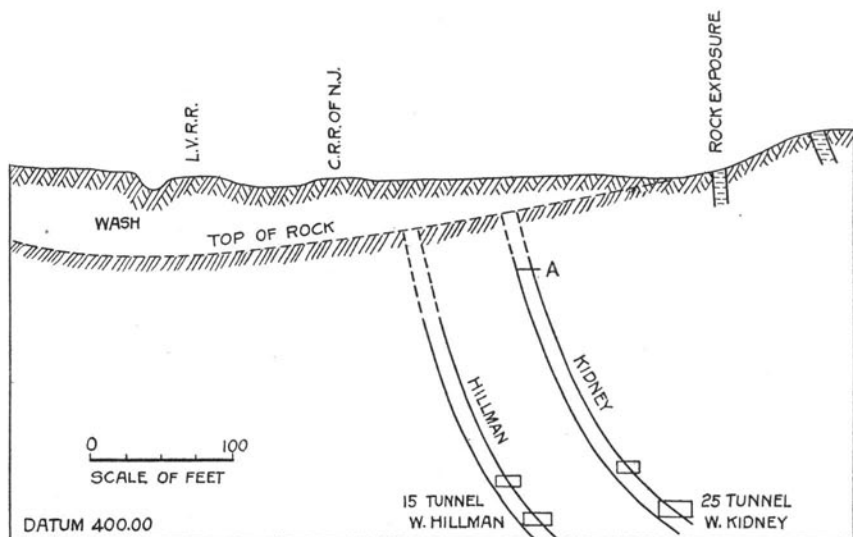


FIG. 6. SUPPOSED CONDITIONS ALONG C-C BEFORE ACCIDENT.

to 48 feet. The subsidence produced a hole in the culm-bank 300 feet across.

One of the most important occurrences of this nature in the anthracite district, as far as amount of material entering the workings is concerned, was the cave at the Prospect colliery of the Lehigh Valley Coal Co., December 12 and 26, 1915.

It was supposed that the rock over the upper bed of coal was 40 to 50 feet thick and that the surface soil was thin, these being the conditions at points near the break. It was found, however, that the rock where the break occurred was only about 10 feet thick and that the

*Williams, G. M. "Dangerous Outcrops," *Mines and Minerals*, Vol. 20, p. 410, 1900; Ashburner, C. A. "The Geologic Relations of the Nanticoke Disaster." *Trans. Amer. Inst. Min. Engrs.*, Vol. 15, p. 629, 1886-87.

remainder of the cover was loose sand, clay and gravel, apparently glacial material deposited in an old valley. Probably the break was due to the collapse of the thin rock at the bottom of a pot-hole.

Two breaks occurred, both at times when a small stream flowing over the loose material was flooded, and a large amount of this material was washed into the mine. It was estimated that about 140,000 cubic

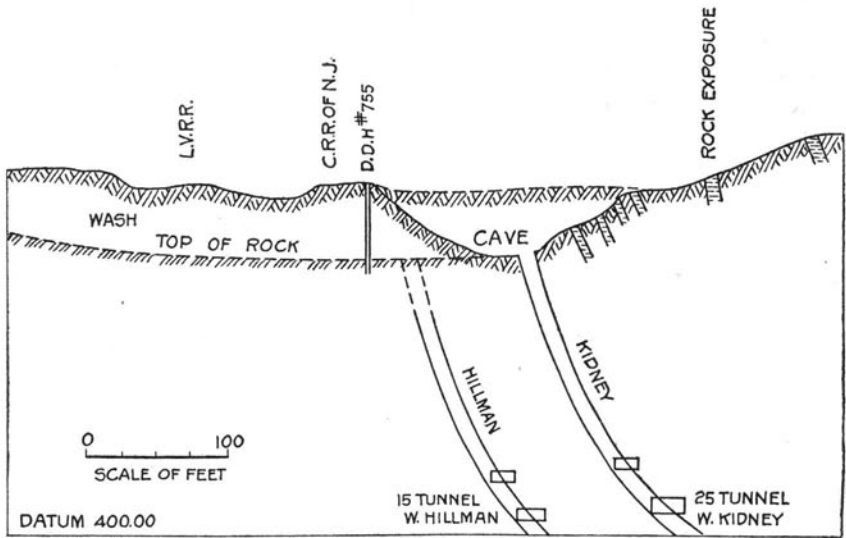


FIG. 7. ACTUAL CONDITIONS ALONG C-C AFTER ACCIDENT.

yards of earth and 350,000,000 gallons of water entered the mine. No lives were lost, but the financial loss was very considerable, as large expense was incurred in changing the channel of the stream, in addition to the cost of pumping out the water and to the loss due to interruption of the work of the colliery.*

Pennsylvania Bituminous Field.—In the bituminous fields of Pennsylvania some damage to the surface has resulted from mining operations, but few references to such subsidence are found in the technical press. Generally the deeds to the coal rights have not required the mining companies to support the surface.

In the Connellsville region the surface is of little value as compared with the coal, the topography is rugged and, although cracks extend through from the mine workings to the surface, little attention is paid to them unless they are near important structures. Mining 8 feet of

*Coal Age, Vol. 9, p. 373, 1916.

coal at a depth of 600 feet produces cracks as much as 20 inches wide. The recovery of coal varies from 84 to 90 per cent. When it is necessary to protect buildings and railroads as much as 25 to 50 per cent of the coal is left in pillars.* It has been found that at shallow depths, up to approximately 150 feet, subsidence will amount to 50 per cent of the thickness of the coal. At greater depths it will be less, approximating 25 per cent at 300 feet. The attempts to correlate data and to generalize from the data available have not been satisfactory. In discussing the observations made in southwestern Pennsylvania, J. P. K. Miller, Chief Engineer of the H. C. Frick Coke Company, said: "The great difference of strata overlying the coal no doubt contributed largely to the great variation noticed throughout the district. In some parts of this region, the stratum immediately above the coal, between it and the sand formation, varies from a few inches to 16 and 20 feet of shale. Where the sandstone is very close to the top of the coal, the subsidence is considerably greater than it is where the shale thickens; then, too, there is a very heavy percentage of limestone and sandstone in the Leisenring district, while immediately southeast of this, or between Uniontown and Fairchance, the sandstone measures rapidly thin out, and this, too, contributes to the variation in subsidence, or, in a word, where the coal has immediately over it a heavy percentage of sandstone measures, the subsidence is greater than where a thick stratum of shales appears immediately above the coal. Of course, this is only our opinion, but it seems to be the only good reason we can give for the difference in subsidence where the cover is approximately the same (thickness). As an illustration, in the territory in the vicinity of Uniontown, where heavy shales appear above the coal, we have observed 18 inches of subsidence where the cover is 300 feet; in the Leisenring district where heavy sandstone measures appear above the coal and there is a thin layer of shale immediately above the coal, the subsidence is approximately 30 inches. There is another condition that, no doubt, contributes largely in bringing about this difference in subsidences and that is the heavy layer of fireclay immediately beneath the seam of coal appearing in the Uniontown district; while very good bottom conditions—'hard bottom'—appear in the Leisenring district, and the writer believes it may be concluded naturally that this difference in the condition of the bottom section has more to do with the difference in subsidence than the first two conditions above mentioned."

*Private correspondence.

The outcrop of the Pittsburgh coal bed extends for many miles in western Pennsylvania, and above these shallow workings many sink-holes have formed. These have attracted very little public attention, as they are considered to be of only a temporary character and most of the buildings above the mined areas are frame and the damage to them has also been only temporary, for if tilted out of line, these buildings have frequently resumed their normal condition after a few months.

Observations made by another company show that the surface subsided 2 feet, 9 inches after practically all of an 8-foot seam had been removed at a depth of 400 feet. The overlying rocks consisted of shales, sandstone and limestone in alternating beds, the thickest limestone bed being 200 feet from the surface and reaching a thickness of 50 feet. There are six other beds of limestone varying from 20 to 30 feet, the total thickness of the seven beds being about 170 feet. The remainder of the column is about equally divided between fireclays, sandstones, and shales. The subsidence took place about twelve months after the mining of the pillars began.*

In the construction of the Greentree Tunnel of the Wabash Pittsburgh Terminal Railway Company in the Pittsburgh district it was found that early mining operations had removed coal from a bed immediately beneath the projected line of the tunnel and that coal had been removed from another bed overlying. W. F. Purdy, Chief Engineer, describes the conditions as follows: "When the heading of the tunnel had proceeded about 500 feet from the west portal we encountered broken ground. The material was fairly solid gray shale which was easy to drill, but none of it could be removed without heavy blasting. At first the only indication of disturbance was that the rock showed soft pockets, and a little later the strata had separated so that large pockets could be excavated without blasting. After having proceeded about 20 feet into the material which had become more or less loosened without our having been able to account satisfactorily for the nature of the ground, the bottom of the heading suddenly broke down about 30 feet back from the face of the heading, permitting partial collapse of the timbering as the settlement was about 2 feet.

"It developed that the broken ground encountered in the heading was at the apex of the mass affected by the subsidence in the mine and the top of the heading was approximately 50 feet above the mine level. Unknown to us at the time, we had been driving the heading for some

*Private correspondence.

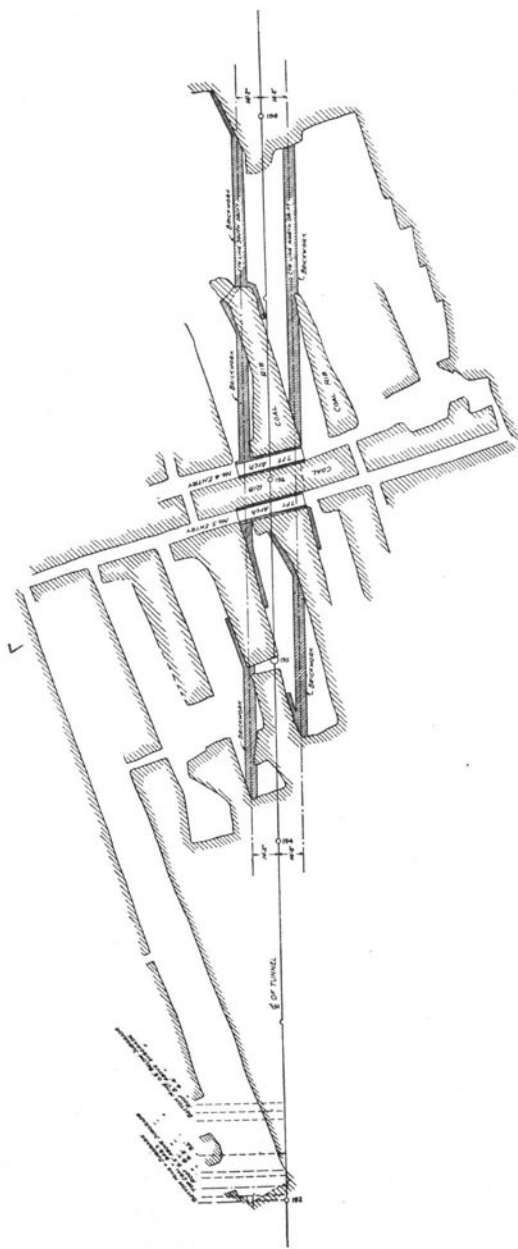


FIG. 8. PLAN OF GREENTREE TUNNEL AND OLD MINE WORKINGS.

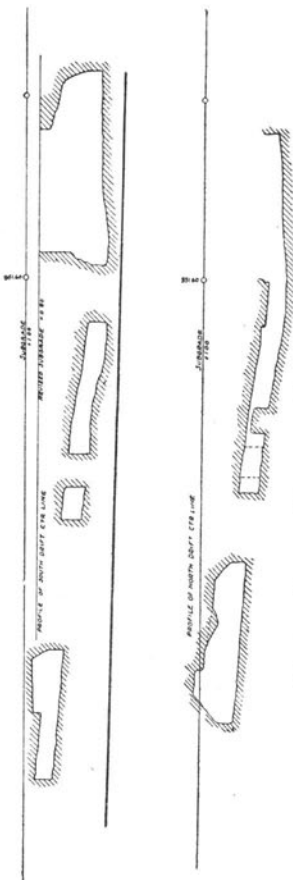


FIG. 9. SECTION THROUGH TUNNEL AND MINE.

distance over the broken ground with a wedge of solid rock between the bottom of the heading and the broken material beneath. When we had reached the point where this continually thinning wedge would no longer support the weight, the ledge broke, practically at right angles to our tunnel, and allowed the timbering to drop as before stated.

"We moved back in the heading to the solid rock and drove a shaft on a steep incline until we reached the floor of the mine about 35 feet below the bottom of our heading. There we found that a considerable area of coal had been mined several years earlier and because of a "swamp" and the apparently heavy expense for pumping the mine was abandoned after having drawn nearly all of the ribs and pillars.

"After reaching the mine level we drove two diverging drifts from the foot of the shaft until we were under the two sides of the tunnel and then carried the two drifts ahead under the prospective tunnel walls. For about 70 feet the ground was entirely broken between the mine and the grade of our tunnel and we built solid brick masonry walls 18 feet in height to provide foundation for the regular tunnel side-walls.

"After leaving the space of about 70 feet already mentioned the ribs and pillars had not been withdrawn and the falling from mine roof was not serious. At some points the roof slate had fallen in to a height about 6 feet above the normal mine roof, and at other places there had been no breakage whatever. We followed up the mine entries and rooms for a distance of about 600 feet at which point on account of the convergence of the tunnel grade toward the mine level the same elevation was common to the floor of mine and the grade of the tunnel.

"The alinement of our tunnel makes an angle of approximately thirty degrees with the rooms in the mine and the work was more complicated on that account. We built solid brick masonry walls diagonally across the mine entries and rooms under each of the two tunnel side-walls. Where there was a space of several feet between the roof of the mine and the normal foundation of tunnel walls, we built the brick walls thick enough to prevent any danger of crushing the slate rock between the brick foundation and the regular tunnel walls. When we reached the point where only two or three feet of natural shale would have been left between the roof of mine and bottom of tunnel wall we cut it all out and carried the brick work up to the grade of the tunnel.

"The tunnel lining is of concrete and the tunnel has been in service for ten years with no sign of settlement or cracking of the concrete.

"We also experienced a good deal of trouble, expense and delay on account of another coal mine above the eastern half of the same tunnel. As the top of our tunnel heading approached the bottom of the coal mine and as the intervening wedge of ground became thinner it became very difficult to support the roof of tunnel and we had much trouble on that account, and also because of the mine drainage which poured through the thin ledge of shale between the roof of tunnel and bottom of mine."

West Virginia.

Owing to the character of the topography and the low value of the surface in the coal districts, very few reliable records are available to show the extent of surface subsidence due to coal mining. Some surface movement has been noted where from 7 to 8 feet of coal has been mined and the pillars drawn at depths over 500 feet. When the thickness of the covers is from 200 to 300 feet, the disturbance is greater and "where the cover is light—from 50 to 150 feet—the cracks are sometimes from 2 to 4 feet in width and show a vertical displacement of from 1 to 2 feet."*

The problem of protecting a seam lying from 70 to 80 feet above the seam now being worked has confronted some of the coal mining companies. It is proposed to mine the upper seam before the pillars are drawn in the lower seam, as the subsidence which follows the mining of the pillars in the lower seam greatly disturbs the overlying seams and makes it unprofitable to mine them.

NATURE OF DAMAGE DUE TO DISTURBANCE OF THE OVERLYING MATERIAL.

The damage resulting from the excavation of minerals may be (a) without the mine or (b) within the mine.

In this study the damage external to the mine is the subject of investigation, the internal damage being noted only when it occurs in connection with external damage.

(a) The damage external to the mine may be due to:

1. The vertical, or horizontal, or both vertical and horizontal movement of surface material or surface structures, caused by the subsidence of the strata overlying the excavation.
2. Surface cracks or fissures due to slips, faults, or shear, or to the tension of the surficial beds.

*Private correspondence.

3. Pit-holes or caves, formed when, instead of gradual and more or less uniform subsidence over a large area, the movement is localized if the excavation is at a shallow depth.
 4. Damage by water on account of the lowering of land below the former drainage channels or the high-water levels, and by the derangement of artificial drainage systems, such as sewers in cities or tiling on farms.
 5. Interference with or destruction of natural or artificial water-supply.
 6. Miniature earthquakes occurring when large masses of rock fall over great areas.
- (b) Within the mine, damage may result from:
1. The inflow of water through cracks or breaks caused by subsidence of the strata.
 2. The inflow of sand through breaks extending to the superficial material.
 3. Local or extensive falls of roof.
 4. The failure of pillars, due to the excessive weight of the superincumbent strata.
 5. "Air-blasts" or "bumps" accompanying the sudden collapse of pillars and the fall of large areas of roof.
 6. Squeezes or creeps.

1. *Nature of Earth Movement.*—Damage to structures on the surface may be the result of either vertical or horizontal movement, or both, and engineering observations in Europe and in America show many interesting facts regarding the extent, the rate, and the duration of surface movements.

"Draw" or "pull" is the variation from the vertical of the line of fracture of rocks that break when the supporting bed or stratum is removed; in other words, the variation from the vertical of the boundary between the disturbed and undisturbed strata. In some cases this is a well-defined plane; in others a zone of indefinite extent. In the case of brittle rocks, the break will be sharp; while in the case of more yielding deposits, such as shales and loose soil, it may be impossible to determine exactly the limits of disturbance.

Several instances of the lifting of objects on the surface have been reported, but no data are available at this time to prove definitely that either a temporary or a permanent elevation of the surface has occurred.

It is claimed that at Northwich, England, where subsidence has resulted from the removal of salt, an elevation of certain streets has occurred.* In Nottinghamshire, England, where a coal seam 3 feet 8 inches thick was mined at a depth of 1,680 feet, it is claimed that there was locally and temporarily an elevation amounting to 4 inches.† Also, it is reported that an "earth tide" is evident in the diamond fields of South Africa, there being noted a rise and fall amounting to 3 inches a day, but this could have no connection with subsidence.‡

The engineer's records at the Warrior Run Colliery of the Lehigh Valley Coal Company in Pennsylvania show that there was a lateral

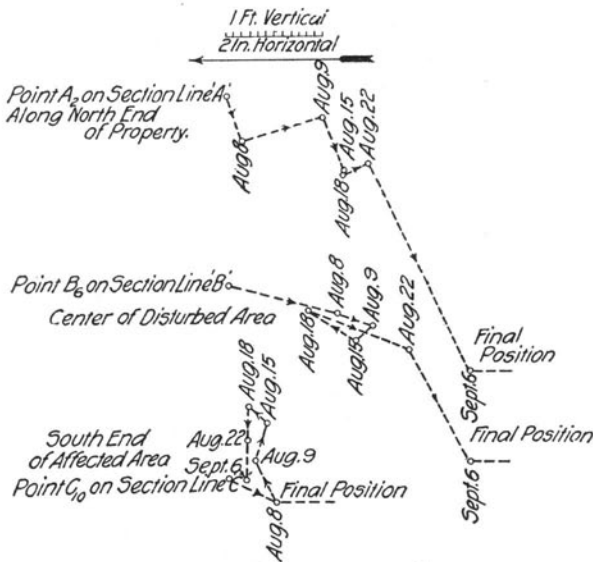


FIG. 10. LATERAL MOVEMENT OF MONUMENTS.

movement of surface monuments as well as vertical movement. (Fig. 10 shows the dates of observation and the amount of the movement.) This resulted from a squeeze in workings extending from 500 to 1,000 feet in depth on a coal seam dipping approximately 30 degrees.§

Sags of the surface, or depressions without important breaks or cracks, occur when the movement is due to the bending rather than to the breaking of the strata and when the surficial material, without sud-

*Trans. Inst. Min. Engrs., Vol. 19, 241, 1899.

†Proc. Inst. of Civ. Engrs., Vol. 135, p. 114, 1898.

‡Jour. Chem. Met. and Min. Soc. of S. A., October, 1911.

§Enzian, Charles "The Warrior Run Mine Disaster," Mines and Minerals, Vol. 27, p. 439, 1907.

den movement, accommodates itself to the new inclination of the bed-rock. Observations in the coal districts indicate that the extent and the gradient of such sags are influenced by the rate of advance of the working face, particularly in longwall mining; by the character and

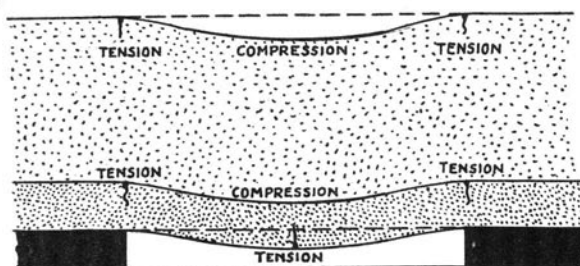


FIG. 11. TENSION AS A CAUSE OF SURFACE CRACKS.

amount of filling; and by the ratio between the depth and the lateral extent of the mine workings; as well as by geological conditions in general.

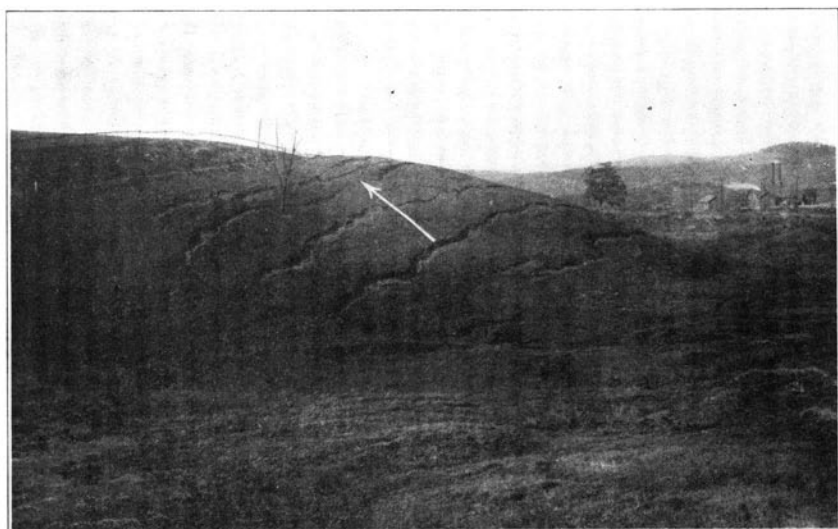


FIG. 12. SURFACE CRACKS IN WESTERN PENNSYLVANIA.

2. *Surface Cracks.*—The surface cracks and fissures that appear commonly when mining is carried on at shallow depths may be due to one of several causes. As the mine roof sags over an excavated area the bending action produces compression in the upper part of the strata

near the center of the basin or sag, while around the rim of the basin the upper strata affected are in tension which may be sufficient to cause the surface to break or crack. (Fig. 11.) If the movement is an extensive one and if the height of the surface above the axis of bending is great, the width of the fissure may be considerable. Fissures 2 feet wide have been noted in Illinois and in West Virginia. Fig. 12 shows such surface cracks in western Pennsylvania.

The formation of surface cracks by tension is well demonstrated by an occurrence in Ashland in the anthracite district of Pennsylvania.

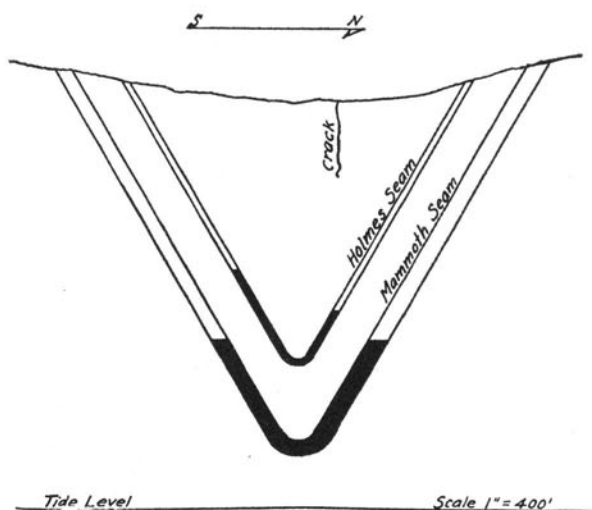


FIG. 13. SURFACE CRACKS AT ASHLAND, PA.

The crack (Fig. 13) extended for a distance of about a quarter of a mile, and was from an inch to six inches wide, causing considerable damage to property. The vertical distance to the first coal seam was over 800 feet, and later development showed that the crack did not extend to the coal. The coal along the outcrops on both the Holmes and the Mammoth seams had been removed and it is presumed that the crack was due to tension resulting from the settling of the overlying beds into the worked-out portion.*

The importance of the effect of surface beds upon draw or pull has been pointed out by A. Sopworth.† According to his observations the following classification of overlying beds may well be made:

*Foster, R. J. Discussion of Paper, Proc. Coal Mining Inst. of America, p. 147, 1912.

†Proc. Inst. C. E., Vol. 135, p. 165, 1898.

- (1). "Measures consisting of fairly equal proportions of rocky and argillaceous beds, and containing thick beds of sandstone.
- (2). "Measures including a small proportion of rocky beds, say 15 per cent, and only thin beds of sandstone.
- (3). "Variations between these two."

In the first case the edge of the subsidence will follow or lie over the excavation and in the second case it will lie over the solid coal. In the third case the draw will vary between (1) and (2).

Kay* has emphasized the serious effects which may result from the "pull over" or draw. In his opinion this may cause much greater damage than the actual downward movement. "The strata appear to bend over the goaf in a curve of radius depending on the depth, and thereby subject the strata overlying the recently-worked area to a strain (rendered passive from the movement of the face), coincident with the progress of the working face, and, owing to its great radius and slow movement, doing very little damage to surface structures of ordinary character, as a rule." If the advance of the face is stopped, buildings over the line of the face may be seriously damaged.

R. E. Cooper† called attention to the absence of pull where the overlying beds include strong layers of limestone, shale and sandstone.

Surface cracks may be due to shear. Cracks caused in this way generally are parallel, but they may constitute more than one system. If there are two systems of fissures, generally the openings due to one system are larger and more regular than those due to the other system.

Cracks may be caused by sliding of surficial material particularly where the topography is rough. The shifting of beds of clay may cause subsidence and form a sag or basin, around the perimeter of which tension cracks will appear.

3. *Pit-holes or Caves*.—When the mining is carried on at a shallow depth where there is very little solid rock cover, or when the roof fails under shear, the movement frequently causes a sharp break in the surface, forming pit-holes or caves. (Fig. 14.) Such holes may be caused by the surficial material running into the mine entries beyond the point at which the break actually occurred.‡ This type of disturbance is the cause of much damage to the anthracite mines of Penn-

*Kay, S. R. "Effects of Subsidence Due to Coal Workings," Proc. I. C. E., Vol. 135, p. 117, 1898.

†Proc. I. C. E., Vol. 135, p. 133, 1898.

‡Fig. 14 is from a photograph of pit-holes in Indiana. In this case, coal 6 to 7 feet thick had been mined at a depth of about 100 feet. The overburden consisted of about 10 feet of shale and 90 feet of drift.

sylvania.* In regions where the surface is valuable for agriculture and for building sites, pit holes are frequently a serious problem because the cost of filling may be great. Subsidence of filled material is likely to continue for some time and the value of such filled ground for building sites is generally low.

Effect of Unwatering Surficial Beds.—Considerable discussion has been aroused by the suggestion that the unwatering of water-bearing beds of clay, marl, and sand may result in subsidence, when no mining

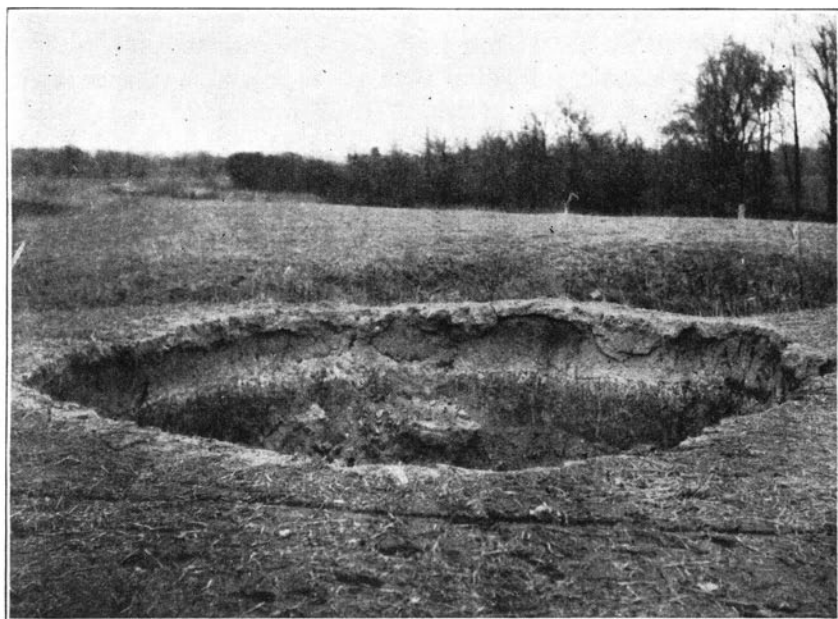


FIG. 14. CAVE IN SOFT SOIL. (Photo by H. I. Smith, U. S. Bureau of Mines.)

has been done. German engineers have had to contend with heavy beds of marl overlying the coal, and have made a number of observations upon the effect of unwatering the surficial beds. There is a difference of opinion, but possibly the majority of the German engineers have thought that unwatering will cause subsidence. It was held by many that when the surficial beds are drained by boreholes or excavation there is a reduction in volume of the beds and that sinking of the

*Bunting, D. "Limits of Mining Under Heavy Wash," Amer. Inst. Min. Eng., Bul. No. 97, p. 1, 1915.

surface will result. The mining industry was held responsible for surface damage, simply because it was acknowledged that unwatering had taken place.

In studying the subsidences about Essen in 1866 and 1868, von Dechen came to the conclusion that the subsidences and surface cracks were not directly the result of the coal workings, but that they were caused by the partial drying of the chalk marl and green sand overlying the coal measures which was caused by unwatering through the mines, boreholes and wells. He also pointed out that there was a shrinkage in volume in the chalk marl, due to the dissolving of carbonate of lime in the marl.

Later investigations led the German engineers to change their views upon the effect of unwatering. Graff made tests and showed* that drainage does not cause any changes in volume in gravel, sand, and quicksand. He concluded that subsidence will not result from unwatering if no solid material is carried away mechanically.

Tests made in the laboratories of the United States Bureau of Mines at Pittsburgh have shown that materials flushed with water do not compress nearly so much as the same material if dry. This would seem to indicate that by unwatering the strata of a mineral deposit, damage may be caused to the surface, even though no solid material is carried away.

F. Bernardi holds that the drying of beds of sand does not cause a decrease in volume or a reduced bearing power.† He reached this conclusion because in "water-soaked sand strata, the grains of sand rest upon grains of sand, and the weight of the surface is carried by these grains of sand resting upon one another and not by the water." If the drying of sand causes a decrease in volume, the wetting of sand should cause an increase.

Of the Austrian engineers Rziha held that unwatering may cause subsidence but the later writers, as Jicinsky and Goldreich,‡ who have had a better opportunity to make observations, hold that no movement occurs if the water does not carry away any solids mechanically or in solution. Data on the shrinkage of beds of loam and clay have been assembled by R. Dawson Hall.§ "A clay slime, 200 feet thick, will reduce to 50 feet and less, as a result of drainage, and though such a

*Graff "Verursacht der Bergbau Bodensenkungen durch die Entwässerung Wasserführender diluvialer Gebirgs schichten," Glückauf, 1901.

†Kolbe, E. "Translocation der Deckgebirge durch Kohlenabbau," p. 63.

‡Goldreich, A. H. "Die Theorie der Bodensenkungen," p. 15, Berlin, 1913.

§Hall, R. Dawson. "Data on Petro Dynamics," Mines and Minerals, Vol. 31, p. 505, 1910.

result is rare, . . . , yet the figures suggest what an action drainage has in shrinkage of roof coverings of mines and how even clays of great age may lose bulk by mining operations and let down the rock or surface with its buildings above them. German and English investigations* have been made of the shrinkage in air of flint clays. A flint clay drying in air will shrink in all directions 5 per cent, so that it will measure linearly only 95 per cent as much as before shrinkage. The loss in drying is 14.26 per cent, and this, if the clay were plastic, so as to give laterally with freedom, would reduce the thickness of the bed 14 feet 3 inches in every 100 feet of depth of measure."

4. *Effect on Drainage.*—In the prairie lands and the river-bottom lands of the coal fields of the Middle West, the complete removal of the coal from horizontal beds at comparatively shallow depths has been attended with the problem of the drainage of the surface. Over large areas of prairie land there may be almost no natural drainage, and if the mining of several feet of coal permits the uniform subsidence of the surface, large sheets of water may stand for a number of months over the subsided land, thereby greatly reducing its value for farming purposes. In many instances (as will be noted fully later) the value of the land for farming purposes exceeds greatly the value of the coal in the ground at the present leasing rates.

Satisfactory artificial drainage has been provided in such flat prairie land by the laying of drain-tile at considerable expense. Subsidence may seriously disturb this tiling and may make the entire drainage system of little or no value. In a district such as the Mississippi Valley, where the streams are bordered by extensive bottom lands that are little if any above the high water line, it is claimed that surface subsidence may materially increase the area flooded at a time of high water and may even produce areas that are continually under water or are too wet for farming purposes.

5. *Effect on Water Supply.*—Subsidence of strata generally results in the formation of cracks and fissures in the rock which may be sufficient to permit the escape of water from a water-bearing bed which may have been the source of the water supply of a community or of an industry; thus the fissuring of the rock beneath gravel beds may permit the drainage of the beds which have been the source of water.

Numerous wells and cisterns have been damaged permanently by subsidence due to mining. Instances of only a temporary loss of water

*Reis, H. U. S. Geol. Survey, 19th An. Report, pp. 404-406, 1897-98.

in wells have been noted in Illinois, Oklahoma, Maryland, and Pennsylvania, the wells furnishing the normal supply of water after subsidence has ceased if below the wells there are beds of such texture that the fissures will close tightly enough to hold water.

SUBAQUEOUS MINING.

The subaqueous mining of coal and other minerals may shatter the overlying strata and permit an inrush of water which will destroy life and property. A number of valuable mineral deposits have been opened at the edge of the ocean, and from time to time the workings first made on the shore portion have been extended seaward until the mining of the under-sea portion by a safe method has become the chief problem in the undertaking.

Much attention has been given to the study of pillars and of subsidence owing to the vital necessity of mining in such a manner that water may not enter the mine. Particulars regarding the working of coal seams under the water of oceans, rivers and lakes are given in table 2:*

England, Scotland, and Wales.

Coal is being worked under the sea along the coasts of the counties of Northumberland, Durham, Carmarthenshire and Flintshire in England and Wales and also to some extent off the coast of Linlithgowshire in Scotland.† The coal beds dipping under the Firth of Forth have been mined extensively. Here there are a number of faults parallel to the shore which drop the seams on the seaward side. The bed of the Firth of Forth, although very deep at places, is covered first by a stratum of very hard, stiff unstratified till or boulder clay, which covers the solid rock, while above this is a deposit of reddish plastic clay, from 30 to 40 feet thick and in places finely laminated. This covering forms a waterproof barrier and prevents the sea from reaching the underlying strata. There are four important coal seams having a total thickness of about 15 feet. The lowest one lies at a depth of 340 feet at the shaft and dips rapidly seaward. "Operations of late years have shown that seams can be worked on the longwall system under the sea, with faces from 4 to 8 feet in height, at depths which are small in comparison with those of the workings in most modern collieries. The seams have been worked in three instances to their outcrop against

*Atkinson, A. A. Trans. Inst. Min. Engrs., Vol. 23, Appendix IV, p. 644, 1901.

†Atkinson, A. A. Trans. Inst. Min. Engrs., Vol. 23, p. 622, 1901.

TABLE 2.

PARTICULARS OF COAL SEAMS WORKED UNDER THE WATERS OF OCEANS, RIVERS, AND LAKES.

No.	Name of Colliery	Name of Coal Seam Being Worked	Depth Below the Water Feet	Thickness of Coal Seam Feet	Water of Oceans, Rivers, and Lakes
<i>New South Wales</i>					
1	Australian Agricultural Company, Sea Pit or New Winning.....	Borehole	145-190	15 to 16	Pacific Ocean (a)
2	Hetton	Borehole	300	7 to 8	Pacific Ocean (b)
3	Hetton	Borehole	165-300	7 to 15	River Hunter (c)
4	Newcastle Coal Mining Company, A and B Pits	Borehole	145-170	6 to 11	Pacific Ocean (d)
5	Stockton	Borehole	240-260	7 to 8	Pacific Ocean (e)
6	Wickham and Bullock Island	Borehole	120-260	6 to 16	River Hunter and Throsby Creek (f)
<i>Cumberland</i>					
7	Harrington	Main Band	126-168	6½	Irish Sea (g)
8	Workington* .....	.....	90	10	Irish Sea (h)
<i>Northumberland</i>					
9	North Seaton and Cambois	Low Main	360	4 to 6	German Ocean (i)
<i>Durham</i>					
10	Ryhope**	Maudlin	1,830	7	German Ocean (j)
11	Seaham**	Maudlin	1,830	5	German Ocean (k)
		Hutton	.....	4½	German Ocean (l)
12	Wearmouth**	Maudlin	.....	5½	German Ocean (m)
		Hutton	.....	4½	.....
13	Whitburn**	Maudlin	.....	.....	..... (n)

*Dunn, M. "A Treatise on the Winning and Working of Collieries," p. 230, 1848.

**Information derived from Mr. Thomas Bell's "Notes on the Working of Coal Mines Under the Sea, and Also Under the Permian Feeder of Water in the County of Durham," Transactions of the Manchester Geological Society, Vol. 36, pp. 366 to 399 and 554 to 559, 1899.

(a) Workings extend about 600 feet beyond high-water mark. The pillars are 96 feet by 36 feet, the bords are 18 feet wide and the cut-through or cross-holings 9 feet wide. About 4 feet of top coal is left next to the roof.

(b) Workings extend about 500 feet beyond high-water mark.

(c) The pillars are made 90 feet by 24 feet; the bords are 18 feet wide, and the cut-through or cross-holings 9 feet wide.

(d) The workings extend about 800 feet beyond high-water mark, including the windings. About 3 feet of top coal is left next to the roof and a little bottom coal is also left.

(e) Workings extend about 2,500 feet beyond high-water mark. The pillars and bords are of the same dimensions as those at the Hetton colliery.

(f) The pillars and bords are of the same dimensions as those at the Hetton colliery.

(g) About 2 feet top coal and slate is left on, next to roof, in narrow places. The minimum thickness of cover has been fixed at 126 feet. The pillars are left 57 feet by 52 feet, the bords are 14 feet wide, and the walls or cross-holings are 9 feet wide. Thus, 32 per cent of coal is worked, and the pillars are not crushed. About 66 per cent of the overlying strata is compact sandstone. Feeders of water, occurring in workings where minimum cover had been reached, have since become quite dry.

(h) The workings extend 4,500 feet under the sea. The bords were 15 feet wide and the pillars 21 to 24 feet thick. The manager, in order to increase the output of coal, commenced to rob the pillars, this resulting in falls and feeders of salt water. Warnings were given as to what would happen, but these were unheeded. On July 30, 1837, the sea broke in and 36 men and boys and a number of horses were drowned, and the colliery irrecoverably destroyed.

(i) At Cambois bord-and-pillar longwall is being worked under the sea and headings are driven 300 feet in advance to ascertain the existence of any fault or break in the strata.

(j) The workings extend 5,500 feet from low-water mark under the ocean, and over 400 acres of goaf have been formed.

(k) The workings in the Maudlin seam extend 5,000 feet under the ocean and about 85 acres of goaf have been formed.

(l) Twelve pillars, each 120 feet by 90 feet, have been removed in this seam under the goaf of the Maudlin seam, rising seawards from 2 to 2½ inches per yard for the last 1,200 feet.

(m) Workings extend 4,000 feet under the ocean.

(n) Workings extend 4,000 feet under the ocean.

the boulder clay, at depths from 137 to 400 feet below high-water mark, without any accident.** The thickness of the cover under which the whole of the coal seam has been mined is less in this mine than in any other submarine mine in Great Britain.

The workings extending farthest seaward are reported to be those at Whitehaven, which at the William pit extend under the Irish Sea a distance of 19,000 feet (1901) from high-water mark. The coal seam is 10 feet thick and is worked by rooms 18 feet wide with pillars 75 feet square. There is also a higher seam about 7 feet thick which has been worked in places.† North of the William pit is an old mine which has been flooded.

The mining of under-sea coal will become a very important matter in time in Scotland.‡

Restrictions have been imposed upon the working of Crown coal in Great Britain. In the case of one colliery the working of coal under the ocean, unless there is at least 126 feet of strata between the bed of the sea and the top of the seam, and the removal of pillars or the adoption of the longwall system, where there is less than 360 feet of intervening strata are prohibited. Under specified conditions the entire removal of the coal-seam is permitted where the minimum thickness of cover is 270 feet.§

It has been advised that the workings of coal on the Northumberland coast be limited to areas where there is a minimum of 270 feet of solid strata above the seam. The bed of the ocean generally consists in this vicinity of a stiff clay.§

Australia.

In New South Wales coal mining has been carried on extensively beneath the River Hunter, the Pacific Ocean, and its tidal waters.** Four seams have been worked in parts of this area, the total thickness ranging from 19 to 43 feet. Operations in the vicinity of the outcrop are dangerous because channels in the coal measures become eroded by old streams, and later these channels become filled with alluvial deposits. In general, the coal measures dip slightly toward the ocean,

*Cadell, H. M. "Submarine Coal Mining at Bridgeness, N. B." *Trans. Inst. Min. Engrs.*, Vol. 14, p. 237, 1897.

†Moore, R. W. *Trans. Inst. Min. Engrs.*, Vol. 23, p. 660, 1901.

‡Atkinson, J. B. *Trans. Inst. Min. Engrs.*, Vol. 14, p. 253, 1897.

§Atkinson, A. A. *Trans. Inst. Min. Engrs.*, Vol. 23, p. 629, 1901.

§Robertson, J. R. M. Discussion. *Trans. Inst. Min. Engrs.*, Vol. 28, p. 133, 1904.

**Atkinson, A. A. "Working Coal Under the River Hunter, the Pacific Ocean, and Its Tidal Waters, Near Newcastle, in the State of New South Wales." *Trans. Inst. Min. Engrs.*, Vol. 23, p. 622, 1901.

but there are many local dips and faults. The usual dip is given as 1 in 36. There are thick deposits of clay covering the outcrops in places.

Owing to the weakness of the roof a number of inundations have resulted at inshore mines from letting down the sand overburden. In consequence of a fall of roof there was a rush of water into the Ferndale Colliery in 1886 and a miner lost his life.* A commission was appointed to investigate this accident and the report submitted included a review of conditions at all the collieries in the district. The title to the coal beneath the River Hunter and the tidal waters resides in the Crown and the leases to these coal lands now include regulations controlling the method of mining beneath bodies of water, with the view of protecting life and also of preventing large volumes of water entering old workings, and thereby interfering with the mining of the coal in the adjacent area.

The mines of the district use the pillar-and-room system. The dimensions of pillars and rooms vary, but in general 50 per cent of the coal is recovered. The practice in a number of the mines is to drive 18-foot rooms, leave 24-foot pillars, and recover part of the pillar coal. When the pillars were left only 18 feet wide on first mining a number of crushes resulted. Owing to the presence of thick, impervious beds of clay no water entered the mines where these crushes occurred, although at equal depths on land the crushes caused surface subsidence and some damage to buildings. In one of the mines the rooms are 18 feet and the pillars 36 feet.

The quantity of water being pumped from the mines varies from 50 to 600 gallons per minute and in most places this water is decidedly salty. Vertical boreholes are put up to determine the thickness and character of the overlying beds.

In determining the safe working limit under the ocean the following conditions have been considered:

- (1) The character of the overlying strata, with special reference to loose deposits of alluvium or beds of clay between the bed of the ocean and the coal seam.
- (2) The presence of faults and dykes in the strata.
- (3) The dimensions of pillars to be left and the width of openings to be made.
- (4) The utility of leaving coal next to the roof in some cases.

*New South Wales Royal Commission on Collieries. Report on the Accidents at Ferndale Colliery, p. 17, Sydney, 1886.

The special conditions of working under tidal waters prescribed in the leases are notably as follows:

(1) The maximum width of rooms shall be 18 feet and the minimum width of pillars 18 feet.

(2) The pillars 18 feet wide shall not be removed.

(3) All headings and rooms shall be driven on sights.

(4) All workings shall be surveyed accurately every three months. All dates of working must be shown on the plan.

(5) The plan of the mine shall contain a faithful record of all dykes, fissures, etc., and shall indicate all excavations as they actually exist.

(6) In one road of every pair of leading headings, a borehole shall be kept going 10 feet in advance, and all leading headings shall be driven at least 150 feet in advance of the working rooms.

(7) When dykes or fissures are struck in the boreholes, precautions must be taken to protect against possible danger which may result from weakness of roof or flow of water when the dykes or fissures are penetrated by the heading.

(8) The coal under the ocean should not be attacked until after a large goaf has been made by extensive workings under the mainland.

(9) The most accurate information available shall be obtained as to thickness and character of the strata and estuarine deposits overlying the coal seam before commencing to work it.

Similar conditions are specified for working under the sea except as follows:

(1) The minimum width of pillar shall be 24 feet.

(6) All leading headings shall be driven at least 300 feet in advance of the working rooms.

(9) Boreholes penetrating the roof for a height of 30 feet above the coal seam shall be driven on the leading headings 300 feet in advance of the work and 60 feet apart.

Newfoundland.

At Wabana there is a series of iron ore beds which lie in a synclinal trough, one edge of which passes through Belle Isle. The three uppermost beds are mined in both the land and in the submarine areas. The ore beds pass beneath Conception Bay and apparently outcrop in the floor of the bay. The center of the basin is estimated to be about three miles from shore. The lowest bed is from 15 to 30 feet thick.

The method of mining is pillar and room, the rooms being 250 feet long and turned on 35-foot centers with 20-foot pillars.

The development in the submarine territory is sufficient to allow an annual output of 1,000,000 tons, and the total ore reserve has been estimated at practically 400,000,000 tons after proper allowance was made for pillars, faults, and poor zones. The principal ore bed outcrops on Belle Isle and dips seaward so that at high water mark it has a depth of 70 feet; at 3,000 feet from shore the bed is 268 feet deep and has 180 feet of cover. The average grade of the slope is 16 per cent.* According to a private communication from E. E. Ellis, Geologist, Tennessee Coal, Iron & R. R. Co., Birmingham, Ala., 1913, the longest slope at the Wabana mines was 7,500 feet and the end was 6,000 feet under the water.

Cape Breton Island.

The coal measures of Cape Breton Island extend under the ocean, and a number of the coal seams have been worked in these submarine areas. The measures dip at a steep angle, while the sea floor dips at a moderate angle so that the thickness of cover increases rapidly. Owing to the rapid erosion of the outcrop by the sea, some of the seams have been lost. The Mabou mine was flooded from the ocean,† because of a break in the roof in 1909, and the Port Hood Colliery was lost by a flood resulting from the entrance of water through a feeder which was opened when pillars were extracted at a point where 942 feet of solid strata were supposed to lie between the coal seam and the floor of the ocean.

The workings of some of the companies have already been extended seaward a distance of $2\frac{1}{2}$ miles from high-water mark and it is probable that in the future a large part of the coal output will be obtained from these submarine fields. The government has prescribed regulations to control the size of openings and methods of working under shallow cover.‡ Where the cover is less than 180 feet the coal may not be mined; mine openings may be driven where there is not less than 100 feet of cover. Where there is less than 500 feet of solid cover the workings must be divided into sections not more than one-half mile square and a coal barrier not less than 90 feet thick must be left around each section. The barrier may be pierced by not more than four openings, not more than 9 feet wide by 6 feet high. In 1904

*Cantley, F. "Wabana Iron Mines." Canadian Min. Inst., Vol. 14, p. 274, 1911.

†"Coal Mines Under the Sea," Coll. Eng., Vol. 34, p. 17, 1913.

‡Coal Mines' Regulation Act of 1912, Sec. 54, Nova Scotia.

the government mine inspectors and the management of the Dominion Coal Company agreed upon the size of pillars to be left in the mining of submarine coal.*

The dimensions of rooms and pillars, the percentage of coal left in the form of pillars, and the thickness of cover are shown in Table 3.

TABLE 3.

DIMENSIONS OF ROOMS AND PILLARS, DOMINION COAL COMPANY.

Depth of cover (feet)	Harbour Seam*		Hub and Phalen Seams**		Percentage of coal left in pillars
	Room width (feet)	Size of pillar (feet)	Room width (feet)	Size of pillar (feet)	
200	20	27 x 75	20	30 x 75	51
250	20	27 x 75	20	30 x 75	51
300	20	30 x 75	20	34 x 75	54
350	20	33 x 75	20	36 x 75	56
400	20	36 x 75	20	42 x 75	58
450	20	39 x 75	20	46 x 75	60
500	20	42 x 75	20	50 x 75	61
550	20	45 x 75	20	54 x 75	63
600	20	48 x 75	20	58 x 75	64
650	20	51 x 75	20	62 x 75	65
700	20	54 x 75	20	66 x 75	66
750	20	57 x 75	20	70 x 75	67
800	20	60 x 75	20	74 x 75	67
850	20	63 x 75	20	78 x 75	68
900	20	66 x 75	20	82 x 75	69
950	20	69 x 75	20	86 x 75	69
1,000	20	72 x 75	20	90 x 75	70

*Thickness mined from Harbour Seam, 6 feet.

**Thickness mined from Hub and Phalen Seams, 9 feet.

British Columbia.

A disaster† which may be compared with those occurring in subaqueous mining resulted when the workings of the old Southfield Colliery near Nanaimo, British Columbia, tapped the drowned workings of the South Wellington Mine No. 1 of the Pacific Coast Coal Company on February 9, 1915. The inrush of water resulted in the death of 20 men. It was believed that the new workings were 450 feet away from the water and it was planned that a 100-foot pillar should be left between the water and the new workings. At the time of writing this report no evidence is available showing whether or not the Coal Mines

*Dick, W. J. "Conservation of Coal in Canada," p. 35. Toronto, 1914.

†"Twenty Men Drowned in Mine Near Nanaimo, B. C." Coal Age, Vol. 7, p. 374., 1915. Watson, R. L. "Coal Mining on Vancouver Island." Mines and Minerals, Vol. 21, p. 249, 1901.

Regulation Act was being complied with; namely, that drill holes shall be kept in advance of the workings.*

Japan.

A large proportion of coal is mined under the ocean in Japan.†

The most serious accident in the whole history of subaqueous mining occurred in this country on April 12, 1915, when 237 men were killed by the flooding of Higashimiso Colliery. The mine is situated in Ube, Yamaguchi-ken and the chief production is from two beds lying wholly under the sea. The output is about 500 tons per day. Four shafts were sunk on the shore, each 119 feet deep, from which two beds are worked to a distance of about 4,000 feet from the coast.

The cause of the accident was the entering of water into the underground workings through a fault in a bed of sandstone 155.4 feet thick, above which there is an alluvial deposit of clay and sand 82.6 feet thick.

A small flow of water occurred when the fault was first reached. The final inrush followed the breaking of a hole about four feet square in the floor of an entry of the upper bed, a few feet back from the fault. Through this the water entered so rapidly that the mine was completely flooded in two hours. The quantity entering was estimated at 392,000 cubic yards. The sea bottom was lowered 60 feet over a small area showing that a considerable amount of solid matter was washed in.

The opening was apparently sealed by the solid material and it was planned that the mine should be reopened by filling the depression in the sea bottom with clay and sand, pumping out the water, and building dams to protect the workings from any future break.‡

INDUSTRIES AND INTERESTS AFFECTED BY SUBSIDENCE.

Surface subsidence involves more than the question of the present value of the land; in many instances the fundamental problem involves the relative present and future importance of various industries and interests. Among the most important of these are agriculture, transportation, and the various interests of municipalities.

*"Where a place is likely to contain a dangerous accumulation of water, the working approaching such place shall not exceed eight feet in width, or such greater width as may be permitted by the Chief Inspector of Mines, and there shall be constantly kept at a sufficient distance, not being less than five yards in advance, at least one borehole near the center of the working, and sufficient blank boreholes on each side. (British Columbia Laws, 1911, Chap. 160, Part XI, Rule 14.)"

†Trans. Inst. Min. Engrs., Vol. 28, p. 133, 1904.

‡Colliery Engineer, Vol. 36, p. 19, 1915.

1. *Agriculture.*—In the consideration of the agricultural interests involved, attention must be directed to the probabilities of subsequent use for agricultural purposes of land not tilled at present. Probably in no state where mining is important is the value of farm lands in the mining districts higher than in Illinois. It will be shown in another bulletin how the present value of these lands for mining purposes (removing all the merchantable coal) and the present value for farming purposes compare. It has been predicted that the value of the fertile lands of the "corn belt" will increase greatly in fifty years.

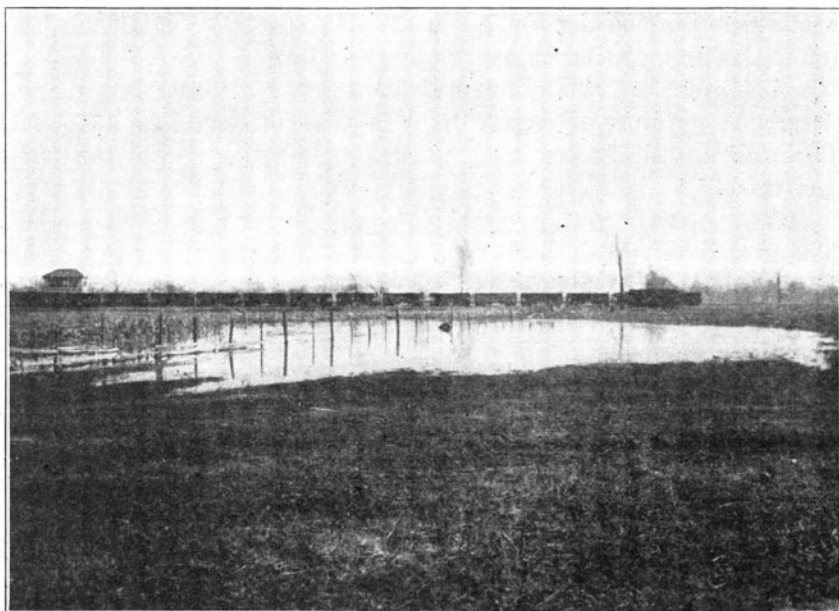


FIG. 15. POND FORMED BY SUBSIDENCE.

An agricultural expert has expressed the belief that northern Illinois land will sell for from \$400 to \$500 per acre, and the best land in the southern counties for \$200 by the year 1965.

In the longwall field of northern Illinois, where it is claimed that mining has lowered the surface so that drainage is deranged, it is estimated that large drainage projects have cost from \$15 to \$40 per acre. Fig. 15 illustrates the formation of a pond in a nearly level country by subsidence after mining. Coal of no greater thickness has been mined and is being mined in adjacent states. Estimates of the

coal resources of Illinois show that only twenty per cent of the coal occurs in beds more than four feet thick and of the total area (37,486 square miles) underlain by workable coal beds, 32,979 square miles do not contain coal more than four feet thick. Over this great area it is possible that sometime mining by the longwall system may produce subsidence unless a filling system is used that is more effective than any at present in use. This statement regarding the thin coal beds in Illinois applies as well to large areas in Michigan, Ohio, Indiana, Kentucky, Missouri, Iowa, Kansas and several other states, and it is evident that the importance of the subject of subsidence will be even greater in the future than at present.

2. *Transportation.*—Surface subsidence may interfere seriously with transportation by injury to the beds of canals and railroads and the caving of highways and streets. As previously noted, mining in Great Britain and on the continent has necessitated the raising of the banks and the filling of the bottom of many canals. In some instances, canals have been maintained on grade, while the land which they traverse has subsided as much as 20 feet. The necessity for protection of these interests has become so great that laws have been enacted which require that thirty days' notice be given of mining under railways, reservoirs, buildings, or pipes or within a prescribed distance.*

The practice regarding the protection of the right of way of railroads has differed from time to time and has varied also in different countries. The general policy in Europe seems to be to remove all the coal if possible, and the tendency on the continent is to use filling under railways in order to reduce the amount of subsidence.

In the United States many of the great railway systems do not grant the right to mine coal beneath the right of way, if the company has ever owned the coal right. However, coal has been mined under many branch lines and under some of the main lines of railroads traversing the coal districts. Fig. 16 shows the effect of one subsidence in southern Illinois. In the anthracite fields of Pennsylvania many instances might be cited of subsidence of railway tracks. No serious accidents have resulted, as the railway companies have guarded carefully all points where movement is feared. There are no laws regulating mining under railways in the United States. When a pit hole or cave extends to the surface near or under a railway track, the problem of restoration is principally a problem of filling. Good

*Cockburn, J. H. "Minerals Under Railways and Statutory Works." Trans. Inst. of Min. Engrs., Vol. 39, p. 104, 1909-10.

illustrations are found in some of the iron mines of the Lake Superior district, where extensive filling has sometimes been necessary to preserve the grade of tracks, amounting in one case to more than 50 feet.

When the movement is gradual and principally a horizontal one due to tension or compression the problem is much different. In Ger-



FIG. 16. DISTURBANCE OF GRADE BY SUBSIDENCE.

many many observations have been made upon railway track subject to tension or compression on account of subsidence over mines. In one instance, because of the crowding of the ground toward the center of the subsiding area, track 150 feet (50 meters) in length had to be shortened from 1 to 2 inches (3 to 5 cm.). Rails were buckled up or to the side, and the crowding forward of the rails and ties caused the earth or ballast to be pushed forward or crowded up and an open space appeared along one side of the tie. These spaces have been noted as much as one-third of an inch wide. In one sag in which the maximum subsidence was about 3 feet (1 meter) in five years it was necessary to shorten the rails 2.66 meters (70 cm.) in a total distance of 658 feet (200 m.). When the track was in tension the rails were stretched and at times the ends were broken.* When the principal horizontal movement is across the right of way, the trouble is easily seen on account of the effect on alinement.

The effect of surface subsidence upon bridges has been noted by

*Nolden "Influence of Mining Upon Buildings and Railways." *Elektrische Kraftbetriebe und Bahnen*, Oct. 4, 1913.

European engineers, including many British engineers.* English engineers suggest steel construction, well-tied abutments and wings, and plenty of height so that there will be sufficient clearance after the bridge has been lowered by the removal of the coal. There has been a difference of opinion in regard to the adaptability of arched or girder bridges. In the reference noted, an example is given of the mining of a seam, 7 feet 6 inches thick, at a depth of 216 feet beneath an arch of 20 feet on the main line of a railroad. The arch was not damaged by subsidence. It was conceded that arches from 50 to 60 feet long would not be advisable under similar conditions.

In 1868 several bridges were built in England on land that was known to be subsiding on account of the mining of the coal, and special precautions were taken to preserve these bridges. The rails were carried on wrought iron girders and cross girders. The foundation was carried deep enough to permit the construction of a concrete base 4 feet thick. On this base was laid two courses of elm planking, each 4 inches thick, on which four courses of brick footing were built, and on these four courses was laid a hoop iron interlaced frame, 4½-inch mesh, extending over the whole of the abutments and wing walls. This arrangement was repeated every four courses. Later, in some places, the foundation sank as much as 4 feet, but the whole bridge was lowered unbroken, and it was necessary only to lift the girders and the track to grade.†

Experience has shown that the damage to a bridge will be least if the workings (longwall) approach it broadside. The working face will pass under the structure much more quickly with that plan of working and there will be probably less difference in elevation between the ends of the structure at any stage of the subsidence.

In the construction of the Hull and Barnsley Railway across the South Yorkshire coal field, which it traversed for twelve miles, the problem of supporting bridges was of great importance. Owing to the great value of the coal beds, the plan of reserving coal pillars was given up. W. Shelford‡ advocated the separation of the bridge masonry into parts which could subside independently of each other, but should have the materials in each part bonded together. Several bridges were designed on this principle with abutments and wings separated only by a straight joint of mortar, which was concealed by a pilaster.

*Kay, S. R. "Effect of Subsidence Due to Coal Workings Upon Bridges." Proc. Inst. of Civ. Eng., Vol. 135, p. 114, 1898.

†Lynder, J. H. Proc. Inst. of Civ. Eng., Vol. 135, p. 161.

‡Proc. Inst. Civ. Eng., Vol. 135, p. 164, 1898.

A large bridge built in 1884 after this plan subsided 3 feet in 1891. The wing walls separated from the abutments, but the abutments themselves were uninjured and subsided bodily, so that they were only 3 or 4 inches out of plumb. When subsidence had ceased the wings were repaired and the bridge was again placed in service.

The effect of subsidence upon railroad tunnels has been noted previously, particularly in the construction of the Merthyr tunnel in Wales, and the Greentree tunnel at Pittsburgh, Pa.

3. *Municipalities.*—As previously noted, many towns in Europe



FIG. 17. BREAK IN SIDEWALK DUE TO SUBSIDENCE.

and America have been damaged by subsidence caused by mining. The damages to property in municipalities may include:

(a) *Injury to Streets, Sidewalks, and Transportation Lines.*—When pit-holes or caves occur, it becomes necessary to fill until subsidence has ceased and then reconstruct the street upon the most satisfactory grade. When there is horizontal movement, due to tension or compression, rather than caves, the streets, curbing, and sidewalks may be crushed or heaved (Fig. 17), or there may be tension great enough to cause serious cracks. This trouble has become so severe in certain

German cities that in the sections where compression occurs the gutters and curbs are laid so as to have elastic and waterproof joints. When large gaps are left in construction between curbstones they are covered with strips of sheet iron about 2 inches wide. In order to prevent the overturning of curbing, due to compression occurring transversely, the flagging is made narrower than the sidewalks and a strip of material that will permit compression is laid between the flagging and the curb. Coherent paving, such as asphalt, cement, and concrete, is not used because it would be cracked or crushed.*

(b) *Injury to Buildings, Towers, and Chimneys.*—This may be due to caves, or to tension, compression, or twisting. Large high buildings suffer more than low buildings covering but little ground. Masonry and concrete structures are damaged more than those of wood.

E. Kolbe has discussed at some length the nature of the damages to buildings,† and has pointed out the various factors and conditions with which one must deal in preserving buildings upon land which has subsided as follows:

- (1) A building may sink wholly or in part into a surface break.
- (2) A building may stand upon the edge of a break and be suddenly and violently twisted or wrenched and shaken.
- (3) A building may be located in the mining area and may be subjected to the earth movement and be damaged by the jamming of the adjoining houses.
- (4) A building lying over the mined area may sink slowly in the subsidence basin without undergoing greater damage than being placed in an inclined position.
- (5) A building may suffer on account of the shock resulting from a fall of roof in the mine.

The types of cracks in brick buildings particularly around and between (Fig. 18) windows have been noted by Kolbe, as shown in the accompanying illustrations. As the illustrations show, the fracture generally follows the joints of the mortar, as these offer the least resistance. When cut stone window sills and lintels are used (Fig. 19), the fracture naturally follows upward around the stone without cracking it. In long brick or tile walls without openings, as for example walls (Fig. 20) surrounding estates, there may be three types of fractures in relation to direction:

*Nolden "Influence of Mining Upon Buildings and Street Railways." *Elektrische Kraftbetriebe und Bahnen*, Oct. 24, 1913.

†Kolbe, E. "Translocation der Deckgebrige durch Kohlenabbau." Essen, 1903.

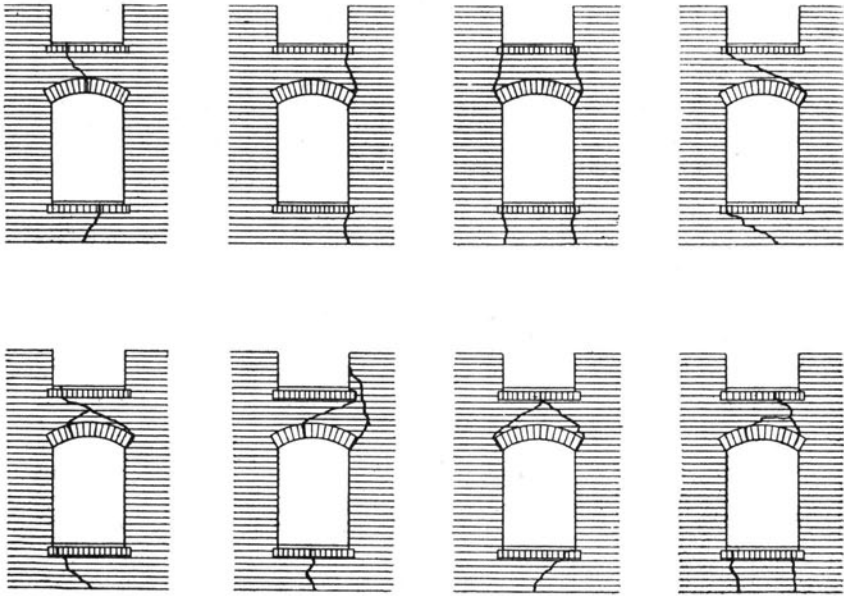


FIG. 18. CRACKS IN BRICK BUILDINGS.

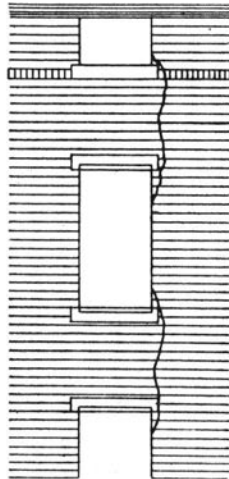


FIG. 19. EFFECT OF SUBSIDIENCE ON STONE LINTELS AND SILLS.

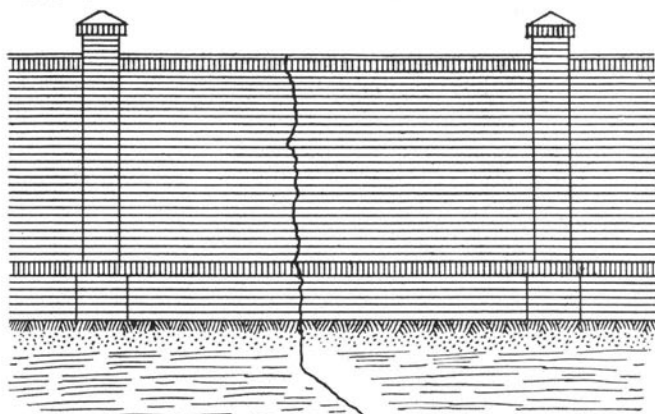


FIG. 20a.

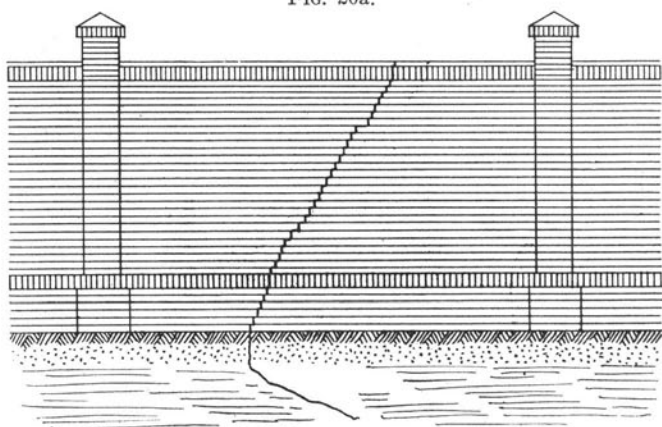


FIG. 20b.

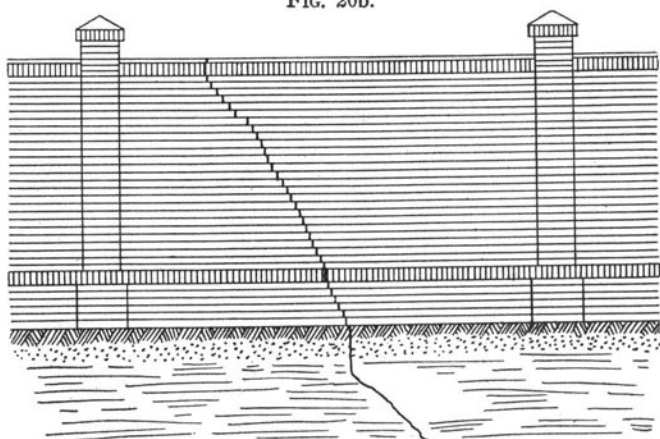


FIG. 20c. CRACKS IN LONG WALLS.

(1) The fracture may go perpendicularly up the wall and break the stone coping. (Fig. 20a.)

(2) It may extend diagonally away from the plane of the crack in the ground following the joints in the brick work. (Fig. 20b.)

(3) It may extend along the joints of the brick work diagonally in the same general direction as the plane of fracture in the ground. (Fig. 20c.) The second type is of most frequent occurrence. The same three types of fracturing are characteristic also of high enclosing walls, partition walls, and fire walls and chimneys.

Buildings may be damaged by side movement in which structures are crowded upon each other. When the mortar in masonry walls is cracked, the arches over doors and windows fail and increased pressure is thrown upon adjacent sections of the structure. When buildings are located over the edge of a pillar or on the side of a trough caused by subsidence, the cracks may extend in step fashion diagonally across a masonry wall. Secondary stresses may cause additional cracks in other directions. An example of this type of damage is shown in Fig. 21, which is an elevation of a post office. The cracks extend in the same general direction as the cracks in the ground.

In Germany, where subsidence has been anticipated, large buildings have been erected in sections from 60 to 120 feet long and these sections have been reinforced in all directions by rods and plates so that they will withstand both tension and compression. The joints between the sections have been calked with suitable material or protected with a covering. When buildings are not of great value European engineers have removed the coal as rapidly as possible and completely if possible, advancing the working face in a direction at right angles to the axis of the most important structure. When such precautions were used, the working of two 4-foot seams of coal at a depth of 600 to 780 feet in England caused practically no damage to two rows of 120 cottages.*

When the structures are important and it is estimated that the damage caused by subsidence will exceed the value of the coal, pillars may be left or filling introduced to prevent or reduce the subsidence.†

The problem of protecting important public buildings has received serious attention in Scranton, Pennsylvania. In several instances buildings have been erected on reinforced concrete piles constructed upon the

*Longden, J. A. "Effect of Coal Workings on the Surface." *Colliery Engineer*, Vol. 11, p. 5.

†Spencer, W. "The Support of Buildings." *Trans. Inst. of Min. Eng.*, Vol. 5, p. 188, 1892-93.

rock underlying shallow coal beds which had been worked by the pillar-and-room method and of which the roof had fallen or seemed likely to do so. Engineers Griffith and Conner made an inspection of the conditions of mining beneath the city and school properties. The tabulated results of their inspection indicate that some coal has been mined under

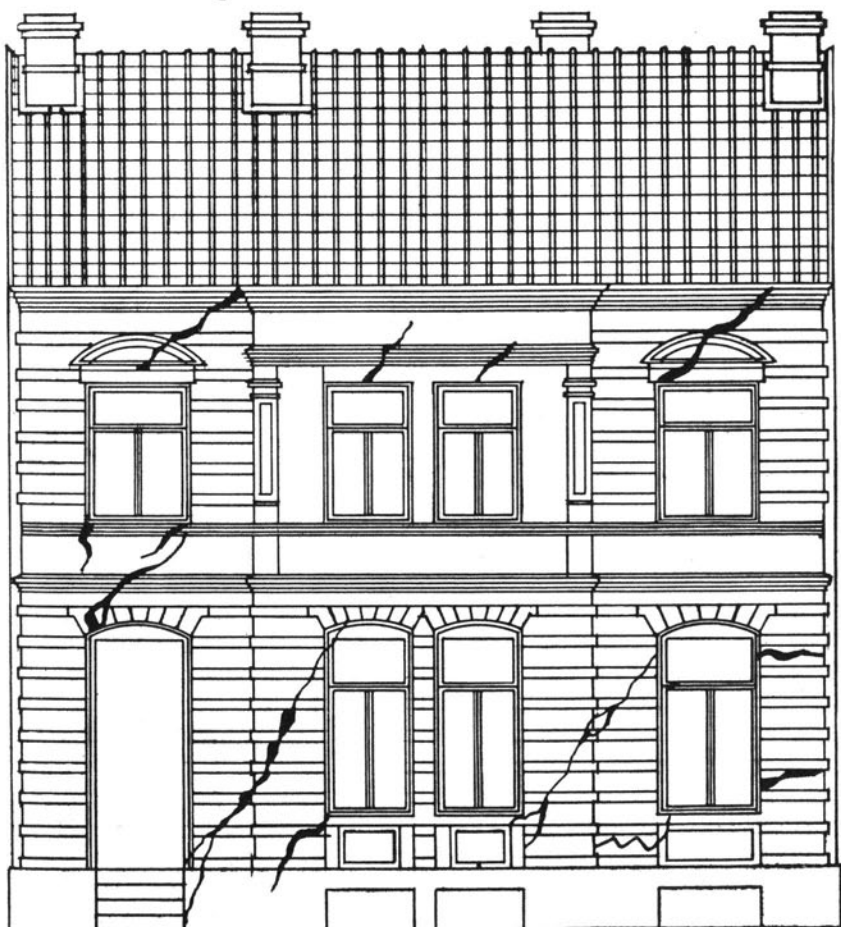


FIG. 21. CRACKS IN MASONRY WALL.

most of the buildings and that in a number of instances mining has been carried on in several beds.* Several of the buildings have been damaged by subsidence. The suggestions (*op. cit.*, p. 60) by these engineers of precautionary measures will be considered later.

*U. S. Bureau of Mines, Bul. No. 25, pp. 19-43, 1912.

The report of Enzian, Johnson, and Williams on the extent of damage done, states the results of their examination as follows:

"In the consideration of a plan which might assist in the adjustment of property damaged we considered it important to compile the following information in connection with the properties of the thirteen city blocks which have been more or less subjected to the influence of subsidences that have occurred from time to time. The total assessed valuation of these properties is \$1,430,000. The assessed valuation of the properties actually damaged is \$411,000. The estimated damage to properties actually affected is \$68,700, or about 17 per cent of their assessed valuation. The estimated damage to all the properties in the thirteen city blocks amounts to approximately 4.7 per cent of their assessed valuation. This estimate does not take into consideration any damage that may have been done to public property."*

(c) *Injury to water, gas, and steam lines.*—This type of damage is not unusual in communities in which mining has been carried on extensively. The cracking of water mains has caused damage not only through the direct injury to the main and the temporary failure of the water supply, but also through the escaping water, which in a number of instances has flooded buildings, washed out foundations, and destroyed streets, roads, and earthen structures. Fires have resulted from the escape of gas from broken gas mains. Necessity has brought about the use of expansion and compression joints of various types for preventing or reducing the damage to such lines. The need for frequent inspection of such pipe lines has made it important that they be laid in tunnels or large conduits.

(d) *Injury to sewers and sewage plants.*—Sewer lines as well as steam, water, and gas mains may suffer from subsidence, but in the case of sewer lines the difficulties are even greater, since these lines are generally constructed of materials which are less able to resist tension and compression, and a change in elevation of part of the line may render the entire system useless. An interesting experience regarding the subsidence of sewage works is reported by an English engineer, Malcolm Patterson.†

"At Ravensthorpe, in the Calder Valley, sewage works constructed in 1874 had remained intact for twenty-four years; they lay on the verge of a colliery leasehold. In August, 1897, the effluent outlet submerged

*Enzian, Johnson, and Williams "Report on Mining Conditions of the Oxford Colliery Workings, Scranton, Pa., Dec. 12, 1913."

†Proc. Inst. Civ. Engrs., Vol. 135, p. 162, 1898.

15 inches below the ordinary level of the stream into which it discharged. At his (the author's) previous visit it was at its normal level, of about 6 inches above the stream. The settling tanks were cracked across the center, and the tank sewer had settled considerably. These settlements arose from getting a 20-inch seam of coal, besides the dirt, about 150 to 160 feet deep, and the boundary of the worked coal terminated in or near the sewage workings. In the same year, a similar disturbance took place at the Castleford sewage works in the same valley. Complete re-levellings of the three roads intersecting the land were taken, and proved an average settlement of 3.3 feet throughout nine-tenths of the 12.5 acres of sewage land, without the surface being broken. In this case the getting of coal, 4 feet to 4½ feet thick, at a depth of 603 feet, was the cause. The contour was singularly constant, the new section being almost parallel with the original section. The strata here were the shales and sandstones of the coal measures, overlaid by the marls and limestones of the Permian formation."

CHAPTER II.

GEOLOGICAL CONDITIONS AFFECTING SUBSIDENCE.

The behavior of the measures overlying the mineral deposit which is being worked depends to a large degree upon the physical character and the structure of the measures themselves. In a recent paper* before the International Geological Congress attention was called to the various geological conditions which influence the effect of underground mining upon the surface as follows:

- (1) The general character of the overlying strata.
- (2) The presence of faults, fissures, etc.
- (3) The dip of the strata.
- (4) The direction of the workings with regard to the jointing of the strata.
- (5) The compressive strength of the rocks of the various overlying beds.
- (6) The bearing power of the underlying beds.
- (7) The angles at which rocks break when stressed.

Geological conditions must be studied in each district, as no generalizations can be made which will apply without reservation to all mining fields. The measures overlying a flat seam may be made up of various beds of sedimentary rocks and in places may include sheets or beds of intrusives. The physical character as well as the thickness of each bed may vary over different parts of the same mine, and there may be faults, fissures, rolls, etc., which greatly influence the supporting power of the bed, as well as the manner in which the weight of the bed itself is distributed upon the underlying supports. Unless the thickness and the character of the beds have been proven, and unless it is known definitely that the beds are fairly uniform throughout the field under consideration, it will be impossible to formulate even approximate rules and theories regarding subsidence which will be useful in the study of the problem of surface support.

MINERAL DEPOSITS.

1. *Physical Character.*—Before considering the overlying and the underlying beds, it will be well to note some of the conditions in the deposit being worked which may greatly influence the problem of sur-

*Knox, George "Mining Subsidence." Proc. International Geological Congress, Vol. 12, p. 797, 1913.

face support. The physical character of the material being mined and of that part, if any, of the deposit which is left in the form of pillars or of filling must be considered. The texture and the structure of the rock left in pillars is of great importance in determining the burden the pillars will carry and in affecting the stability of the pillar after it has been subjected to the action of explosives in the adjacent portion of the deposit and after it has been exposed to the action of the atmosphere and water. In many coal mines, owing to the friability of the coal, it has been necessary to reduce the charges of powder used along the rib and in some instances to avoid the use of powder entirely because the pillars are more or less shattered by the force of the explosives. Rock and coal may be so weakened by jointing or cleats that the pillars offer little support. Moreover, the action of the atmosphere and moisture, particularly upon a deposit jointed as described, may greatly weaken the pillar. Soluble minerals in the pillars may be dissolved by the mine water or the moisture in the air and the pillar thus weakened. Pyrite and other minerals may be oxidized and a deterioration of the pillar will follow. It has been suggested by some that the loss of the included gas in coal beds tends to reduce the strength of the coal. The hydration or the dehydration of minerals may result in the weakening of pillars. The terms "rashing," "slacking," and "slabbing" have been applied to the process of weakening of pillars by the gradual dropping of material from the ribs, due in part to the action of moisture, oxygen, or pressure, or a combination of these agents. In mines operating in soluble minerals the preservation of pillars may be difficult owing to the flow of water in the mine or the moisture in the air. It may become necessary in mines of all types when pillars deteriorate to protect important pillars by a coating of cement or concrete.

Strength tests have been made upon coal and other minerals in order to determine how serviceable they will prove when left in pillars and in order to estimate, in advance of the opening of a mine in a new field, the minimum size of pillar which may be left in safety for the protection of the mine openings themselves and of objects on the surface.

Numerous tests have been made upon rocks used for building purposes, and the data thus secured are of service in determining the size of the pillars to be left in such rock. But more commonly the pillars left in mines are not composed of materials used for building purposes, but rather of coal, ores of the various metals, and rock mineralized more or less with substances which are not permitted in structural materials.

Moreover, the natural structural materials used are generally a selected product. Underground the pillar is frequently made up of the weakest portion of the deposit. Tests upon pillar materials are often of doubtful service, for, as a rule, they indicate the maximum load which can be borne by a unit of the mineral and one that is often a selected unit. A coal bed, for instance, is composed of layers of varying hardness, and frequently it contains streaks of mother coal that would not be included in a sample tested for crushing strength.

TABLE 4.
COMPRESSION TESTS OF ILLINOIS COAL FEBRUARY 6, 1907.
Laboratory of Applied Mechanics, University of Illinois.

Laboratory No.	Specimen from	Equivalent Section, Inches		Height, Inches	Maximum Load	
		Top	Bottom		Pounds	Lb. per Sq. In.
12401	Penwell Coal Co., Pana, Ill.	11 3/4 x 12	11 3/4 x 12	12 1/2	316,000	2,090
12402	Empire Coal Co.	15 1/5 x 17 3/5	15 x 15 1/3	11.3	540,000	2,170
12403	W. W. Williams, Litchfield, Ill..	13 1/4 x 13 1/4	14 x 14	14 1/2	186,000	1,000
12404	Herdien Coal Co., Galva, Ill.	11 1/2 x 17 1/4	16 x 13	12	208,000	1,020
12405	T. H. Watson, Litchfield, Ill..	13 3/4 x 12	13 3/4 x 12	15	224,000	1,360
12406	C. N. & V. Coal Co., Streator, Ill.	11 3/4 x 9 1/4	11 x 11 1/4	13	140,000	1,280

Tests were made in the Laboratory of Applied Mechanics of the University of Illinois upon samples of Illinois coal furnished by the Illinois Geological Survey.* The data regarding the samples and the results of the tests are given in Table 4.

	Dimensions in Inches	Area in Sq. In.	Crushing Strength per Sq. In.
Sample M—			
Parallel with cleavage.....	2.01 by 2.02	4,060	3,170
Right angles to cleavage.....	1.75 by 1.70	2,975	2,970
Sample B—			
Parallel with cleavage.....	1.95 by 2.01	3,925	3,430
Right angles to cleavage.....	1.92 by 1.98	3,802	3,050

Tests were made by the H. C. Frick Coal Company upon samples of coal from the Pittsburgh seam. These are particularly interesting as they show the strength when compression is parallel to the cleavage and also when it is at right angles to it.

*Talbot, A. N. "Compression Tests of Illinois Coal." Ill. State Geol. Sur., Bul. No. 4, p. 198, 1909.

A series of tests was made upon Pennsylvania anthracite during 1901 and 1902 by a committee from the Scranton Engineers' Club. In all 416 samples were tested. The samples were uniformly 2 inches square, but were of three different heights: namely, 1 inch, 2 inches, and 4 inches. The results are given in pounds avoirdupois per square inch of horizontal area as presented in the following summary:

Samples	Height of Sample	Grand Average as Per Sq. In.		Number of Tests
		First Crack	Maximum Load	
Northern Field	1	3022	6241	122
	2	2025	4087	116
	4	1875	2854	113
Eastern Middle Field.....	1	4996	7417	7
	2	3343	3857	6
	4	3413	3821	7
Western Middle Field.....	1	3001	8631	3
	2	788	3499	3
	4	1440	2447	3
Southern Field	1	1124	3814	12
	2	1099	2377	12
	4	988	1809	13

From the data obtained the following conclusions have been drawn: "That the squeezing strength of a mine pillar of anthracite whose width is twice its height is about 3,000 pounds to the square inch, and the crushing strength about 6,000 pounds per square inch, or, approximately twice as much. And in general, other things being equal, the crushing strength of mine pillars would vary inversely as the square root of the thickness of the bed.

"The same general rule apparently holds true also for the squeezing strength in all cases in which the height of the pillar is less than the width. In tall pillars, having a height greater than their width, the squeezing strength apparently remains nearly constant while the crushing strength continues to diminish with height according to the foregoing rule."*

Subsequently additional tests were made at Lehigh University on samples of anthracite and of bituminous coal.† Forty-five anthracite specimens were tested. "There seems to have been no uniformity in the amount of compression of the specimens taken as a whole or between the specimens from the same seam." The results of the tests upon twelve bituminous specimens were more uniform. The crushing strength

*Mines and Minerals, Vol. 23, p. 368, 1903. U. S. Bureau of Mines, Bul. No. 25, Appendix, 1912.

†Daniel, J., and Moore, L. D. "The Ultimate Crushing Strength of Coal." Eng. and Min. Jour., Vol. 84, p. 263, 1907.

per square inch ranged from 584 to 1,583 pounds, but nine ranged from 1,000 to 1,538 pounds. All of the bituminous specimens were taken from the Pittsburgh seam. Additional data on the crushing strength of anthracite coal have been secured by Bunting* and Table 5 shows the crushing strength and the relation between prism strength and cube strength.

TABLE 5.
AVERAGE RESULTS OF TESTS ON ANTHRACITE SPECIMENS.

Name of Company	Ratio $\frac{h}{b}$	Crushing Strength Lb. per Sq. In.	Prism Strength Cube Strength
P. & R. C. & I. Co. (25 specimens)	1	2,393	1.00
(25 specimens)	2	2,296	0.96
L. V. C. Co. (13 specimens)	1	1,982	1.00
(13 specimens)	2	1,591	0.80
(13 specimens)	3	1,405	0.71
L. & W-B. C. Co. (20 specimens)	0.71	3,025	1.22
(20 specimens)	1.07	2,566	1.00
(20 specimens)	1.24	2,393	0.87
(20 specimens)	1.43	2,008	0.81
(20 specimens)	1.77	2,090	0.76
(20 specimens)	2.06	1,880	0.84
D. & H. C. et al. (146 specimens)	0.50	5,113	1.63
(146 specimens)	1.00	3,131	1.00
(146 specimens)	2.00	2,234	0.71

b=Least lateral dimension.
h=Height of prism.

The crushing strength of some British coals has been measured and reported by Henry Louis.† McNair in discussing the conditions of deep mining in the Lake Superior District‡ refers to the crushing strength of the trap rock left in pillars as 1,200 tons per sq. ft. Richardson§ gives a table of the compressive strength of quartzite cubes taken from the depths of from 1,000 to 3,500 feet in Rand mines. The first fractures appeared in the specimens under a pressure of 1,945 to 6,804 pounds per square inch. The crushing strengths of these specimens were 8,054 and 9,029 pounds per square inch, respectively.

2. *Extent and Dip of Deposit.*—The problem of surface support is naturally different in the case of a deposit which underlies an area of great lateral extent from that of support when the lateral extent is small. When the deposit underlies a small area the geological structure

*Bunting, D. "Chamber Pillars in Deep Anthracite Mines." Trans. Amer. Inst. Min. Engrs., Vol. 42, p. 236, 1911.

†Trans. Inst. Min. Engrs., Vol. 28, p. 319, 1904.

‡Eng. and Min. Jour., Vol. 23, p. 322, 1907.

§Richardson, A. "Subsidence in Underground Mines." Jour. Chem. Met. and Min. Soc. of S. Africa, Mar., 1907. Eng. and Min. Jour., Vol. 84, p. 196, 1907.

of that area may be worked out fairly accurately and precautions may be taken to protect important structures on the surface.

The dip and the position of the deposit may greatly modify the necessity for and the general policy of surface support.

3. *Uniformity of Mineral Deposit.*—If there is fair uniformity in thickness, structure, quality, and depth over a large area, a systematic plan of support may be adopted, including, for example, pillars of uniform size at regular intervals or a complete removal of the deposit with or without filling. If there is not regularity as to these conditions, it becomes more difficult to employ a system of support or of working which will be economical and at the same time provide support for the surface. Notable examples of such conditions may be found in some of the coal fields of Illinois where rolls, horsebacks, and faults complicate mining, and in some of the lead and zinc fields of the Mississippi Valley, where pillars of barren rock are left in the mines and the rich portion of the deposits is mined out as completely as possible under such conditions. The pillars as a rule are neither uniform in size nor uniformly spaced. While such irregularities in the mineral deposit interfere to a degree with systematic working, yet they at times assist materially in preventing or checking extensive underground movements or subsidence.

UNDERLYING ROCKS.

The physical character of the rocks immediately underlying the mineral deposit is of great importance. Frequently coal beds are underlaid with beds of clay of such consistency that it will not support the pillars when the weight upon them is increased by the opening of rooms. The pillars are slowly pushed into the clay while the clay is forced into the rooms which have been mined. Similarly, when water reaches clay beds underlying the coal, the clay may be softened and forced into the rooms by the weight of the pillars, and a subsidence results. The term "creep" is very commonly applied to such a movement.

Very few tests have been made upon the bearing power of the clays occurring in mines, but numerous tests have been made upon clays and soils upon the surface. Owing to the importance of not placing upon the clay floor of a mine a burden which shall exceed the bearing power of clay, which is usually much less than the compressive strength of coal, the following values are of interest:*

*Baker, I. O. "A Treatise on Masonry Construction," p. 342, 10th Ed., 1912.

Kind of Material	Safe Bearing Power in Tons per Sq. Ft.	
	Minimum	Maximum
Rock—the hardest—in thick layers in native bed.....	200.0	....
Rock equal to best ashlar masonry.....	25.0	80
Rock equal to best brick masonry.....	15.0	20
Rock equal to poor brick masonry.....	5.0	10
Clay in thick beds, always dry	6.0	8
Clay in thick beds, moderately dry.....	4.0	6
Clay in soft beds	1.0	2
Gravel and coarse sand, well cemented.....	8.0	10
Sand, dry, compact, and well cemented.....	4.0	6
Sand, clean, dry	2.0	4
Quicksand, alluvial soils, etc.....	0.5	1

The data on clay given in the table are not for fireclay, and no data have been obtainable which are the results of observations upon the supporting power of such clay of the character and occurring under conditions similar to those found in coal mines.

OVERLYING ROCKS.

The study of subsidence due to mining operations involves particularly a consideration of the rocks overlying the mineral deposit. Lack of uniformity in the overlying measures is the rule, not the exception, and this fact must be recognized in all attempts to formulate theories and rules. The effect of different conditions of the overlying beds is well illustrated by two examples in England. "At Sunderland, where the measures contain 50 per cent of hard-rock beds, seams at a depth of from 1,400 to 1,800 feet have been worked for seventy years without reference to the surface. On the other hand, in the Midland and South Yorkshire coal fields, where the cover is composed largely of soft shales, the effect of workings at as much as 2,000 feet is appreciable on the surface."*

Investigations of the thickness and physical character of each overlying bed are fundamentally necessary to the accurate study of subsidence in any district. Much of the data as to the behavior of various strata that can be secured will be at best only relative. However, the more data that can be secured the fewer will be the variables with which the investigator must deal.

Practically every theory of subsidence which has been advanced, when analyzed, involves some fundamental principle of mechanics. The beds may be subject to tension, compression, bending, or shear. Samples

*Eng. and Min. Jour., Vol. 84, p. 196, 1907.

of the various rocks may be tested in the laboratory in order to secure data to be used in the study of each problem. The great difficulty of obtaining specimens which will be representative of the section under investigation is largely responsible for the scarcity of data along certain lines, notably those concerning the strength of rock in tension and in bending.

Data on the strength of the rocks that are of importance in the study of subsidence have been collected and published by Bunting.*

"Numerous tests of various stones have proved that sandstones take permanent sets for the smallest loads, whereas granite and limestones are nearly perfectly elastic. It has also been proved by tests on various stones that the modulus of elasticity in compression is practically the same as in cross bending, but no fixed relation has been determined of the compressive, tensile, or shearing strength of the various kinds of stone.

"The shearing strength of sandstones and slates per square inch is generally slightly in excess of the modulus of rupture, and the compressive strength of various stones is variable and of comparatively little consequence here, as the compressive strength of even the lightest sandstone ranges from 4,000 to 6,000 lbs. per sq. inch."

The moduli of rupture of various kinds of stone as given by a number of authorities are shown in Table 6.

"Safe unit stresses for various stones have been given by many authorities. Below are given the stresses in pounds per square inch recommended by W. J. Douglas as illustrative of possibly a fair average of such values:

SAFE UNIT STRESSES FOR STONE.

	Compressive Lb. per Sq. In.	Shear Lb. per Sq. In.	Tension Lb. per Sq. In.
Blue stone flagging.....	1,500	....	200
Granite	1,020	200	150
Limestone	800	150	125
Sandstone	700	150	75

"It is to be observed, in the case of sandstone, that a safe tensile strength of 75 lbs. and a shearing strength of 150 pounds per square inch are given. Now, in consideration of the fact that the modulus of rupture is invariably in excess of the tensile strength, also that the resistance to shear slightly exceeds the modulus of rupture, a value of 100

*Bunting, D. "The Limits of Mining Under Heavy Wash." Amer. Inst. Min. Engrs., Bul. No. 97, p. 1, 1914.

pounds per square inch for the modulus of rupture of sandstone would be consistent. . . .

“When sandstones and slates, which generally overlie the coal veins, are considered as beams or slabs spanning mine openings for the support of overlying strata or other superimposed load, their transverse strength

TABLE 6.
MODULI OF RUPTURE OF STONES.

	Maximum	Minimum	Average	Authority
Blue stone flagging.....	4,511	360	2,700	Baker
Slate	9,000	1,800	5,400	Baker
Slate	11,230	7,425	.....	Arsenal tests, 1902
Slate .....	.....	.....	8,480	Merriman
Granite	2,700	900	1,800	Baker
Granite .....	.....	.....	1,754	Merrill
Granite .....	.....	.....	2,610	Arsenal tests, 1907
Granite .....	.....	.....	1,667	Arsenal tests, 1905
Granite .....	.....	.....	1,365	Bauschinger
Granite .....	.....	.....	1,194	Bauschinger
Glass	3,500	.....	.....	Church
Glass	4,132	.....	.....	Fairbairn
Sandstone .....	.....	.....	1,576	Technology Quarterly
Sandstone .....	.....	.....	1,200	Merriman
Sandstone	1,273	655	.....	Arsenal tests, 1895
Sandstone	2,243	1,500	.....	Arsenal tests, 1895
Sandstone	2,340	576	1,260	Baker
Sandstone (variegated) .....	.....	.....	469	Bauschinger
Sandstone (variegated) .....	.....	.....	718	Bauschinger
Sandstone (variegated) .....	.....	.....	1,109	Bauschinger
Sandstone (variegated) .....	.....	.....	341	Bauschinger
Sandstone (carboniferous) .....	.....	.....	483	Bauschinger
Sandstone (slaty) .....	.....	.....	249	Bauschinger
Sandstone (slaty) .....	.....	.....	135	Bauschinger
Sandstone (green) .....	.....	.....	156	Bauschinger
Sandstone (cretaceous) .....	.....	.....	597	Bauschinger
Sandstone (cretaceous) .....	.....	.....	967	Bauschinger
Gray stone	2,200	.....	.....	Kent
Light stone	1,170	.....	.....	Kent
Stone .....	.....	.....	2,000	Merriman
Quartz conglomerate .....	.....	.....	654	Merriman

From the results of tests as given in Table 6, the average moduli of rupture of the various stones are as follows:

	Pounds per Square Inch
Blue stone flagging.....	2,700
Slate	7,736
Granite	1,681
Sandstone	806

is of first importance. The ability of such material to serve as a beam depends upon its tensile strength, since that is always less than its compressive strength.” The action of the atmosphere and of water upon

rocks which have previously been protected from these natural agents occasionally reduces the strength of rocks.

TABLE 7.
SPECIFIC GRAVITY OF ROCKS.*

Rocks	Average Specific Gravity	Lb. Wt. per Cu. Ft.	No. of Cu. Ft. per Ton 2,000 Lbs.
Quartz	2.6	162.1	12.3
Andisite	2.9	181.0	11.1
Basalt	2.9	181.0	11.1
Diabase	3.0	187.0	10.6
Diarite	3.0	187.0	10.6
Granite	2.7	168.0	11.9
Limestone	2.7	168.0	11.9
Porphyry	2.7	170.0	11.8
Rhyolite	2.4	149.6	13.4
Sandstone	2.4	149.6	13.4
Schist	2.7	168.0	11.9
Shale	2.6	162.1	12.3

As previously noted, structural features are of great importance and the application of theories and rules will serve only as an indication of tendencies and possibilities. If the various rocks and strata were uniformly homogeneous the problem would be greatly simplified.

Natural processes may give rise to conditions which result in surface subsidence. Possibly the most comparable examples of subsidence due to natural agencies are those of surface sinks which result from the removal of portions of the supporting minerals by natural agencies.

Numerous examples of sink-holes and caves have been noted in the salt districts of Europe and in areas underlain by calcareous materials which may be dissolved in part by underground waters.† In the United States similar phenomena have been noted. The sink-holes of the Ozark plateau have been studied in Missouri‡ and the information available indicates that they have been caused either by the caving of the roof over solution basins in limestone beds, or by the enlargement through solution of joints leading from the surface to an underground channel. It is probable that the larger sinks are the result of the former cause. Usually these sinks vary in diameter from 100 to 300 feet, although single sinks are known to include as much as 150 acres.

In Illinois, near Millstadt, in the Waterloo Quadrangle numerous sinks have resulted from solution cavities in limestone beds lying at shallow depth.

Apparently the same forces which act during the subsidence of the

*Herzig, C. S. "Mine Sampling and Valuing," p. 139, San Francisco, 1914.

†Woodward, H. B. "Geology of Soils and Substrata." London, 1912. Quotes Darwin on p. 64, reference to Cheshire salt district, p. 67.

‡Crane, G. W. "Iron Ores of Missouri." Missouri Bureau of Geology and Mines. Vol. 10, 2d ser., p. 34. Lee, Wallace, "Geology of the Rolla Quadrangle." Vol. 12, 2d ser., ch. VIII.

surface over these cavities caused by nature also cause subsidence over mine workings. It has been suggested that the fissure systems in volcanic areas have resulted from vertical movement or settling due to the transfer of material by volcanic action to the surface; the resulting cavity having probably been closed, in part at least, by the subsequent settling of the surface under the load of extrusive material.* The dropping of a block of the earth's crust tends to produce normal faults, and it may be appropriate to consult the authorities on structural geology regarding the observations which have been made upon faults and fractures which apparently have resulted from forces and processes somewhat similar to those which characterize subsidence due to mining.

As will be noted later, the investigator of subsidence desires to learn among other things how the strata bend and break when subjected to various forces, and in what direction fracture will occur when various forces act. He desires to learn how rapidly the deformation of rocks occurs and to what depths mining openings may be carried with safety. In the laboratory the angle of break of various rocks may be measured and many other data may be obtained, but the investigator requires also data based upon larger volumes of materials, greater and more slowly acting forces, and conditions more nearly approximating those which result from mining operations.

1. *Cleavage*.—"The planes of cleavage, incipient or pronounced, existing in the overlying roof strata may strike in the same general direction as the planes of cleavage existing in the coal below. The importance of this principle and the necessity of its acceptance justify a reference by way of proof to the natural philosophy of the case. According to geological theory, the cleavage in the coal and in the roof strata was produced by the action of the same force. Assuming that in a given case the planes of cleavage are vertical, the theory is that some force, acting laterally and at right angles to what are now planes of cleavage, was the cause of such cleavage being created in the strata. Such a lateral force is supplied by the shrinkage of the earth's crust. This force, acting with immense energy on the particles of matter in the strata and subjecting them to enormous lateral compression, obliged such particles so to arrange themselves that their longer axes finally lay at right angles to the line of action of the compressing force. The planes of cleavage are thus defined as the planes in which the particles of matter now extend their longer axes."†

*Lindgren, W. "Mineral Deposits." P. 136.

†Halbaum, H. W. G. "The Action, Influence and Control of the Roof in Longwall Workings." Trans. Inst. Min. Eng., Vol. 27, p. 214, 1903.

2. *Fractures.*—The subject of fractures has been discussed in various works on geology, notably in the recent work of Leith.* “Under tension fractures tend to develop in planes normal to the maximum stress. Tension fractures may develop when a mass is deformed by shearing. Under compressive stresses, fractures tend to develop above the planes of maximum shear, which are inclined to the direction of principal stresses; but the degree of inclination and the direction of dip of the planes away from the direction of maximum stress vary.”† Joints in rocks may be due to tension or to compression. Faults, which are “fractures along which there has been some relative displacement of the rock,”‡ may be regarded as the result of tension or of compression. A “gravity” or “normal” fault is generally the result of tension while compression causes “thrust” or “reverse” faults.

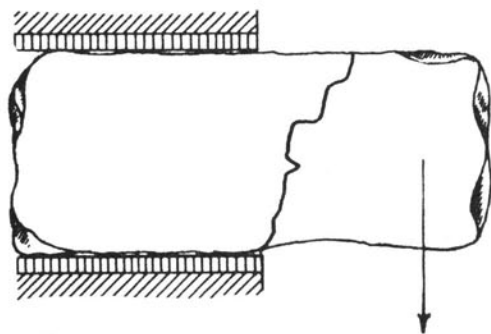


FIG. 22. ANGLE OF FRACTURE OF STONE.

The angle of fracture of rocks under stress has been noted and measured in the field and in the laboratory. Daubrée carried on extensive experiments in 1879 to show the effect of tension and compression.§ Experiments made upon wax and resin prisms showed that compression causes rupture along a plane at an angle of 45 degrees to the line of force. If there has been preliminary deformation, the angle will be greater than 45 degrees.

Fayol tested pieces of sandstone and shale, as shown in Fig. 22, to discover the angle of fracture when the test piece is held firmly by one end and subjected to a steady and increasing pressure applied upon the projecting portion.

Leith states that data given in United States Geological Survey

*Leith, C. K. "Structural Geology." 1913.

†In subsidence following the advance of longwall mining strata may first be subject to tension and later to compression.

‡Leith, P. 81.

§Daubrée, A. "Études Synthétiques de Géologie Expérimentale." P. 179.

Folios show an average dip of 78 degrees for normal fault planes and 36 degrees for reverse fault planes. Faults noted in Illinois have dips ranging from 35 degrees to 75 degrees, the majority, however, approximate 55 degrees.

Lindgren observes* that veins may dip at any angle but "veins dipping 50 degrees to 80 degrees are most common."

Stevens has formulated a law of fissures.† "In a homogeneous mass under pressure, slipping tends to take place only along those planes on which the ratio of tangential stress to direct stress is equal to the coefficient of friction of the material sliding on itself. If the axis of greatest principal stress is vertical, the displacement along the fissure will be that of a normal fault, and the dip of the normal fault which is most favorable to slipping will be 66 degrees. Similarly, when the axis of greatest principal stress is horizontal, the displacement along the fissures is that of a reverse fault, and the dip most favorable to slipping is 24 degrees."

Spencer has studied in the field the veins of southeastern Alaska.‡ There is a systematic arrangement of veinlets in two main sets standing at right angles to each other and dipping in opposite directions. Becker§ concluded that the fracture had been produced through compressive shearing stresses which were caused by nearly tangential forces acting in a direction normal to the strike of the two sets of fractures. Spencer supports the theory that these fractures were caused by compressive thrust but questions the statement that the thrust was the result of tangential compression. He developed the theory that the general fissuring was a result of "gravitative adjustment in the rock-masses, tending to restore internal equilibrium disturbed during the uplifts which are known to have taken place." A broad mountainous zone rises about 5,000 feet above the interior plateau and 15,000 feet above the plateau bordering the Pacific Ocean. "Standing so far above the neighboring earth blocks, it seems that in this great orographic mass there must even now exist a tendency to bulge toward the unrestrained sides. If so, conditions are favorable for the opening of fractures at a depth dependent upon the crushing strength of the rocks which compose the great mountainous mass."

*Lindgren "Mineral Deposits." P. 151.

†Stevens, B. "The Laws of Fissures." Trans. Amer. Inst. Min. Engrs., Vol. 40, p. 475, 1909.

‡Spencer, A. C. "The Origin of Vein-Filled Openings in Southeastern Alaska." Trans. Amer. Inst. Min. Engrs., Vol. 36, p. 581, 1906. "The Geology of the Treadwell Ore Deposits." Trans. Amer. Inst. Min. Engrs., Vol. 35, p. 507, 1905.

§Becker, G. F. 18th Annual Report, U. S. Geol. Sur. Pt. III, pp. 7-86.

The discussion and theory of Spencer is of great interest in this connection as it develops the idea of the settling of a mass of rock under its own weight and when movement is less restrained in one direction than in another. It also emphasizes the question of angle of fracture and systems of fractures which will be referred to later.

The theory of a "dome of equilibrium" developed by Fayol suggests the question of the possibility of removing a layer or bed from the earth without disturbing the surface, owing to the sphericity of the earth. The question of the supporting power of the dome of the earth's crust has been studied by a number of eminent geologists. Chamberlain and Salisbury refer to each portion of the crust as "ideally" an arch or dome. When large areas like the continents are considered, it is the dome rather than the arch that is involved, and in this the thrust is ideally towards all parts of the periphery. According to Hoskins, a dome corresponding perfectly to the sphericity of the earth, formed of firm crystalline rock of the high crushing strength of 25,000 pounds to the square inch, and having a weight of 180 pounds to the cubic foot would, if unsupported below, sustain only $1/525$ of its own weight. This result is essentially independent of the extent of the earth's radius.*

The idea that extensive areas can be left entirely unsupported if the curvature of the arch corresponds to the sphericity of the earth is entirely unwarranted, judging from the calculations made and from the experience at many mines.

Various structural features must be noted in determining the cause, effect, and probability of subsidence following mining operations. Among the most important of these are the conformability of the overlying rocks, joints, cleavage, bedding planes, folds, faults, fissures, dikes, and intrusives.

In many mining districts there are heavy beds of surficial material which complicate the problem on account of the water they contain and because they are more or less fluid and have little supporting power. The lateral extent of subsidence is greater when the area is covered with such beds. This is due largely to the smaller sliding angles upon which beds of sand, earth, marl, and gravel will move.

EXPERIMENTS TO DETERMINE ROCK FRACTURE.

Many experiments have been carried on by eminent geologists in order to discover by work in the laboratory fundamental data upon

*Chamberlain, T. C., and Salisbury, R. D. "Geology." Vol. 1, p. 581.

which theories may be based and also to verify if possible, by artificial processes, theories accounting for conditions which may have been the results of complex forces and reactions.

As previously noted, numerous tests have been made to determine the strength of rocks and minerals under various conditions and various properties of rocks have been studied.* Among the most interesting experiments in addition to the tests of materials are the following: Fayol conducted elaborate tests of materials such as those which composed the beds overlying the Commentry Mine and by ingeniously constructed models attempted to measure the lateral and vertical extent of subsidence.† The work of Daubrée has been noted previously. Extensive experiments have been made also by Meade and by Paulcke. In America among the experiments which have attracted most attention are those described by Willis in "Mechanics of Appalachian Structure"; those by Adams and Coker on elastic constants, flowage, and the cubic compressibility of rocks; those by Becker on schistosity and slaty cleavage; and those by Hobbs on mountain formation.

Most of these experiments consider tangential pressures rather than vertical pressure. Very few of them develop conditions which approximate those which occur when the support of rock is removed.

*Consult the Bibliography, p. 180, for records of these experiments.

†See page 76.

CHAPTER III.

THEORIES OF SUBSIDENCE—GENERAL PRINCIPLES.

In this bulletin no attempt will be made to discuss theories of mechanics or derive formulæ applying to subsidence, but an effort will be made to state briefly the conditions that exist and to point out the fundamental and controlling factors in a study of the problem.

In order to study the reactions which may exist in the rocks overlying a mineral deposit, it will be necessary to make certain assumptions in order to arrive at some definite conclusions. For example, it must be assumed that the rock is uniformly of a known strength, that it is free from structural weaknesses, and that it exists in masses or beds whose extent, thickness, depth, and dip are known.

The principles of mechanics may be applied to various types of mine openings, notably: (1) The long narrow excavation which may be driven through massive or bedded rocks, or along the strike or the dip of bedded rocks, as tunnels, drifts, crosscuts, and entries. (2) Excavations of greater width, as rooms or stopes. (3) Excavations of great lateral extent, as those of a longwall coal mine, or sections of a pillar-and-room mine after the pillars have been drawn. In these various types of openings the fact must be recognized that maximum pressure may not always be due to a thrust acting vertically downward.

In order to simplify the problem it may be suggested that the rock and mineral overlying and surrounding the excavation be considered as forming one of the following:

- (1) A beam of rock lying horizontally or inclined and extending from pillar to pillar or column to column.
- (2) A cantilever supported by a pier of rock or mineral.
- (3) An arch or series of arches of equal or unequal spans.
- (4) A column or pier, either vertical or inclined, supporting (1), (2), or (3).
- (5) A dome of the earth's crust.

It should be noted further that when the roof is considered as acting as a beam it may be supported by piers of mineral, of noncoherent filling, of timber, or of masonry, resting upon a more or less yielding floor. With these explanatory statements, the various theories of subsidence that have been formulated will be considered.

HISTORICAL REVIEW OF THEORIES OF SUBSIDENCE.*

Belgian-French Theories.

Belgian engineers were among the first to make a scientific study of earth movements due to mining operations. In 1825 a commission investigating the cause of surface cracks about the city of Liege expressed the opinion that a distance of 300 feet between the mine workings and the surface is more than sufficient to protect the surface. Further disturbance of the surface raised the same questions in 1839. Another commission of mining engineers concluded that there would be no danger to buildings or wells from mining operations at a depth of 300 feet.†

Although credit for formulating the first theory of subsidence is usually given to the Belgian engineer, J. Gonot, it is claimed by L. Thir-

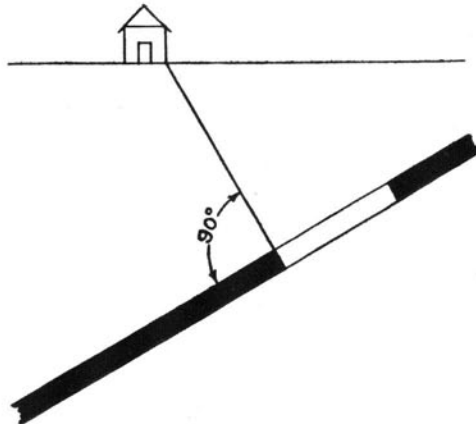


FIG. 23. DIAGRAM ILLUSTRATING THE "LAW OF THE NORMAL."

part that the fundamental idea of the theory of the normal was first presented by the French engineer, Toillez, in 1838. Gonot studied surface subsidence in the vicinity of Liege in 1839 and formulated a theory which was published in 1858. He claimed that following the removal of coal the overlying strata would sink and the angle of fracture would be perpendicular to the plane of the coal bed. (Fig. 23.) This theory was later referred to as the "Law of the Normal." Mining operators in general and many engineers criticised this theory and, while many later writers accepted the principle as it applied to horizontal

*Fayol, H. "Sur les Mouvements de Terrain Provoqués par l'Exploitation des Mines." *Bul. Soc. Ind. Min.*, IIe ser., Vol. 14, p. 862; Kolbe, E., "Translocation der Deckgebirge durch Kohlenabbau," pp. 2-51, Essen, 1908.

†Vuillemin, E. and G. *Bul. Soc. Ind. Min.*, IIe ser., Vol. 14, p. 858, 1885.

and slightly dipping beds, various qualifications were suggested in regard to the angle of fracture of steeply inclined beds. (Fig. 24.) Gonot also held that the break extends through to the surface, irrespective of the depth of mining. He based this theory on observations he had made on subsidence at Liege. The Belgian engineer, Rucloux, who was appointed with Wellekens to investigate subsidence about Liege in 1858, called attention to the fact that Gonot's theory undoubtedly could not be applied to vertical and highly inclined beds. While many criticisms were offered, no new theory was presented. The commission held that the observed facts were sufficient to establish the principle that with solid beds of an ordinary thickness and at moderate depths exploitation by contiguous openings and successive fillings up to a considerable extent may be made without affecting the surface. Where the depths

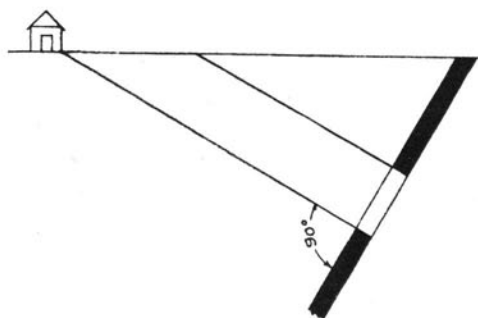


FIG. 24. THE "LAW OF THE NORMAL" NOT APPLICABLE TO STEEPLY DIPPING BEDS.

are slight, or when for one reason or another the beds lose their solidity, subsidence may be prevented by preserving pillars. The subsidences which are produced on account of the underground work generally follow vertical lines, but may deviate from these lines according to the direction of the beds, more often toward the lower side and often also toward the upper side.

In 1868 four engineers were commissioned by the Prussian Government to collect information on the question of the "influence that mine workings may have on surface building" in the coal fields of various countries. They found that at that time the majority of Belgian engineers believed that when the coal is entirely removed the most careful packing gives no guarantee against damage to surface building; that the packing only lessens the sinking; and that the surface may be protected by leaving pillars. In order to make this method effective only half the area of the coal seams must be removed.

In 1871 the Belgian engineer, G. Dumont, who had been appointed to make an investigation of conditions in and about Liege, made a careful study of the problem and submitted a voluminous report of 331 pages, in which he supported the fundamental idea of the "Law of the Normal" but limited its applicability to beds dipping not more than 68 degrees from the horizontal. This conclusion was based in part upon upwards of a thousand levels at various parts of the town. He* called attention to the direction and amount of the forces acting on the block of rock overlying the excavation. The broken pieces must fall into the excavation, and on highly inclined seams, according to Gonot's theory, the masses of broken rock would have to move toward the excavation on an angle less than the sliding angle. If $a-b$, in Fig. 25, represents the weight of the rock A-B, and this force is resolved into the forces $a-d$ and

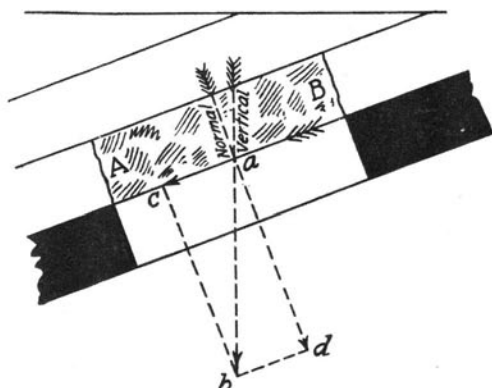


FIG. 25. FORCES ACTING ON ROCK IN AN INCLINED BED.

$a-c$, it is evident that, as the bed becomes steeper, the force corresponding to $a-d$ will become less and the force corresponding to $a-c$ greater. The tendency, then, will be to create a cavity vertically above the excavation rather than in a direction perpendicular to the plane of the bed.

Dumont held that the "inclination of the strata lessens the depth of the subsidence, but increases the area damaged. Timbering hinders the beds forming the roof of a seam from breaking, and therefore prevents the increase in their volume, which takes place when they break. It thus increases rather than diminishes the subsidence at the surface."[†]

*Dumont, G. "Des Affaissements du Sol Produits par l'Exploitation Houillère," Liege, 1871.

†Colliery Engineer, Vol. 11, p. 25, 1890-91.

The period during which the movement of the surface may continue is uncertain. In Belgium it extends generally over ten to twelve years but in certain instances has been known to continue twenty and even fifty years. The draining of old workings or the flooding of a mine may bring about fresh movements a long time after the original movement has ceased.

J. Callon, of the École des Mines, Paris, supported Gonot's theory but with some reservations.* He believed that when the coal bed is overlaid with unconformable beds, the angle of fracture will extend through each bed perpendicular to its plane of bedding. (Fig. 26.) He held that the amount of surface subsidence would depend on the compressibility of the material which fell into the excavation. In hard rocks a cavity narrowing upwards would be formed, while in soft rocks the cavity would be funnel-shaped.

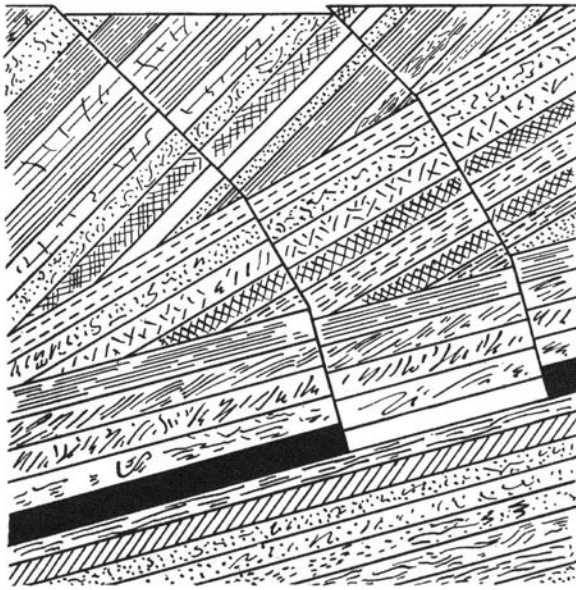


FIG. 26. FRACTURE NORMAL TO BEDDING PLANE.

The Colliery Owners' Association of Liege published a reply to Dumont in 1875.† The validity of Gonot's theory for beds of low dip was admitted, but his claim that the fracture would be normal to highly inclined seams was disputed. They argued that the fracture over the

*"Cours d'Exploitation des Mines," Vol. 2, p. 334, 1874.

†"Des Affaissements du Sol. Attribués à l'Exploitation Houillère," Liege, 1875.

workings would take place in a series of breaks approximately perpendicular to the bedding plane of each stratum, but that the force of gravity would cause the material to fall from the outcrop side of the excavation, causing the line of fracture to lie between the vertical and the perpendicular to the vein; while on the lower side of the excavation, each bed would tend to support the bed above and there would be an overhanging of slabs of rock toward the excavation. Thus the line of

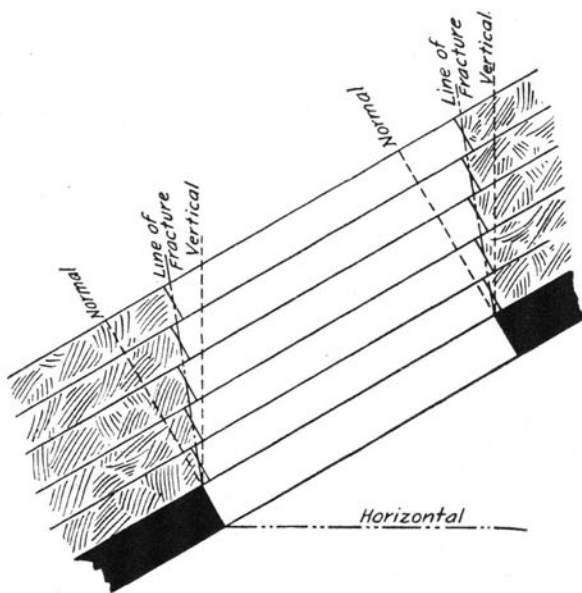


FIG. 27. LINE OF BREAK BETWEEN NORMAL AND VERTICAL.

fracture would be between the vertical and the normal to the bedding planes. (Fig. 27.) They also called attention to Coulomb's measurement of the angle of fracture by crushing. "The combination of this force producing crushing with that tending to break the bed by bending induces fracture along a line intermediate between the two directions, and such line goes further from the normal as the inclination of the strata increases."* On the whole the Colliery Owners' Association thought the Dumont's theory was unsatisfactory and often of no practical use and

*Hughes, H. W. "Textbook of Coal Mining," London, 1904.

that the only rule to follow was the examination of the special facts in each particular case.

M. Haton de la Goupilliere (1884), Professor of Mining at the École des Mines, Paris, held views similar to those of Callon. He pointed out the effect of the fallen material, which tends to check subsidence and in fact may stop it at a certain level. With longwall mining and filling he thought the movement would be almost independent of the depth. He held that it would be impossible to have the "Law of the Normal" completely verified in practice.*

The continued subsidence of the surface at Liege and the disagreement among engineers as to the theories of subsidence induced H. Fayol† to make observations of elevations at mines and to conduct laboratory experiments. He first summarized the contradictory opinions of the time as follows:‡

(1) Upon the extension of the movement upwards.

(a) The movement is transmitted to the surface whatever may be the depth of the workings.

(b) The surface is not affected when the workings exceed a certain depth.

(2) Upon the amplitude of the movements.

(a) Subsidence extends to the surface without sensible diminution.

(b) Movements become more and more feeble as they extend upwards.

(3) Upon the relative positions of the surface subsidence and of the mining excavation.

(a) Subsidence always takes place vertically above the workings.

(b) Subsidence is limited to an area bounded by lines drawn from the perimeter of the workings and perpendicular to the beds.

(c) Subsidence can not be referred to the excavation either by vertical lines or lines normal to the beds, but only by lines drawn at an angle of 45 degrees to the horizon, by the angle of repose of the ground, or by some other similar angle.

(4) Upon the influence of gobbing.

(a) The use of packing protects the surface effectually.

(b) Packing simply reduces the effect of subsidence.

*"Cours d'Exploitation des Mines," 1883.

†Director, Commentry and Montvicq Mines in France.

‡Bul. Soc. Ind. Min., IIe ser., Vol. 14, p. 805, 1885.

(c) Subsidence is greater with stowing than without it.

Fayol conducted a long series of investigations and experiments* and came to the conclusion that the movements of the ground are limited by a kind of dome which has for its base the area of the excavation and that their amplitude diminishes by degrees as they extend further away from the center of the area.

"Fayol's rule agrees with all the facts observed; absence of subsidence, more or less important subsidences, movements limited to the vertical above the perimeter of the excavations, those limited to the normal or to other inclinations, and so on. It has the disadvantage of being indefinite; but in a question which embraces so many elements, many of which are unknown or not well known, such as the nature of the rocks, the thickness of the beds, irregularities in geological structure, the action of water, etc., we cannot hope to arrive at absolutely accurate formulæ; we shall have accomplished much when we get to know very nearly the true form, the direction, and the relative amplitude of the subsidences, and are in a position to combat false ideas successfully."†

According to Fayol the disturbance of the strata is greatest over the center of the area excavated and it diminishes in amount toward the perimeter of the excavated area. As the vertical distance above the excavation increases, the amount of the movement decreases, and, if the workings are at great depth, there will be a depth beyond which the movement will cease. When graphically represented the limits of the movement are depicted by a dome; outside of this dome there can be no disturbance whatever. However, Fayol called attention to the possibility of movement if there should be a series of these domes in close proximity to each other, and to the effect of dip, rock structure, etc. upon the practical application of this theory. As a result of his experiments and observations, Fayol concluded:

(1) If excavations were stowed in a thoroughly tight and efficient manner with incompressible materials there would be no subsidence, but ordinary stowing is not done under these conditions, because the materials employed are all more or less compressible and the excavations are never perfectly filled up. When the roof settles the stowing resists feebly at first, after which the resistance rapidly increases and finally arrests the downward movement.

(2) The amplitude of the subsidence diminishes in proportion to

*See page 138.

†Galloway, W. "Subsidences Caused by the Workings in Mines," Proc. South Wales Inst. of Engrs., Vol. 20, p. 311, 1897.

the depth of the workings below the surface, the diminution being proportional to the increase of depth.

Leon Thiriart in 1912 called attention* to the theory of Banneux, which Thiriart called the "Law of the Tangent." Thiriart's theory is a modification of Banneux's, and Banneux's theory resembles that of Hausse.† The bending moment is considered for each bed successively, beginning with the one immediately overlying the coal. By elaborate calculation, based on observations of subsidence, formulæ are derived by which a table showing the angle of break for various dips has been compiled.

German Theories.

A. Schulz, one of the first German engineers to study surface subsidence due to mining operations, in 1867 published his ideas on the

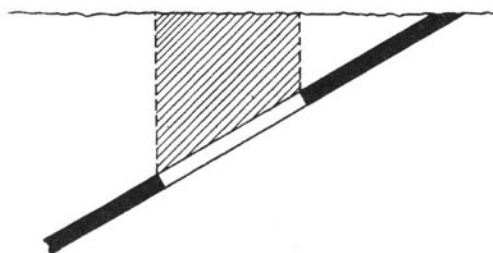


FIG. 28. VERTICAL FRACTURE OF DIPPING BEDS OF SHALE.

angle of fracture and the size of pillars necessary to protect objects on the surface.‡

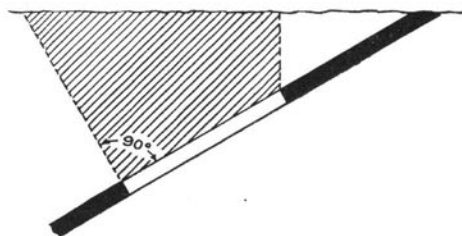


FIG. 29. SCHULZ'S IDEA OF FRACTURE OF SANDSTONE BEDS.

He criticised Gonot's "Law of the Normal" and held that in dipping beds of shale the fracture will occur along vertical planes (Fig. 28), while in sandstone the fracture on the dip side will approach the nor-

*Thiriart Leon "Les Affaissements du Sol Produits par l'Exploitation Houillère," Ann. des Mines de Belgique, Vol. 17, p. 3, Bruxelles, 1912.

†See page 97.

‡Schulz, A. "Investigations on the Dimensions of the Safety Pillars for the Saarbeck Coal Mining Industry and on the Angle of Fracture at Which the Strata Settle Into Worked-Out Rooms." Zeit. für B., H., u. S.-W., 1867.

mal, but on the outcrop side it will be vertical. He held in general that the fracture would occur between the vertical and the normal to the bed.

During the same year that Schulz published his paper on the angle of fracture, Mining Assessor von Sparre published a criticism of Gonot's theory.* He held ideas similar to those of Schulz; namely, that the fracture will occur between the vertical and the normal. He suggested the consideration of the separate beds and showed that for each bed the fracture would occur between the vertical and the normal on both sides of the excavation in a dipping coal seam. As shown in Fig. 30, the bounding planes of the break will be not ab and lh nor ac and hm but midway between.

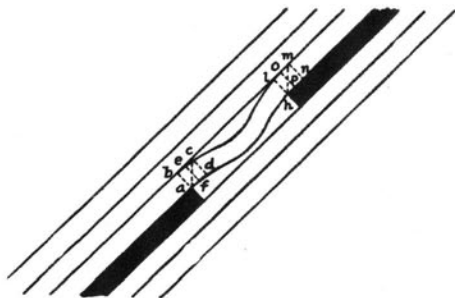


FIG. 30. FRACTURE IN DIPPING BEDS ACCORDING TO VON SPARRE.

Von Dechen called attention in 1866 to the importance of studying the part played in subsidence by the heavy marl beds overlying the coal measures. Some engineers, in fact, held that subsidence was due entirely to the unwatering and drying of these marl beds. Von Dechen noted also that the "Law of the Normal" could not be applied to very steeply inclined or vertical beds.†

In 1894 the project of constructing a canal between Herne and Ruhrart caused an investigation of the stability of the surface over which it was proposed to build the canal. A survey of conditions in the Dortmund district was made by the Board of Mines of Dortmund; levels were run and maps were made, and a very complete report was submitted in 1897.‡ It was concluded from observation on the West-

*Von Sparre, J. "On the Angle of Fracture of Strata of the Coal Measures," Glückauf, 1867.

†Von Dechen, H. "Opinion on the Surface Subsidence in and About the City of Essen," Manuscript, 1869.

‡"On the Influence of Coal Mines Under Marl Capping Upon the Earth's Surface in the Dortmund District." Zeitschrift für B., H., u. S.-W., Vol. 45, pp. 372-392, 1897.

phalian mines and for the conditions of that district that there would be no "harmless depth." The lateral extent of subsidence was found to increase greatly with thickness of the marl covering. It was noted that careful filling of the mine workings will greatly reduce the amount of vertical subsidence but will not affect greatly the lateral extent, in fact, in some instances it was found that with filling the lateral extent of subsidence is greater than when no filling whatever is used.

From the data collected an effort was made to determine the angle of fracture in rock and also the angle at which the limiting plane of subsidence of the marl extends from bedrock to the surface. In rock dipping not more than 15 degrees, the angle of fracture was found to

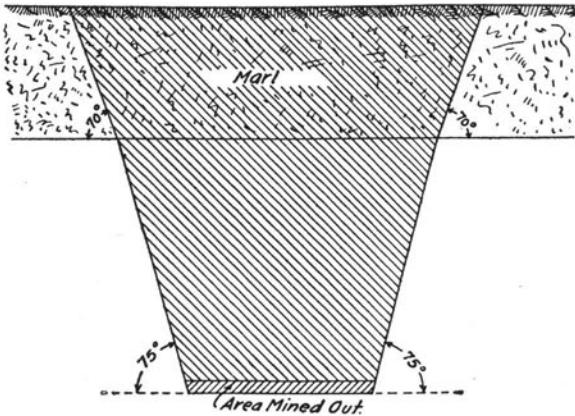


FIG. 31. SUBSIDENCE BEYOND ANGLE OF BREAK ACCORDING TO WACHSMANN.

be about 75 degrees, measured from the horizontal (Fig. 31), while in steep seams the angle approaches the natural slope, generally not less than 55 degrees.

For dips up to 65 degrees the vertical amount of subsidence may be found by the formula:

$$S = f \cdot m \cdot \cos a$$

in which S = vertical amount of subsidence,

m = thickness of coal worked,

a = angle of dip of coal seam.

f is a coefficient whose maximum values are as follows, if filling is complete:

- 0.40 for dips 0—10°,
- 0.30 for dips 10—35°,
- 0.25 for dips over 35°.

When no filling is used f may be as much as 0.80.

Wachsmann* held that when an underlying coal bed is mined, the lowermost strata collapse, the next higher strata sink and crack if the

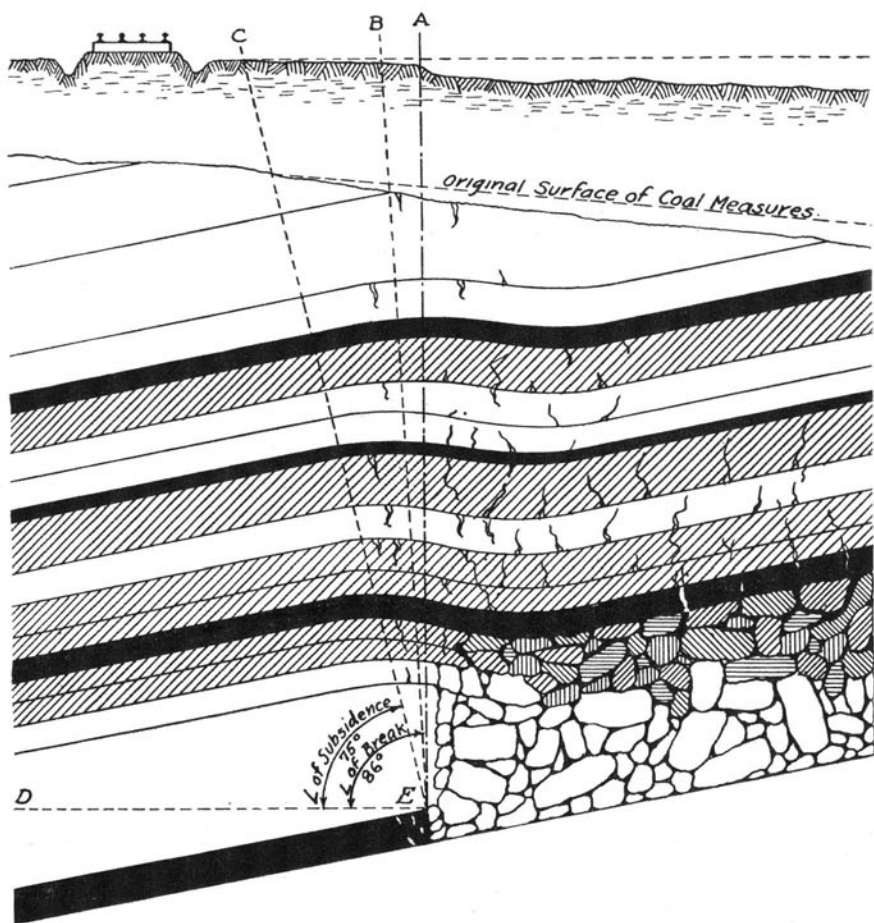


FIG. 32. ANGLES OF FRACTURE IN ROCK AND OF SUBSIDENCE IN MARL.

excavation is of sufficient extent, while the uppermost strata sink without breaking or cracking. There is subsidence beyond the actual angle of break, as shown in Fig. 32.

In 1885 Mining Engineer R. Hausse published some observations

*Über die Einwirkung des Oberschlesischen Steinkohlenbergbaues auf die Oberfläche. Zeit. f. Obersches B.- u., Hüttenmannischen Verein, p. 313, 1900.

on the angle of break.* Owing to the great interest in the problem of subsidence, Hausse directed his entire time to the scientific investigation of various phases of the problem in Germany, particularly in Saxony, and published the results of his work in 1907.† In his preliminary

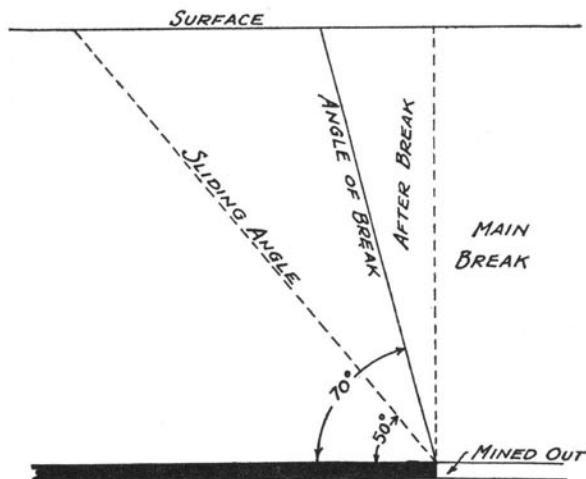


FIG. 33. HAUSSE'S THEORY; ANGLE OF BREAK BETWEEN VERTICAL AND SLIDING ANGLE.

chapter Hausse discusses the behavior of rocks over excavated areas and distinguishes between the "first" or "main break" and the "afterbreak." Over a horizontal bed he found that the main fracture is vertical and that the after break extends upward over the unmined coal. He pointed out that after the first falls occur, filling the cavity, the overlying strata subside, compressing the fallen material as filling is compressed by the roof in longwall mining. He stated that the plane of fracture lies between the vertical and the plane of sliding for the rock in question, and generally the plane of fracture will bisect the angle between the two limiting planes (Fig. 33). He discussed the relation between the directions of the main break, the after break, and the angle of inclination of the seam, as follows:

The angle of main fracture on the upper side = $90 \frac{a}{2}$, in which a = angle of dip. The angle of after break is assumed to be either con-

*Hausse, R. "Von der Niedergehen des Gebirges beim Kohlenbergbau und den damit Zusammenhängenden Boden- und Gebäudesenkungen," Ziet für das Berg-Hütten und Salinenwesen, pp. 324-446, 1907.

†Hausse, R. "Beitrag zur Bruch Theorie; Ehrfahrungen über Bodensenkungen und Gebirgsdruckwirkungen," Jahrbuch für das Berg-und Hüttenwesen in Sachsen, 1885.

stant or equal to 20° , or it is taken as decreasing from 20° to 10° in proportion to the increase of the dip from 0° to 45° . In a series of tables, Hausse presents the angle of fracture for various dips, making certain assumptions. He determined coefficients of increase of volume for mining with filling and without filling on the basis of observations made in the Royal Colliery at Plauen under the Dresden-Tharandt Government Railway. Where there was no filling, the coefficient was found to be 0.01 and with filling the coefficient was found to be 0.002.

Starting from Rziha's assumption of sliding angles, Trompeter* determined by the use of Hausse's observations the breaking zone with

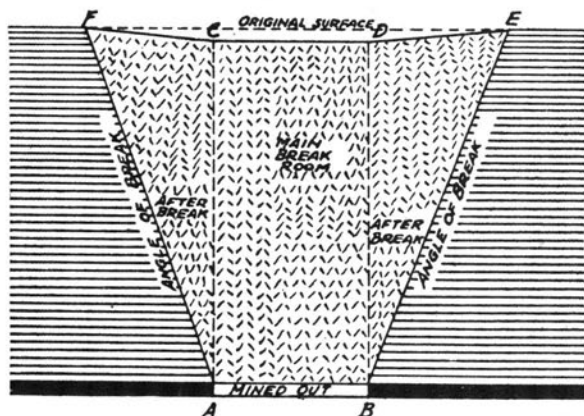


FIG. 34. "MAIN BREAK" AND "AFTER BREAK." (HAUSSE.)

regard to the expansive power or increase in volume of broken rock. From his experience he found this for the Rhenish-Westphalian coal district to be an increase of 12 meters for every 100 meters in depth.

Puschmann has described the subsequent working of overlying seams in the coal district of Upper Silesia.†

According to many engineers, the unwatering of the surficial material has been the immediate and sole cause of surface subsidence. Those who hold this opinion claim that surface movement has resulted from the sinking of shafts and the driving of boreholes alone and without any actual removal of the mineral deposit. There is, however, a wide difference of opinion on this matter. Von Dechen held that the

*Trompeter, W. H. "Die Expansivkraft im Gestein als Hauptursache der Bewegung des den Bergbau Umgehenden Gebirges," Oestreichische Zeit., für Berg- und Hüttenwesen, 1899.

†Puschmann "Über den Nachträglichen Abbau Hangender Flöze beim Oberschlesischen Steinkohlenbergbau," Zeit. für d. B., H., u. S.-W., Vol. 58, p. 387, 1910.

subsidences* near Essen in 1866 and 1868 were caused by the partial drying of the marl and green sand overlying the coal measures. Graff† demonstrated by tests that drainage does not cause any change of volume of sand or quicksand and held that, when the water does not carry away any solids, there can be no subsidence resulting simply from unwatering.

The principal value of the work of the Germans has been in determining the angle of break, extent of surface subsidence relative to mine workings, and the practical coefficients of increase in the volume of the measures overlying the mined area, as these measures sink into the worked out area. Data upon these phases of subsidence have been collected in a systematic and accurate manner during a long period of years by engineers in the coal mining districts of Germany.

Austrian Theories.

Subsidence of surface due to mining operations has attracted considerable attention in the Ostrau-Karwin coal region in Austria. Ministerial regulations controlling the removal of coal under railways were formulated and became effective January 2, 1859. In 1876 Mining Director W. Jicinsky‡ published a treatise on subsidence.

The question of the applicability of the government regulations for the protection of railroads to the railroads leading to the mines and serving the mines almost exclusively aroused discussion in the late 70's and the early 80's. The Board of Mines of Olmutz framed a regulation to modify the existing regulations so that they would not apply so strictly to mining railroads. F. Rziha, Professor of Railroad Construction at the Technical School of Vienna, was engaged to advise on the proposed regulation. He expressed his opinion on this question, formulated a theory of subsidence, and presented regulations to govern the exploitation of the coal under the mining railway.§ Rziha formulated a theory covering (1) the direction of fracture and (2) the amount of the vertical sinking of the earth, a brief statement of which follows:

(1) The Direction of Fracture. When rock is undercut, there is a tendency for it to fall or sink in proportion as gravity exceeds cohesion. The action may be falling or tearing, or both. He distinguished what he

*Goldreich Die Theorieder Bodensenkungen in Kohlengebieten, p. 20.

†Graff "Verursacht der Bergbau Bodensenkungen durch die Entwässerung Wasserführender diluvialer Gebirgsschichten," Glückauf, 1901.

‡Jicinsky, W. "The Subsidences and Breaks of the Surface in Consequence of Coal Mining," 1876. Published later as a monograph of the Ostrau-Karwin coal district, 1884, "The Effects of Coal Mining on the Surface."

§Oest. Zeit. f. B., u. H.-W., Vol. 29, 1881, and Vol. 30, 1882.

called a "falling space" and surrounding it, more or less concentrically, a "friability" or "tearing space." He found the falling space to approximate the shape of a paraboloid. First the rock becomes loosened and afterwards falls when gravity exceeds cohesion. In time, limited by the structure of the rock, a dome-shaped space *abc* is formed (Fig. 35),

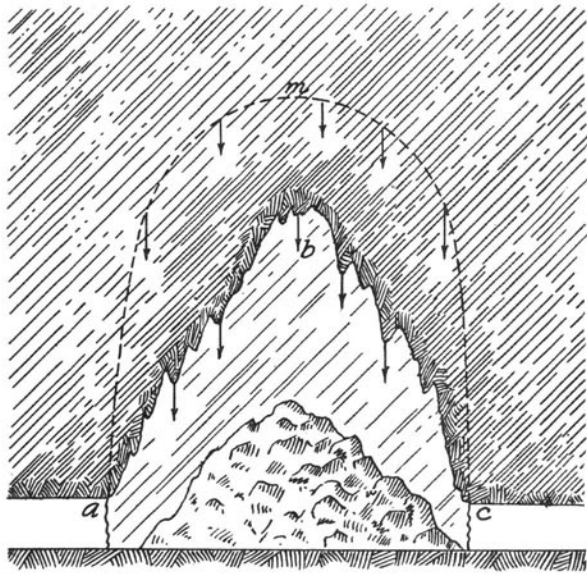


FIG. 35. "ZONE OF FALLING" AND "ZONE OF TEARING."

working laterally and vertically from the center of disturbance. Outside this space and more or less concentric is the dome of tearing, indicated by the dotted line *amc*. If the tearing sphere extends to the surface, it will cause surface disturbance within the area bounded by *mn* (Fig. 36), and the overhanging wall will gradually change its slope, depending upon the lateral extent and degree of the tearing and the relation between gravity and cohesion (see Fig. 37). Rziha thought that the stratification of the beds did not have much effect upon the angle of break. It may be noted that he did not make a detailed study of the subsided area in the field. The Mining and Metallurgical Society of M-Ostrau held that actual subsidence in the Ostrau-Karwin district did not conform to Rziha's theory.

(2) Vertical Movement. Rziha treated this subject under two headings: (a) The collapse into the underground excavation, and (b) the unwatering of the roof, causing a decrease in volume. He held

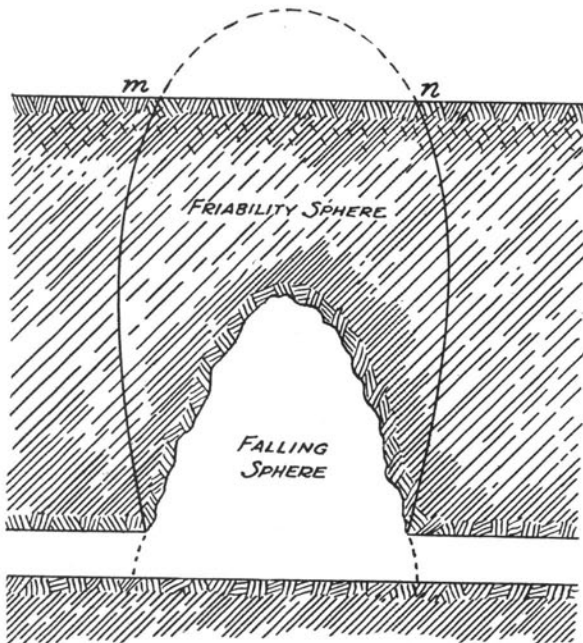


FIG. 36. "ZONE OF TEARING" EXTENDED TO SURFACE.

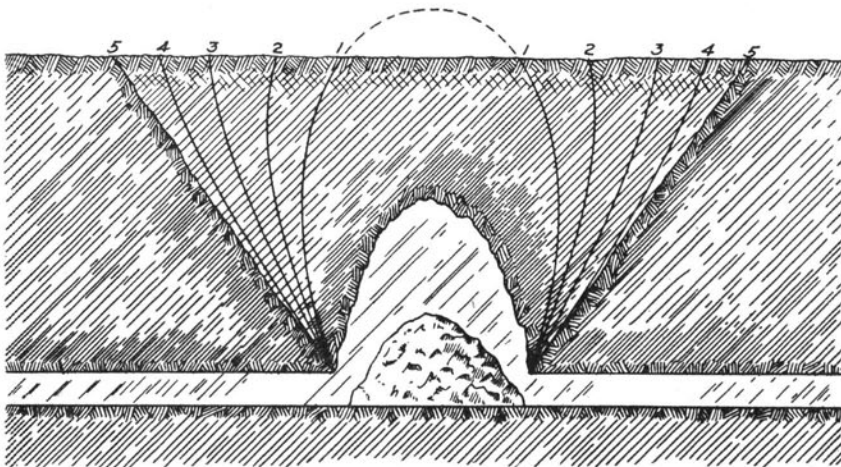


FIG. 37. SUBSIDENCE OUTSIDE UNDERMINED AREA.

that when mining is carried on at a great depth there may be no disturbance of the surface, and attempted to determine this depth by the formula:

$$h = \frac{M}{a}$$

in which h = harmless depth,
 a = coefficient of increase of volume,
 M = vertical seam thickness.

When pillars are left, he assumed that they will reduce subsidence, and the formula used to determine the harmless depth is:

$$h = \frac{M B}{a}$$

in which B is a coefficient for pillars and the filling, varying from 0.50 to 0.60. Rziha presented coefficients for the increase in volume of six kinds of rock. Goldreich* is of the opinion that an additional factor, overlooked by Rziha, is height of excavation. The less the height, the greater is the probability that the overlying rock will sink without complete or extensive crushing. Moreover, the completeness of the compression of the packing under the roof weight depends somewhat upon the height and extent of the excavation. These coefficients were not secured by mine investigation.

Goldreich criticises Rziha's suggestion of leaving pillars, and states: "If Rziha had been acquainted with the shape of the surface depressions, he would never have recommended the working methods given in his report." Objection is made also to the idea of a harmless depth as it "logically implies there ought to be the possibility of creating cavities of unlimited size beneath the harmless depth without giving rise to land movements on the surface." The Mining and Metallurgical Society of Ostrau (Moravia) to which organization Rziha's regulation was submitted, published its opinion in 1882.† Observations over a period of thirty years in the Austrian coal fields lead Goldreich to support Jicinsky's statement that no movement occurs if the water does not carry away from the volume under observation any solids mechanically or in solution.

Goldreich states‡ that the efforts to study theoretically the causes of subsidence in Austria date from the year, 1882. The Committee of the Mining and Metallurgical Society of Ostrau, Moravia, consisting of W. Jicinsky, J. Mayer, and von Wurzian, attacked Rziha's theory on the basis of observations in the Ostrau-Karwin district. Rziha failed to

*Goldreich Op. cit., p. 53.

†Oestrr. Zeit. für B.- u. H.-W., Vol. 30, 1882.

‡Goldreich Op. cit., p. 45.

consider the probability of the overlying rock bending and sagging without breaking to fill the worked-out space, as shown in Fig. 38. In the event that sagging takes place, the increase in volume will be much smaller than that figured by Rziha, who assumed a breaking up of rock. (Fig. 39.)

The Committee preferred to use the term "undangerous depth" in addition to Rziha's phrase "harmless depth" for those depths at which

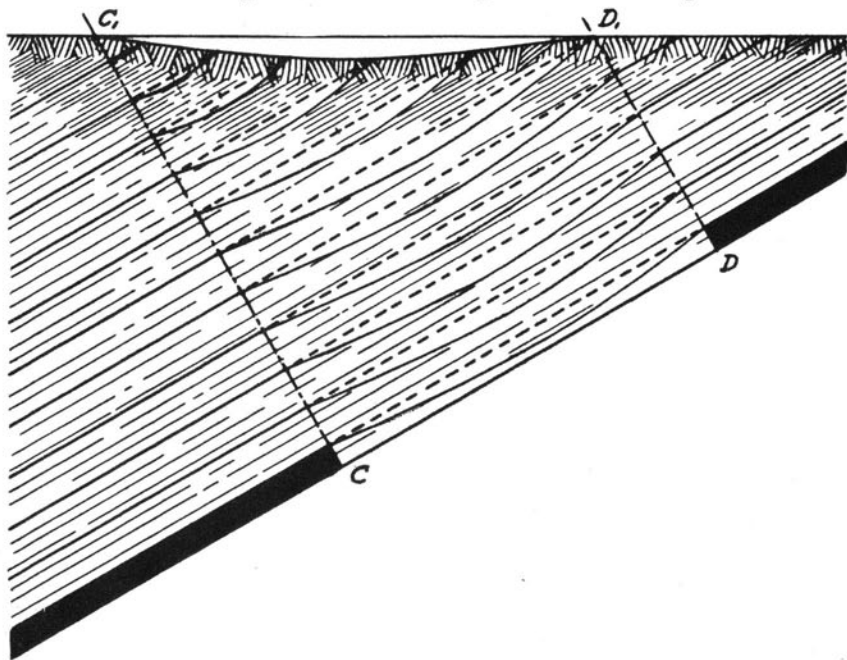


FIG. 38. LARGE SUBSIDENCE IN CASE OF BENDING OF ROCK.

mining will produce a gradual subsidence of the surface without damage to small objects or structures.

Jicinsky, a member of the committee, found the average increase in the volume of the rock of the coal measures and calculated the harmless depth from the maximum surface subsidence observed, according to the formula:

$$s = t + m - a t$$

$$\text{or } a = 1 + \frac{m - s}{t}$$

in which

s = surface subsidence,

t = thickness of coal rock exclusive of the coal bed,

m = thickness of coal bed,

a = average coefficient of increase of volume of the coal rock considered as a whole.

The term "coal rock" means the bed of rock overlying the coal which is broken in the course of subsidence, with consequent increase of volume. If s is made 0, the formula shows the thickness of overlying rock, exclusive of the marl, necessary to prevent surface subsidence. The entire mass of material above the coal rock is believed to settle without increase in volume and is not taken into account in the formula.

The average coefficient of increase of volume of the coal rock is found to be 0.01 (i. e., $a = 1.01$) for several cases of subsidence indicated by Jicinsky. His conclusion is then, as expressed by the formula, that the surface subsidence is equal to the thickness of the bed taken out

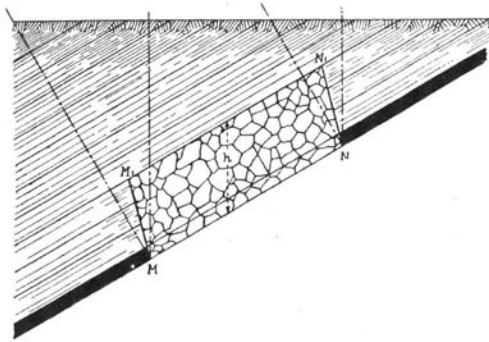


FIG. 39. SMALL SUBSIDENCE IN CASE OF BREAKING OF ROCK.

minus 0.01 of the thickness of the overlying rock which is shattered by movement.

The Committee also noted the vertical amount of subsidence and the duration of the movement, and special protective devices for shallow depths were considered. It was estimated that filling was compressed to 0.6 of the thickness of the bed so that in determining the harmless depth only 0.4 of thickness of the coal bed should be used in the formula. The committee agreed that "the interests of national economy demand that the leaving of coal pillars shall be prescribed in the rarest cases" and "the cost of the surface objects to be protected is to be compared with the coal losses." The Committee prepared regulations for coal mining under the mining railways, and these later became the basis of the regulations adopted.

Jicinsky's* monograph on subsidence appeared in 1884 and contained a complete statement of the principles accepted at that time by the leading Austrian engineers, and in it he formulated the following principles:

"The subsidence depends: (1) on the thickness of the seam, (2) on the dip of the seam, (3) on the depth of the mine, and (4) on the constitution of the roof rock of the seam. It may be regarded as a rule: (a) That the depth of the land subsidence is directly proportioned to the thickness of the seam, and the extension of subsidence is in direct proportion to the mined area; (b) that the depth of the surface subsidence increases with the dip of the seam, whereas its extension decreases, and for this reason in vertical seams the land subsidence is deep but manifests itself in the form of a kettle-shaped pit."

Jicinsky held further: "During every collapse of a solid rock there takes place a piling up of the broken masses. It follows that such a break causes an increase of volume and at a certain height in consequence of this increase in volume the entire empty space is so filled that no further after-break is possible; hence the effects of the break upon the surface must decrease with increasing depth. Every rock, even every single rock stratum, has its own hardness and toughness, and for this reason not all the kinds of rock behave in the same way during their collapse."

The subsidence formula of Jicinsky can be used to determine the harmless depth. Jicinsky discussed this point at length. He also made a study of the direction of fracture in the overlying rocks, and held that along the strike fracture is always normal to the coal bed. He objected to Gonot's and Schulz's theories for fracture on the dip and held that the angle was midway between the normal and the vertical. His views have been supported by 80 per cent of his observations.

He also considered in his monograph the amount of surface subsidence resulting from the mining of several superimposed seams, the various stages of rock movements, and safety pillars. In his opinion arbitrary rules cannot be used for determining the size of pillars, but each case must be studied separately and figured according to the local conditions.

C. Balling made a study of the angle of fracture in the northwest Bohemian brown coal basin and found that, for a depth of not more

*Jicinsky, W. "The Influences of Coal Mining Upon the Surface." Monograph of the Ostrau-Karwin Coal District, 1884.

than 300 feet and a dip of 8 degrees, the angle varied from 68 to 74 degrees.*

Chief Mine Inspector Anton Padour also made a report upon subsidence in the northwest Bohemian brown coal district.† He noted the vertical amount of subsidence and found the following relation:

$$H = 46 \sqrt[3]{h^2}$$

in which

H = vertical height of subsidence,

h = height of excavation.

He found that in the Bruch district, where the covering is firm marl, the angle of fracture is as follows:

(1) Thickness of capping from 1,000 to 1,200 feet, angle of seam from 0 to 8 degrees.

(a) towards the dip, angle varies from 72 to 69 degrees.

(b) towards the rise, angle varies from 72 to 74 degrees.

(2) Thickness of from 1,000 to 1,100 feet, angle of seam from 27 to 30 degrees.

(a) towards the dip, angle varies from 63 to 60 degrees.

(b) towards the rise, angle varies from 78 to 77 degrees.

In 1911 Goldreich delivered a lecture before the Austrian Society of Engineers and Architects of Vienna on the "Theory of the Railway Subsidence in the Mining District, With Special Consideration of the Ostrau-Karwin Coal District." Since that date he has made several important contributions to the literature of this subject.

In 1912 Franz Bartonik discussed the causes of subsidence, but made no contribution to the theory.‡

In 1913 Goldreich published his work on "The Theory of Land Subsidence in Coal Regions with special Regard to the Railway Subsidence of the Ostrau-Karwin Coal District," and followed this with a volume entitled, "Land Movements in the Coal District and their Influence on the Surface."¶

Goldreich criticises Jicinsky's contribution and theory in a number of points. He takes no exception to the fundamental principles but objects to the formula. Goldreich questions the assumption of a coefficient of increase of volume that will be applicable to all cases.

*Ballig, C. "Die Schätzung von Bergbauen nebst einer Skizze über die Einwirkung des Verbruches unter-irdischer, durch den Bergbau geschaffener Hohlräume, auf die Erdoberfläche," A. Becker, 1906.

†Padour, Anton Chapter on "Damage to the Land and Buildings" in the "Guide Through the Northwest Bohemian Brown Coal District," 1908.

‡Bartonik, Franz "Die Ursachen von Oberächenbewegungen im Ostrau-Karwiner Bergrevier. Montanist, Rundschau, Feb. 16, March 1 and March 16, 1912.

¶In press.

He points out the fact that the so-called "after-slide" of surficial material is not considered in the formula. He accepts Jicinsky's determination of the fracture in the coal measures, but objects to the formulating of general rules for determining the size of pillars. The principal portion of Goldreich's work is given to a discussion of the phenomena of subsidence in connection with railways. "From the profiles of sunken railway sections of the Ostrau-Karwin coal district it can be seen that these profiles have a parabolic form, that the maximum subsidences are found in the middle of these depressions, and that the amounts of subsidence decrease almost regularly towards the two ends of the curves until they finally become equal to zero." This regularity of the depressions caused Goldreich to undertake to formulate a theory of subsidence applicable to conditions such as those which exist in the Ostrau-Karwin district, the most distinctive feature being the surficial bed of plastic marl as much as 1,200 feet thick in places. Where the coal measures outcrop, the regularity of the surface depressions disappears and Goldreich takes refuge in the statement that we must depend merely upon experience.

Goldreich's observations developed the fact that following the subsidence of bed rock there is a vertical subsidence of the marl directly overlying and a lateral after-sliding of the adjacent and outlying marl. In discussing the subsidence of the roof strata he emphasizes the effect of the elasticity of each stratum. "When the elasticity of the subsiding roof strata is so great that the latter reach the floor of the worked out room without any disturbance in the coherence of the superimposed strata, then the volume of these subsiding strata remains unchanged." The subsidence of roof strata without increase of volume will occur in the case of the extraction of thin and flat seams. "The increase of volume which takes place during the first stage of the subsidence process is not enduring; for in consequence of the weight of the following roof strata the broken rock is again compressed, so that at the end of the rock movement there results a decrease of volume which is certainly not identical with the initial increase of volume." Only by observing the amount of surface subsidence caused by an underground working can a basis for estimating the coefficient of increase of volume under actual conditions be obtained. When the overlying beds are elastic there will be little increase in volume as the movement proceeds upward; under such conditions the term "harmless depth" cannot properly be used. "It cannot be pointed out strongly enough how absurd is the establishment of a harmless depth which should be valid for all work-

ings; the harmless depth has rather a theoretical character because the presuppositions required for the actual existence of the harmless depth are very seldom true in practice."

British Theories.

As previously noted, subsidences resulting from the mining of salt and coal in the British Isles were observed at an early date and were the cause of investigation by British engineers, who in general have supported the important principles of Belgian-French theories, although certain persons have taken exception to particular points in these theories. Numerous observations have been made upon subsiding areas and considerable valuable information has been collected, the data have been correlated and arranged, and empirical formulæ have been constructed so that adequate pillars may be left for the protection of surface structures and property of various kinds.

In 1868 a commission of Prussian engineers investigated subsidence in the various coal mining districts of England, and found that in England the opinion was approximately as follows:

(1) The working of coal at every known depth may affect the surface, but at depths greater than 400 meters (1,300 feet) it can cause damage only to certain buildings, such as cotton mills.

(2) In the case of complete extraction, filling may be a means of effective protection against movements of the earth.

(3) The practice of leaving pillars constitutes an efficient protection against the effects of exploitation upon the surface. The extent of these pillars of safety should be determined by the surface to be protected, the depth being known and the angle of rupture being assumed.

Observations carried on by J. S. Dixon demonstrated that the wave of maximum subsidence regularly followed the advancing face and that a wave of disturbance was just as regularly projected in advance of it;* that is, the wave of disturbance preceded the working face, but the maximum subsidence followed it. Joseph Dickinson called attention to the similarity between earth movements due to natural causes and those resulting from mining operations. He considered that "the direction of subsidence may be judged by analogy from the slopes taken by faults and mineral veins. The slope of a fault in horizontal strata averages about 1 in 3.07 from the perpendicular, varying according to the hardness and cohesion of the strata from

*Dixon, J. S. "Some Notes on Subsidence and Draw." Trans. Min. Inst., Scotland, Vol. 7, p. 224, 1885.

about 1 in 5 in hard rock to 1 in 3.75 in medium, and 1 in 2.5 in soft. He considered that for horizontal seams not exceeding 6 feet in thickness, and with strata of the average hardness of those in Lancashire, ordinary subsidence may be taken as extending on all sides to one-tenth of the depth, and that to obtain security a margin should be added. This margin is limited by some engineers to an additional one-tenth of the depth, while others add an arbitrary amount. When the strata are softer the extent of the subsidence is sometimes taken as one-sixth, or even one-fourth of the depth of the working, while, on the other hand, for hard siliceous rock, such as is found in South Wales, reductions are needed. He also agrees with other writers, that in seams of moderate inclination larger areas are required for support on the rise side than on the dip.”* T. A. O’Donahue in discussing subsidence† endorses the observations of J. Dickinson in the following language: “Joseph Dickinson is practically the only writer who has succeeded in connecting the threads of what was apparently a mass of contradictory evidence and in showing that the majority of cases approximately agree with a more or less definite rule.” In O’Donahue’s opinion, which is the result of considerable experience in studying the effect of surface subsidence, including the taking of levels, the “breaking lines of strata may be estimated within narrow limits with average conditions.” He enumerates the important factors affecting the position of the breaking lines and the ultimate extent of the subsidence as (1) the relative hardness of the strata, (2) the inclination, and (3) the thickness of the coal seam. He also mentions the influence of surface deposits. He considers the various angles of draw that have been noted and points out that for safety the maximum angle for given conditions must be taken as the limit for safety. For coal beds 6 feet thick and overlying strata of moderate hardness, he has found that the angle of draw is from 5 to 8 degrees beyond the vertical. This means that if a pillar is to be left to protect objects on the surface, a margin of one-twentieth to one-tenth of the depth should be left in order to provide against the draw. With inclined strata the draw increases roughly in proportion to the degree of inclination of the strata. He accepts the normal theory as correct when applied to dips of 18 to 24 degrees, but only for dip workings. When the mine workings are on the *rise* the maximum draw is estimated at 8 degrees for strata

*Hughes, H. W. “A Textbook of Coal Mining,” 5th Edition, p. 185, London, 1904.
Dickinson, J. “Subsidence Due to Colliery Workings,” Proc. Man. Geol. Soc., Vol. 25, p. 600, 1898, and Colliery Guardian, Oct. 28 and Nov. 11, 1898.

†O’Donahue, T. A. “Mining Formulæ,” p. 244, Wegan, 1907.

nearly horizontal and the draw is taken to cease with strata at an inclination of 24 degrees.

The ideas of O'Donahue are expressed in his formula for shaft pillars as follows:

M = Margin of safety, say from 5 to 10 per cent of the depth,

D = depth of shaft,

X = distance at the seam, between two lines drawn from a point at the surface, one line being vertical and the other at right angles to the seam.

Shaft pillar in horizontal strata

$$\text{Radius of pillar} = M + \frac{D}{7}$$

In inclined strata

$$\text{Rise side} = M + \frac{D}{7} + \frac{2}{3} X$$

$$\text{Dip side} = M + \frac{D}{7} - \frac{1}{3} X$$

For seams less than 6 feet thick the size of the pillar may be decreased, while for thick seams it is suggested that the size of pillars determined for a 6-foot seam be multiplied by the "square root of the thickness of the seam in fathoms."

In discussing the effect of the thickness of the seam upon the amount of subsidence, O'Donahue calls attention to the effect of the material stowed in the goaf or gob. He makes the point that, other conditions being the same, the mining of a 6-foot seam would result in more than twice the vertical subsidence caused by mining a 3-foot seam, owing to the fact that little material is thrown into the gob in mining the 6-foot seam, while in mining the 3-foot seam undoubtedly much "brushing" would have to be done and, therefore, there would be considerable material left in the goaf or gob. Therefore, the total subsidence per foot of coal removed will be greater in the case of the thicker seam.

He objects to the statement that mining at depths of 1,800 to 2,000 feet will not cause subsidence, because careful levellings will show that the complete removal of the coal at even greater depths will cause a sinking of the surface. "When the whole of the mine is taken out subsidence of the surface follows at all workable depths. The writer's observations show that the working of a seam, for instance 4 feet thick, will cause the surface to subside about 3 feet if the seam be not greater

than 600 feet in depth, and will cause a subsidence of from 12 to 18 inches at a depth of 2,400 feet.

H. W. G. Halbaum has made a careful study of roof pressures in longwall work and has made some notable contributions to the theories of subsidence. In his study of the action of the roof in longwall mining* he called attention to the *locking of the roof* due to the lateral thrust in great roof sections. "The great roof sections, by successive slips, have descended a few inches. The motion has been arrested for the time being by the lateral thrust, and the great body of strata remains securely gripped in the powerful jaws of its natural clamps." Subsequently Halbaum formulated the following proposition: "Contained in the total force of the roof action, there is a horizontal component, the action of which is contrary to the direction of working, and the power of which is sufficient to deflect the roof action from the vertical line."†

After discussing carefully the planes of strain, Halbaum considers the cantilever idea. He likens the unsupported roof strata to a huge cantilever whose load consists primarily of its own weight. "It is evident that if the cantilever were homogeneous and if the neutral surface were at half-depth, and if efficiencies of the compressive and tensile stresses to propagate their respective strains were equal, we should, under such conditions, obtain a mean line which would be vertical; for the tensile and compressive components would be equal in length and equal, though opposite in obliquity. The obliquity of one component would thus exactly balance the opposite obliquity of the other, and the mean line would be vertical." He then points out that such a balancing of components is unlikely, for the resistance of ordinary coal-measure strata to compression is usually greater than their resistance to tension. The neutral surface of the cantilever must generally lie below the half-depth of the beam. Moreover, the beam is not homogeneous. "Viewed from the broader standpoint of internal nature and external environment combined, there must be little or no exaggeration in the statement that our cantilever is immeasurably stronger to resist compression than to resist tension; and hence we are bound to infer that its neutral surface is very low indeed and probably not many feet above the roof-line itself." "It follows that by far the greater portion of the absolute line of elementary strain is supplied by the tensile

*Halbaum, H. W. G. "The Action, Influence and Control of the Roof in Longwall Workings." Trans. Inst. Min. Engrs., Vol. 27, p. 211, 1903.

†Halbaum, H. W. G. "The Great Planes of Strain in the Absolute Roof of Mines." Trans. Inst. Min Engrs., Vol. 30, p. 175, 1905.

component, that by far the greater portion is projected over and towards the solid, and that the mean elementary line must, therefore, possess a normal obliquity little less in magnitude than that of the tensile component itself." Stated in brief the idea is this: "We start with a thick unloaded cantilever and we end with a thinner but loaded beam; thinner, because from the standpoint of their efficiency, the upper layers are gone; and loaded, because from the standpoint of their dead weight, the upper layers remain only as a true load on the effective beam beneath. This simultaneous thinning and loading of the effective cantilever seems probable for several reasons: The principal one perhaps is to be found in the fact that the original beam is a composite beam formed by an aggregation of smaller beams (strata) in superposition. The whole of the composite beam is an effective beam only so long as its several layers firmly adhere at their conterminous horizontal planes or boundaries. As soon as the uppermost layer (or series of layers) separates from its subjacent layer, or tends to slide thereon, it ceases at once to form any part of the effective cantilever, to which cantilever it must thenceforward sustain the relation of a load only." He calls attention to the fact that "when we examine the cases of natural subsidences of the earth's crust, we find that the great planes of strain, in the normal case, are always projected over and towards the solid (or unsubsidized) strata."

In a paper before the International Geological Congress, Professor George Knox summarized the various points "which may be considered sufficiently well established to form a basis for further investigations—namely:

(a) That surface subsidence invariably extends over a greater area than that excavated.

(b) The angle of pull is determined by the ratio between the excavated and subsided areas.

(c) That this ratio is determined by a large number of factors, among which may be included the following:

1. The amount of permanent support left in the unmined area.
2. The thickness of the seam worked.
3. The depth of the workings from the surface.
4. The method of working adopted.
5. The direction of working in relation to the jointing of the strata.
6. The rate at which the workings advance.

7. The nature of the strata overlying the workings.
8. The presence of faults, fissures, etc., in the strata.
9. The permeability of the overlying rocks.
10. The dip of the strata.
11. The surface contour.
12. The potential compressive forces existing in the strata containing the workings.”*

He concludes that the ratio between subsidence and draw must be the joint result of the forces liberated by the withdrawal of support from underneath the strata in the mined area. The larger the proportion of settlement resulting in subsidence the less can occur in the form of draw, and vice versa “The number of factors that may influence the results produced by the settlement of undermined strata is so great that only a wide and comprehensive inquiry by geologists and mining engineers in those countries where mining is conducted on a large scale can be hoped to provide sufficient evidence to establish a definite theory or theories to assist in overcoming some of the more common dangers due to subsidence.”

Alexander Richardson, in a paper before the Chemical, Metallurgical, and Mining Society of South Africa, took up the question of stresses in deep masses of rock unsupported for hundreds of feet horizontally. “Where the strata are unfaulted, one would be justified in considering the mass as a huge slab supported on two or more sides or as a lever hinged at the bottom of the workings. Over extensive areas the pressure on the roof of an excavation, assuming the bed to be horizontal, will become in time equal to the weight of the superincumbent strata; under no circumstances is it immediately so, since the overlying beds must have some carrying strength.”†

Opinions of American Engineers.

While no new theories have been advanced by American engineers it may be profitable to review their opinions as given to the public through papers, investigations, or testimony.

As previously noted, a number of prominent engineers have made investigations as to the nature, extent and cause of the damage to property resulting from surface subsidence in Scranton, Pennsylvania. The published and the special reports noted on page 28 include ex-

*Knox, George “Mining Subsidence.” Proc. Int. Geol. Congress, Vol. 12, p. 798, 1913.

†Richardson, Alexander “Subsidence in Underground Mines,” Jour. Chem. Met. and Min. Soc. of S. Africa, Vol. 7, p. 279, March, 1907; Eng. and Min. Jour., Vol. 84, p. 196, 1907.

pressions of opinion, but little discussion of the principles and theories of subsidence.

Douglas Bunting, who has made a study of the "Limits of Mining under Heavy Wash" in the anthracite region of Pennsylvania,* considered the various sedimentary rocks of the coal measures and determined the minimum thickness of rock cover for various depths below the surface and for rooms of various widths. He had previously made a study of chamber pillars in deep anthracite mines, and had calculated the width of rooms for various depths upon the basis of the compressive strength of anthracite.†

In discussing subsidence in the longwall district of Illinois, G. S. Rice said, "The roof settles most in the first few months, but it is several years before it is entirely settled, by which time the gob has been squeezed down to one-half or one-third its original thickness." The roof is very free from slips and vertical cracks or joints until the coal has been mined below it, but when the coal is brought down in a long strip, it marks the roof just where the break of coal has occurred, and along these marks the roof afterwards breaks. These breaks seem to run up indefinitely, and oftentimes they can be followed up to the black slate, 8 or 10 feet above. As a result of mining the seam, which varies in thickness from 2 feet, 10 inches to 4 feet, or an average of 3 to 3½ feet, "the settling of the roof is appreciable at the surface even when the seam is at a depth of 400 or 500 feet; but so gradual is it and without vibration that the deep mines have caused no trouble in going under railroad tracks, and even under brick buildings, as has been done at La Salle."‡

Charles Connor believes "If we extract all the coal we, naturally, will have a subsidence of the surface. That must inevitably follow because, when the support is all removed, the rock settles down on the floor of the mine." He cited observations made in the county of Lanark, Scotland, where the mining of seven seams approximating 30 feet in thickness and lying at depths of from 900 to 2,700 feet necessitated the raising of canal banks 18 feet. The sinking was gradual and no water was lost out of the canal.§

In discussing the action of beds overlying mine workings

*Amer. Inst. Min. Engrs., Bul. No. 97, p. 1, 1915.

†Bunting, Douglas "Chamber Pillars in Deep Anthracite Mines." Trans. Amer. Inst. Min. Engrs., vol. 42, p. 236, 1911.

‡Rice, G. S. "System of Longwall Used in Northern Illinois Coal Mines," Columbia Univ. School of Mines Quart., Vol. 16, p. 344, 1894.

§Connor, Charles "Discussion of Paper." Proc. Coal Min. Inst. of America, p. 149, 1912.

W. A. Silliman expressed the opinion that these beds do not act as a monolith, but that the beds may have little adherence to each other. Where the measures are weakest the strain will be greatest, as in the fireclay bottom.*

S. A. Taylor has pointed out the fact that the tendency of one measure to slip on another is "counteracted by the fact that the roof is a continuous mass, so that as soon as any part tends to give, it has to slide to get past adjacent surfaces and the surfaces are pressed together with no little weight. If any part is weak, it is nevertheless held in place and the strain goes to the other measure." In his opinion the roof rock acts as a monolith in most cases.† He also believes that the occurrence or absence of subsidence depends on the height and character of the overlying strata. "You cannot set any hard and fast rule; the rule set down by the English authority 'one to ten' (there will be no breakage on the surface if the rock cover is ten times the thickness of the coal worked) will not hold. It may be true in some cases, but it will not serve as a universal rule, as its truth or falsity in any instance depends on the character of the overlying strata."‡

R. D. Hall has suggested that when the roof sags down over the edge of a pillar the curve of the roof tends to follow back over the solid coal, criticising the general notion that the roof lies flat upon pillar and then sags down over the edge of the pillar.§ He has also shown to what extent in his opinion shear is the cause of the failure of mine roof.¶ He concludes his discussion of shear, "In the case of mine roof, everyone seems to be confident that we have a structure which invariably fails from shear. The idea is contrary to all the evidence and should be dismissed. The raggedness of roof fractures disproves it if other reasoning does not."** In discussing the strength of mine roofs R. D. Hall has presented a series of sketches, showing conditions producing breakage of roof.†† He suggests that the roof over rooms acts after the first fractures not like a beam but like an arch, and that continuous beams or plates are replaced by disconnected arches or vaults. He concludes by suggesting a "progressive advance in demolition: First, a condition, as yet unnamed, symbolized by the tunnel in solid rock in which roof and sides and floor

*Proc. Coal Mining Inst. of America, p. 84, 1911.

†Op. cit., p. 85.

‡Taylor, S. A. In discussion of R. D. Hall's paper, "Effect of Shear on Roof Action."

Proc. Coal Mining Inst. of America, p. 146, 1912.

§Hall, R. D. "Action of the Roof." Proc. Coal Min. Inst. of America, p. 64, 1911.

¶Hall, R. D. "Data of Petrodynamics." Mines and Minerals, Vol. 31, p. 210, 1910.

**Hall, R. D. "Effect of Shear on Roof Action." Proc. Coal Min. Inst. of America, p. 144, 1912.

††Hall, R. D. "The Strength of Mine Roofs," Mines and Minerals, Vol. 30, p. 474, 1910.

all partake of the beam strain. Second, a horizontal shear which converts the sides into mere supports and the roof into a true beam or plate; Third, a rupture of the roof which converts it into an arch, and finally, a failure of the arch or vault by one of the many weaknesses to which such structures are subject.”*

The tendency of the roof to arch has long been noted, and the mechanics of natural rock arches has been discussed by a number of engineers. However, there has been little agreement among engineers as to the portion of the burden of the overlying beds which is actually borne by such natural arches. The strata acting as a uniformly loaded

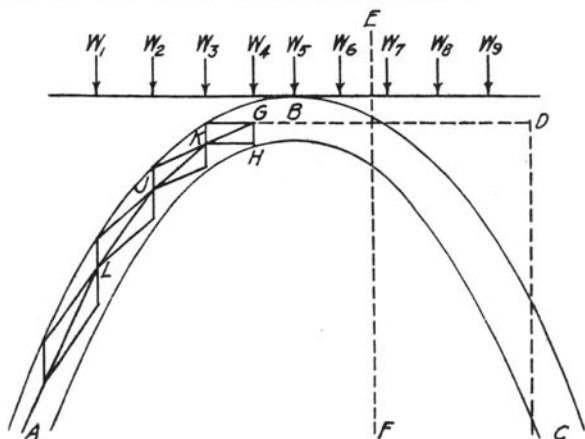


FIG. 40. STRESSES IN ARCH.

horizontal beam cannot support a great load, and as the strata sink the upper measures tend to arch and eventually the entire mass may be supported by the arch.

The theory of the arch as applied to this problem has been discussed by B. S. Randolph† as follows: In the arch $A B C$, Fig. 40, the two sides $A B$ and $B C$ are mutually supported at B where the thrust is horizontal. Assuming the load to be evenly distributed over the arch, it is found that the points B, G, K, J, L all lie in the line of stress. This line of stress “when lying in solid material over an excavated cavity will constitute, for all practical purposes, an arch supporting all the material above it and allowing the removal of all the material below it up to the point where this material becomes effective

*Hall, R. D. “The Last Stand of the Mine Roof.” *Coal Min. Inst. of Amer.*, 1914, and *Coal Age*, Vol. 6, p. 982, 1914.

†Randolph, B. S. “Theory of the Arch Applied to Mining.” *Coll. Engineer*, Vol. 35, p. 427, 1915.

in resisting the stress. There will, of course, exist along and on each side this line of stress a zone of material under more or less pressure, depending for its width on the total stress and the elasticity of the material. The position and character of the forces acting on the arch will vitally affect the shape of this line of stress. In an arch under a perfect fluid, where the pressures are all radial acting toward a common center, the line of stress becomes the arc of a circle. With an excess of load toward the center, it takes the shape of the parabola, the focal distance shortening as the central load exceeds that on the side. With the excess of pressure on the sides, say at an angle of 45 degrees, it assumes the shape of an ellipse, the focal distance shortening as the pressures at the side exceed those in the middle." In the arch formed over rooms, as the load for all practical purposes is equally distributed, "the curve will be a parabola with a longer or shorter focal distance

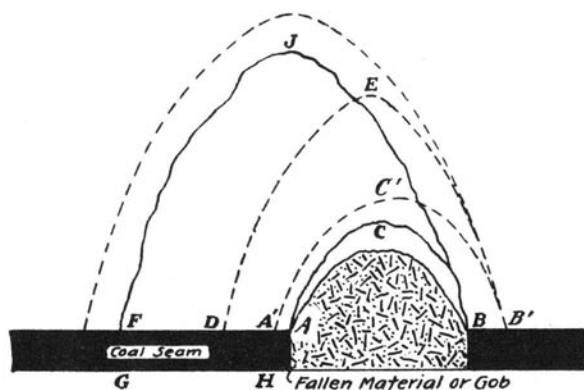


FIG. 41. ARCH STRESSES IN MINE ROOF.

depending on the nature of the strata." "Let Fig. 41 represent the section of a coal seam from which the coal has been removed between A and B, the roof having fallen to the irregular line A C B. The dotted line A' C' B' will indicate the line of stress. This, it will be seen, impinges on the coal close to the edge at A. The stress at this point represents half the weight of the strata overlying the span A B which is assumed to be sufficient to crush the coal about the point A. The integrity of the arch being destroyed, the line of stress must seek a new position such as D E B. Naturally this movement will be no greater than is absolutely necessary to gain a solid footing for the arch, which will again be so near the edge of the coal already crushed that it will fail again in a short while, necessitating a further adjustment

of the position of the arch. With this continuing failure and readjustment we have the well-known phenomena of a crush or squeeze advancing slowly over the workings, destroying coal as it goes.

If now a considerable body of the seam, as $A H G F$, is quickly removed a "fall" may result which will reach high above the seam, say to the line $F J B$, which will cause the line of stress to move quickly and reach the coal well back from the point F , where it is sufficiently solid to give the needed support, and the working will be said to have "gotten ahead of the crush," when in fact the crushing force has gone ahead of the working. This explains the common experience of the relief at the working end of the pillar caused by an extended break in the roof over the exhausted area.

Under other conditions, especially when the arching line of stress has a wide span, thus carrying a large amount of weight, the crushing force may prove too much for even the solid coal well back from the end of the pillar and cause the phenomena of crushed coal, broken tim-

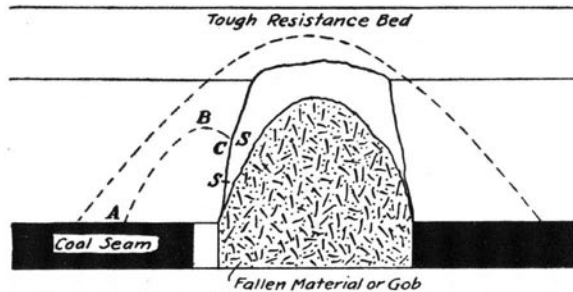


FIG. 42. SPACE SHORTENED BY FALLING OF ROOF.

bers, creeping floor, etc., well down the room or stall, while the ends of the pillars will be free from any trouble, as they carry only the small amount of material which is below the line of stress. This condition will sometimes be cured automatically by the material falling from the top of the cavity over the exhausted area in such a manner that the space between the material already down and the undisturbed measures will be filled and the opposite limb of the arch (the right hand in the figure) will find support on this already fallen material and thus shorten the span of the arch and lessen the total weight, as illustrated in Fig. 42.

When the break has reached the surface, this filling takes place more rapidly owing to the fracture of the overhanging beds along the edge of the break and, since the arch has a new point of support for

its inner or right hand limb, the conditions are ripe for further working undisturbed under the smaller arch.

While the general shape of the line of stress in the cases under consideration is the parabola, for all practical purposes the ratio between the span and the rise or height of the arch will vary much as the material varies in which it exists. After the fall of the first mass the cavity grows through the crushing and falling of the material along the top of the arch, due to the pressure along the line of stress, and by the splitting off along the joint planes of the material on the sides due to the same cause. Since the pressure along the upper portion of the line of stress is manifestly less in a high sharp arch than in a low flat one, the shape of the arch in this respect may be expected to vary with the capacity of the material to withstand this stress. Hence, there will be a high arch in a soft material with numerous joints and a flat arch in tough material with fewer joints. This may be verified practically by the examination of old drifts or tunnels where the overlying material has had an opportunity to fall and take the shape due to such conditions without regard to other influences.

If, then, the cavity in its upward progress encounters a bed of tough resistant shale or sandstone, it may fall so slowly that a large area may be opened by continuous mining during the delay, resulting in a heavy weight along the line of stress due to the wide span and crushing the coal either at the working end of the pillar or at such point along the course of the room as the line of stress may meet the coal as shown in Fig. 42. Such a crush is not likely to find relief until the overlying measures are sufficiently broken down to fill the space $S S$, and allow the development of a new smaller arch of stress $A B C$, which, having less span and consequently less load, will transmit less load to the point A .

Dr. F. W. McNair has reviewed the question of pressures and support in the deep copper mines of the Lake Superior region. In a lode dipping 38 degrees and with pillars 50 feet wide, having on either side an open space of 150 feet, the pressure on the pillar at a depth of 5,000 feet would be 1,239 tons per square foot, allowing for neither rigidity nor arching and supposing the weight on the pillar evenly distributed. The pillar would fail under this pressure if it were mainly trap rock. "As a matter of fact, in such a case, the rigidity of the mass distributes a large part of the load out over the rock beyond the walls of the opening. That this rigidity may be considerable is illustrated in several cases in which areas of hanging wall as wide as 200 feet or more have

no support between walls and yet have stood up for several years. As the rock between pillars and walls bends downward the tendency is to concentrate the load at the edge or face of the pillar or walls. The outer parts of the pillar may thus become overloaded and fail by the splitting off of pieces of rock, that break from the base as well as the top, and like any hard rock under a crushing load, the pillar usually fails suddenly. The hanging rock mass moves, of course, when the pillar crushes, and the vibration due to the sudden though slight displacement is often conveyed to the surface. The result is a miniature but perfectly genuine earthquake that may be felt over a distance several times that of the pillar from the surface. With the crushing of the pillar and the movement of the hanging wall, a readjustment of the weight takes place, and the process begins over again. Eventually, at great depths, the hanging and foot walls must come together.

"The readjustments that take place when a pillar fails sometimes put an enormous longitudinal thrust on the foot wall, and in places its surface portion has buckled under such stress. Experience seems to show that at the great depths recently reached it is useless to expect to hold up the hanging rock mass for a long time by any scheme of pillars unless far too much of the lode is left in place, and that the only feasible method is to cut away the entire lode and permit the hanging to cave as rapidly as it will to the point where the broken rock fills again the whole space and redistributes the weight over the foot wall."*

C. T. Rice objects to the general statement that stopes will cave until filled, except in the case of running ground. In the few caved stopes which he has inspected he has "always found an open space between the arched roof and the pile of caved rock. In general, such a large stope opening is necessary before caving commences; the self-supporting dome is assumed before the stope fills itself. The caving action is progressive, and as the slabs accumulate in the stope they so support the sides that caving ceases. Finally, owing to the weakening of other stopes, the faulting stage is reached; not until then does the opening become completely filled.

"In supporting the roof of a stope, only that portion of the roof that is below the line of the dome of equilibrium requires support; the rock above this dome sustains itself. If, therefore, the shape of this dome of equilibrium in each kind of rock were known, it would be easy

*McNair, F. W. "Deep Mining in the Lake Superior Region." Min. and Sci. Press, Vol. 94, p. 275, 1907, and Eng. and Min. Jour., Vol. 84, p. 322, 1907.

to calculate the weight of rock hanging below the dome, and so timber the stope as to hold up this weight." C. T. Rice is under the impression that the shape of this dome is fairly constant in each kind of rock; especially in the same rock in the same district. "Of course, slips and joints, sudden changes in chemical composition, the dip of the strata in sediments, and many other facts, would affect the shape of the dome, but as long as these were small their effect would also be small. If investigation of the shape of this dome should suggest any formula to determine the strength of timber necessary to support the ground below the dome, the effect of these joints, etc., could easily be included by the factor of safety used."*

*Rice, Claude T. "The Dome of Equilibrium and the Caving System of Mining." *Mining and Sci. Press*, Vol. 95, p. 85, 1907.

CHAPTER IV.

ENGINEERING DATA AND OBSERVATIONS.

In America very few data have been collected on subsidence due to mining operations, at least the data, if collected, have not been made available for scientific purposes.

In order that observations may be of value the following correlated data are desirable:

(1) The elevations of a number of points on the surface for a period of years both prior to, during, and following the mining directly beneath.

(2) The position of these points with regard to permanent stations located outside of the mining field or upon ground which has not been or will not be subject to the influence of the mining operations.

(3) The position of the working face in the mine on the various dates of survey.

(4) An accurate location and description of the character of the portions of the mineral deposit left unmined.

(5) An accurate location and a description of the supporting materials placed in the excavated area.

(6) The thickness and dip of the material mined.

(7) The thickness and character of the bed immediately underlying.

(8) The thickness, dip, and character of the overlying rocks and all available information in regard to structure.

(9) The thickness and character of the surficial material.

(10) The quantity of water removed from the mine.

(11) The location, extent, and data of underground movements of rocks overlying the mineral deposit.

In Europe records have been kept for many years in various districts in order to determine the vertical amount, lateral extent, rate, and duration of subsidence.

Among the first surveys made to determine the movement of the surface were those of Fayol.* At Commentry Mine from 1879 to 1885, as shown in Figs. 43 and 44, surveys were made to correlate surface movement and the advance of the working face. The seam which was almost 48 feet thick was worked in horizontal slices of about 8 feet in

*Fayol, H. Bul. Soc. Ind. Min., II ser., Vol. 14, p. 818, 1885. Coll. Eng., Vol. 11, p. 26, 1890-91.

ascending order. The thickness of rock cover was 321 feet. Some filling of shale and sandstone quarried on the surface was used. It was observed that:

(1) During the removal of the first slice, the lowering of the surface gradually grew greater, and was further increased considerably by the working of the second.

(2) The area of subsidence was about four times larger than the area worked.

(3) The maximum sinking was 3 feet 5 inches or one-fifth of the height of the two slices.

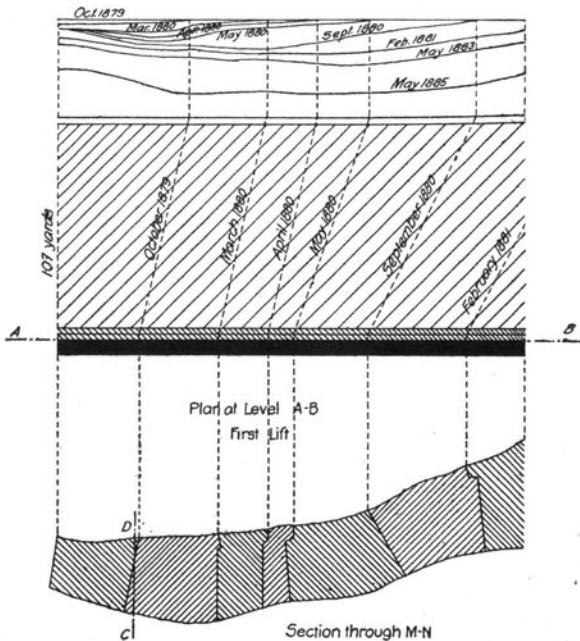


FIG. 43. SUBSIDENCE AT COMMENTRY MINE.

(4) The movements of the ground appeared at first at a certain horizontal distance in advance of the working faces and this distance remained nearly constant.

(5) The subsidences increased during a certain time while the working proceeded.

(6) The second lift caused a total subsidence almost equal to that of the first lift. This subsidence was 2 feet 1 inch for the first and 1 foot 11 inches for the second, in all 4 feet.

(7) The area of subsidence cannot be determined, either by normals or verticals from the bed worked.

The surveyor's records showing surface movement in connection with the Warrior Run Mine disaster have been noted previously.* The ratio between the volume of subsidence as noted on the surface and the volume of excavation has been noted for the caving system of mining on the Gogebic range.† "When a slope caves, and the dome above it runs up into sand or loose rock, the depression formed is usually in the shape of an inverted cone; but where the ore body is wide, or deep below the surface, the subsidence usually takes the form of terraces. Sometimes comparatively large areas will break through cleanly and the whole surface will drop suddenly and as a unit, but this is exceptional.

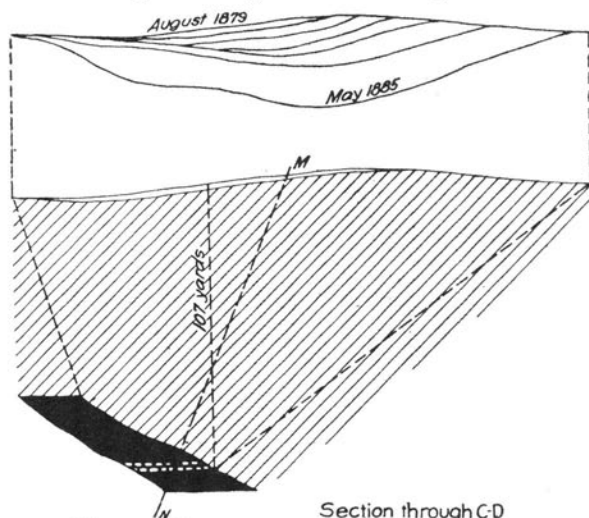


FIG. 44. SUBSIDENCE AT COMMENTRY MINE.

After the back has once started to cave, the surface usually sinks in terraces." In the area under observation the deposit consisted of a lense of soft hematite about 40 feet in average width and 150 feet high, with a length of nearly 1,600 feet on the incline, lying in a trough between a dike of diorite and a thick band of slate. The trough pitched 11 degrees, the hanging wall was hard jasper, and the ore was mined first by square-set rooms and pillars, about 60 per cent of the ore being secured on first mining, but later the pillars were robbed. The hanging wall has dropped from 15 to 75 feet and subsidence has extended to

*See page 43.

†Eaton, L. "Surface Effects of the Caving System," Min. and Sci. Press, Vol. 97, p. 428, 1908.

the surface. The proportion between the volume of surface subsidence and the volume of excavation is shown by the following figures:

	Cubic Feet
Original volume of ore body.....	7,680,000
Present volume of ore body, including rock, timber, etc.....	2,360,000
Volume of material removed.....	5,320,000
Volume of material removed under cave.....	2,300,000
Volume of material removed under subsidence on surface.....	3,020,000
Volume of cave on surface.....	790,000
Volume of subsidence on surface.....	1,430,000
Volume of cave on surface	1
Volume of ore taken from under it	= $\frac{2.91}{1}$
Volume of subsidence on surface	= $\frac{1}{1}$
Volume of ore taken from under it	= 2.11

J. S. Dixon made observations at Bent Colliery* A line was selected at right angles to the advancing workings and as nearly as possible on the level course of the coal. Stations were put in every 100 feet and afterwards every 50 feet. The excavation was 5 feet 6 inches high and the overlying strata were allowed to fall and fill it. The surface was principally boulder clay. The original level of the surface before the pillars were drawn is shown in Table 8.

The pillars were removed for a distance of 240 feet back from the solid coal on Jan. 21, 1882, and no subsidence of the surface had ensued. On May 27, 1882, the levels showed the maximum subsidence to have been 1.80 feet at station 1650, which was 145 feet back from the face, and the draw extended to 60 feet in advance of the working face. On November 14, 1882, the face was 610 feet from the solid, and the subsidence was as is shown in the table. On April 15, 1883, the face was 750 feet from the solid; on November 27, 1863, it was 1,060 feet distant; and on October 23, 1884, the removal of the pillars had been completed for some months, and the face was 1,230 feet from the solid. On June 17, 1885, the workings had been in the same position for about a year. On December 4, 1885, it was found that subsidence had practically ceased and the draw had not altered.

The conclusion arrived at is that subsidence from the removal of coal in this case attains its maximum towards the center of the excavated space, and gradually decreases in each direction. The maximum subsidence, 4 feet, was 73 per cent of the thickness of the coal, and the average, 3.76 feet, was 68 per cent. The wave of maximum subsidence regularly followed the working face at an average distance back of 186

*Trans. Mining Inst., Vol. 7, p. 224, Scotland, 1886. Cit. in Brough, B. H., "A Treatise on Mine Surveying," pp. 241-245.

TABLE 8.
OBSERVATIONS AT BENT COLLIERY.

Peg.	Original Level of Surface	Subsidence From Original Level at					
	1881	Nov. 14, 1882	April 5, 1883	Nov. 27, 1883	Oct. 23, 1884	June 17, 1885	Dec. 4, 1885
600	640.6	.....	.....	.....	0.25	0.35	0.45
650	648.9	.....	.....	.....	0.35	0.60	0.60
700	657.2	.....	.....	.....	0.77	0.94	0.94
750	664.6	.....	.....	.....	1.18	1.27	1.40
800	667.5	.....	.....	0.23	1.37	1.75	2.00
850	673.1	.....	.....	0.63	1.50	2.24	2.34
900	675.6	.....	.....	1.13	2.57	2.74	2.82
950	676.0	.....	.....	1.61	2.97	3.14	3.22
1000	677.1	.....	.....	2.10	3.27	3.49	3.60
1050	677.3	.....	.....	2.43	3.32	3.64	3.75
1100	678.8	.....	0.50	2.80	3.52	3.80	4.00
1150	679.7	.....	0.70	2.93	3.57	3.81	3.92
1200	680.6	.....	1.20	.....	3.52	3.52	3.52
1250	680.9	0.60	1.60	3.08	3.45	3.45	3.45
1300	679.2	0.40	2.09	3.03	3.42	3.42	3.42
1350	677.9	1.60	2.25	3.00	3.27	3.27	3.27
1400	677.5	1.60	2.45	3.83	3.17	3.17	3.17
1450	680.8	2.30	2.90	3.42	3.42	3.42	3.42
1500	680.1	.....	3.05	3.05	3.05	3.05	3.05
1550	677.1	2.90	3.20	3.20	3.20	3.20	3.20
1600	675.5	3.00	3.00	3.00	3.00	3.00	3.00
1750	672.8	2.80	2.80	2.80	2.80	2.80	2.80
1850	663.4	1.70	1.70	1.70	1.70	1.70	1.70
1950	648.6	0.60	0.60	0.60	0.60	0.60	0.60
2000	649.7	0.04	0.04	0.04	0.04	0.04	0.04

feet, or 1 foot horizontal for each $3\frac{1}{2}$ feet perpendicular. The permanent lengths of the draw may be taken as 100 feet on one side and 83 feet on the other. At these points the depth of the coal was 650 and 646 feet, representing a draw of 1 horizontal for each 7.14 feet perpendicular on the average. The coal dips at 1 in 20.

Surveys were made at the South Kirby Colliery in order to determine the extent and amount of surface movement due to the removal of a shaft pillar.* No observations were made until two years after the mining of the pillar was commenced. The seam in which the pillar was removed lies at a depth of 2,108 feet, is 3 feet 9 inches thick, and dips 1 in 18. Above the coal is one foot of clod. Some movement of the surface was noted before the surveys were made. At depths of 1,600 and 1,800 feet occur the Beamshaw seam of 3 feet and the Barnsley seam of 9 feet which had been worked previously. The data of the surveys are given in Table 9. The unusually large ratio of subsidence (3.47 feet) to the total thickness excavated in removing the pillar (4.75 feet) is attributed to the failure of the shaft pillar in the overlying Barnsley seam.

*Snow, Charles "Removal of a Shaft Pillar at South Kirby Colliery." Trans. I. M. E., Vol. 46, p. 8, 1913.

TABLE 9.

DATES OF LEVELING AND PARTICULARS OF SUBSIDENCE AT SOUTH KIRBY COLLIERY.

Dates of Levelings	Subsidence Since Previous Leveling	Total Subsidence
November, 1903.....	Feet	Feet
July, 1904.....	Nil.	Nil.
March, 1905.....	Nil.	Nil.
October, 1905.....	0.74	0.74
April, 1906.....	0.17	0.91
October, 1906.....	0.22	1.13
June, 1907.....	0.77	1.90
April, 1908.....	0.17	2.07
December, 1908.....	Nil.	2.07
May, 1909.....	Nil.	2.07
May, 1910.....	0.82	2.89
May, 1911.....	0.18	3.07
June, 1912.....	0.40	3.47
June, 1913.....	Nil.	3.47

Levelings made by Chas. Snow at the Hickleton Main Colliery (details not given) showed that subsidence was evident 433 feet in advance of a rapidly advancing longwall face, and that total subsidence occurred

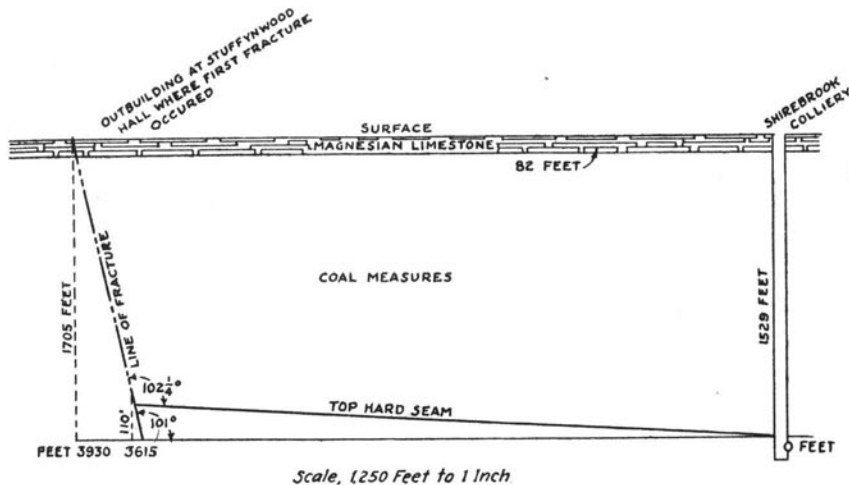
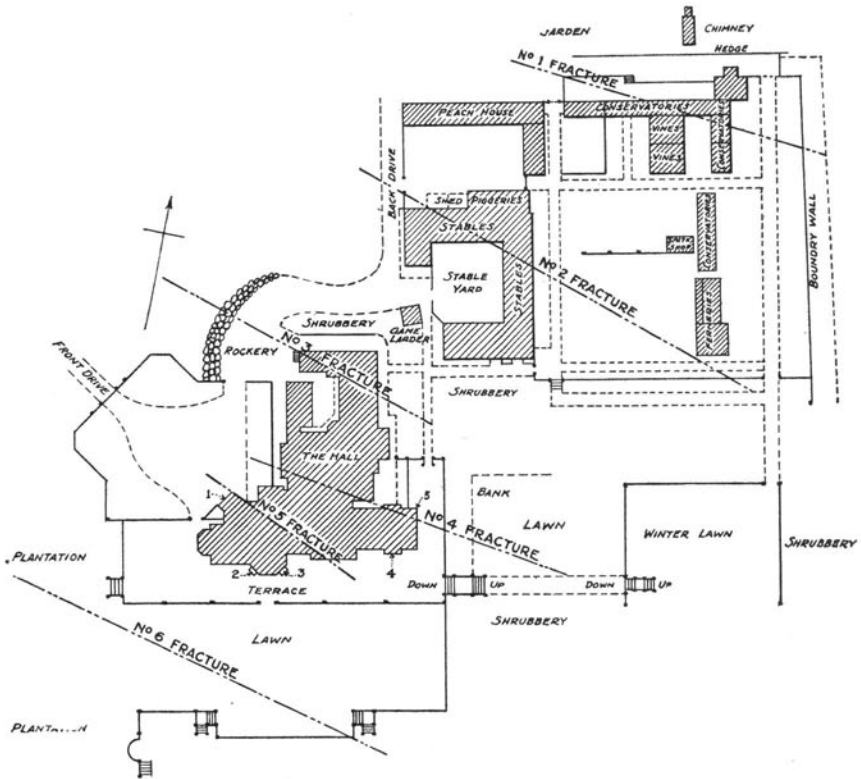


FIG. 45. ANGLE OF FRACTURE AT SHIREBROOK COLLIERY.

666 feet back from the face, the amount of subsidence being 4.5 feet. At the edge of the shaft pillar, 500 feet back from where the greatest subsidence occurred, the subsidence was 1.28 feet. Subsidence extended for a distance of approximately 600 feet over the shaft pillar.*

*Trans. I. M. E., Vol. 46, p. 21, 1913.

For a period of 16 years surveys were made at the Teversal and Pleasley Collieries by J. Piggford,* but details of the surveys have not been published. The angle of draw or fracture was estimated to be approximately 16 degrees from the vertical and toward the unworked coal. The depth of the coal seam was approximately 600 feet and the coal was from 5 to 6 feet thick.



Scale, 120 Feet to 1 Inch

FIG. 46. FRACTURES AND SURVEY STATIONS, SHIREBROOK COLLIERY.

Records were kept at Shirebrook Colliery and reported by W. Hay.† The coal lies at a depth of from 1,500 to 1,700 feet, dips 1 in 24, and is 5 feet thick. When the longwall face was 240 feet from Stuffynwood Hall cracks were noted in the surface, the direction of fracture varying as much as 15 degrees from the direction of the coal

*Trans. I. M. E., Vol. 38, p. 128, 1909.

†Hay, W. "Damage to Surface Buildings Caused by Underground Workings." Trans. I. M. E., Vol. 36, p. 427, 1908.

face. Fig. 45 shows the angle of fracture in section. When the working face was almost vertically beneath, the cracks had attained their maximum width and thereafter commenced to close. When the face had advanced 300 feet farther, the walls of the buildings had assumed practically their normal position.

Levels taken at regular intervals are given in Table 10. The survey stations are indicated on Fig. 46.

TABLE 10.
SUBSIDENCE AT STUFFYWOOD HALL.

Date	Time in Months From First Levels	Station No. 1a	Station No. 1	Station No. 2	Station No. 3	Station No. 4	Station No. 5
March 7, 1906	0	0.00	0.00	0.00	0.00	0.00	0.00
May 18, 1906.	2	0.00	0.00	0.00	0.00	0.00	0.00
June 11, 1906.	3	0.00	0.00	0.00	0.00	0.00	0.00
June 20, 1906.	3	0.00	0.00	0.00	0.00	0.00	0.00
July 10, 1906.	4	0.02	0.00	0.01	0.02	0.02	0.03
Aug. 27, 1906.	5½	0.11	0.09	0.16	0.18	0.18	0.20
Oct. 25, 1906.	7½	0.19	0.17	0.17	0.19	0.18	0.20
Dec. 10, 1906.	9	0.20	0.18	0.17	0.19	0.17	0.21
Feb. 6, 1907..	11	0.22	0.18	0.17	0.19	0.23	0.29
Mar. 9, 1907.	12	0.26	0.26	0.17	0.25	0.31	0.37
Mar. 29, 1907.	12½	0.28	0.26	0.26	0.25	0.31	0.37
June 20, 1907.	15½	0.67	0.43	0.44	0.44	0.52	0.63
Aug. 21, 1907.	17½	0.86	0.67	0.67	0.68	0.80	0.91
Nov. 12, 1907.	20	1.09	0.84	0.83	0.84	0.99	1.10
Jan. 30, 1908.	23	1.23	0.96	0.91	0.97	1.15	1.26
July 9, 1908..	28	1.56	1.23	1.21	1.34	1.41	1.51
Nov. 12, 1908.	32	1.74	1.34	1.35	1.37	1.54	1.63

The maximum subsidence was 1.74 feet and the minimum 1.34 feet, the average being practically 30 per cent of the total height of excavation.

Levels extending over a period of five years were taken by S. R. Kay on the surface of a portion of two collieries mining at depths of 360 feet and 990 feet.* Where the levels were run, the surface was fairly level, the strata were nearly horizontal and were free from faults of any magnitude. The strata consisted of alternating beds of shale, sandstone and limestone, none being massive. Figs. 47 and 48 show the data secured. The working of the 5-foot seam at a depth of 360 feet resulted in subsidence amounting to practically 70 per cent of the thickness excavated. Similar effects resulted from mining the 3-foot, 6-inch bed. At the greater depth subsidence began about six months after the coal had been mined and continued for years.

*Kay, S. R. "Effect of Subsidence Due to Coal Workings." Proc. I. C. E., Vol. 135, p. 115, 1898.

A report by C. Menzel* showed that since 1885 observations of the rate of settlement had been made at eight-two points in the vicinity of the collieries of Zwickau, Saxony. The depth of the coal beds varies from 600 to 2,400 feet. A maximum subsidence of 7.1 feet was noted twelve years after three seams had been mined out at a depth of from

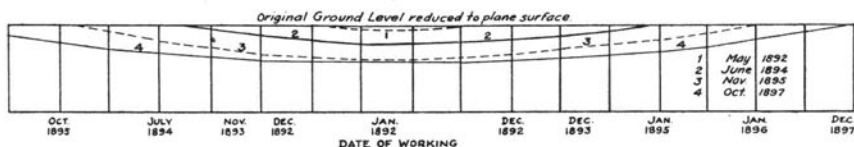


FIG. 47. DATA OBTAINED BY S. R. KAY.

600 to 900 feet. At a depth of 1,500 feet the subsidence was only 0.6 feet. By the use of filling subsidence was greatly reduced, it being noted that on an average the filling was compressed to one-half of its volume when stowed. The ratio of subsidence to thickness of seam excavated was found to vary from 1:1 to 1:7, the average being 1:2. Frenzel suggested this latter ratio for shallow seams.

Numerous observations have been made in Germany during the last thirty years. R. Hausse has reported upon the angle of break, angle of draw, and the coefficient of increase of volume. Jicinsky, Gold-

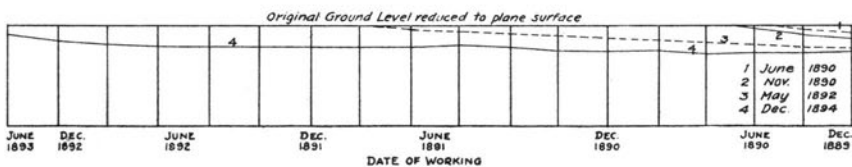


FIG. 48. DATA OBTAINED BY S. R. KAY.

reich, and others have reported upon subsidence in Austria-Hungary but in general these data have been secured in districts where the coal measures are covered with heavy beds of marl. From the foregoing statements of observations the following may be presented as representative in so far as general statements can be made to apply to mining operations each of which is conducted under different geological conditions.

ANGLE OF BREAK AND DRAW.

Dr. Niesz has made many observations upon subsidence, particularly on the angle of fracture in various kinds of rock and on the com-

*Menzel, C. "On the Relation of Surface Subsidence to the Thickness of Worked-Out Coal Seams at Zwickau." Abs. Proc. I. C. E., Vol. 140, p. 331. Jahrbuch für B., u. Hüttenwesen im K. Sachsen, p. 147, 1899.

pressibility of filling. He states that "the angle of fracture of limestones, conglomerates, etc., is found to be from 45 to 48 degrees—nearly the angle of repose. In quicksand the angle is greater, while in clay, slate, and marl it may be 60 degrees, and in stone under favorable conditions even 75 degrees. Sandstones with silicious binding material are ranked as nonplastic strata. Initial subsidences in these are followed by others, but at longer intervals than in plastic strata. The angle of fracture is generally not less than 82 degrees."*

Dr. J. S. Dixon reported, "In a level seam about 6 feet thick, by careful leveling on the surface prior to and after working, it was found that the draw or angle of subsidence of the strata was about 76 degrees from the horizontal plane."†

H. F. Bulman says that in a seam dipping 1 in 10, the lines of break extended over the solid coal forming an angle of 45 degrees with the horizontal on rise workings, 50 degrees in level workings, and 56 degrees on dip workings. In a wide goaf area the average inclination of the planes of fracture was 68 degrees from the horizontal plane; and at the rise side of a shaft pillar, the inclination was roughly 58 degrees from the horizontal plane over the solid coal.‡

S. R. Kay§ has presented the following formula for determining the radius of support:

$$r = \frac{3 \sqrt{d} x \sqrt[3]{t}}{0.8}$$

r = radius of support in feet,

d = depth in feet,

t = thickness excavated in feet.

This allows for the angle of break or draw.

Joseph Dickinson says, "the direction of subsidence may be judged of from the slopes of faults and mineral veins." He gives these slopes as 1 in 5 for hard rock, 1 in 3.75 for medium rock, and 1 in 2.5 for soft rock.§

O'Donahue says that the angle of break will be from 5 to 8 degrees beyond the vertical for horizontal beds, and that the maximum draw on dip workings will be 24 degrees; he finds the same angle to be the limit for workings to the rise.**

*Zeit. für Berg-, Hütt-, u. Salinenwesen, Vol. 58, p. 418, 1910.

†Trans. Inst. Min. Eng., Vol. 34, p. 416, 1907.

‡Trans. Inst. Min. Eng., Vol. 34, p. 417, 1907.

§Proc. Inst. Civ. Eng., Vol. 135, p. 149, 1898.

§Trans. Manchester Geol. Soc., Vol. 25, p. 600, 1885.

**O'Donahue, T. A. "Mining Formula," p. 248.

O'Donahue* offers two formulæ to determine the angle of draw:

$$d = 8 + \frac{2}{3} D$$

$$d' = 8 - \frac{1}{3} D, \text{ in which}$$

D = inclination of seam in degrees,

d = angle of draw toward dip workings,

d' = angle of draw toward rise workings.

E. H. Robertson gives a rule for shaft pillars (used in Northumberland and Durham) which allows for the angle of break and draw:

$$\text{Radius of shaft pillar in feet} = \frac{D}{6} + 2\sqrt{Dt},$$

D = depth of shaft in feet,

t = thickness of seam in feet.

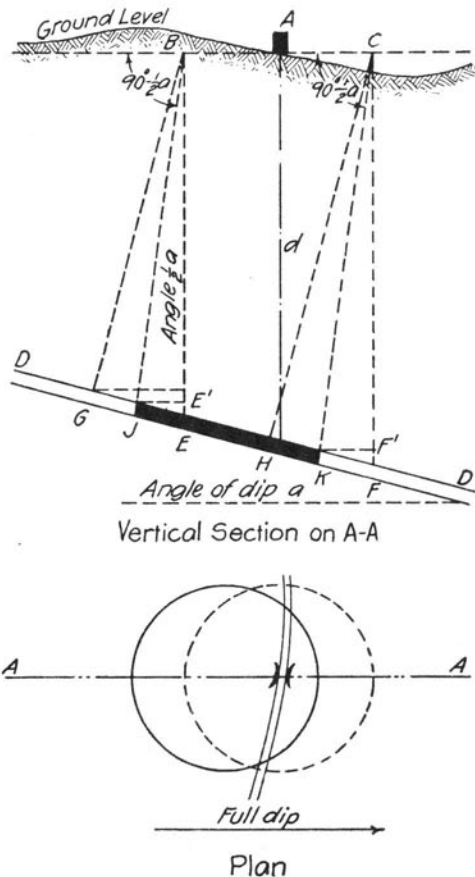


FIG. 49. LOCATION OF SHAFT PILLAR IN DIPPING BED. (O'DONAHUE.)

*O'Donahue, T. A. "Mining Formula," p. 248.

Hausse estimated that in general the line of fracture will be between the vertical and the normal to the seam. In addition to the line of main fracture, Hausse refers to the secondary break or draw. He says that in case of horizontal beds this line of secondary break is situated along the bisector of sliding materials of the supplementary angle of the natural slope.

The effect of the dip of the strata has been considered by many authors in their discussion of the simplest cases, in fact, most of the formulæ for angle of break consider the dip of the strata.

Gonot's law of the normal and Schulz's rule, the earliest of the theories, considered the angle of dip. As previously noted, Hausse, following Jicinsky, supports the theory that the angle of break will fall midway between the normal to the seam and the vertical. From a careful study of the subsidence occurring in the Saxon coal field R. Hausse determined the direction of the plane of fracture by the following formula:*

$$\begin{aligned}
 &a = \text{angle of fracture,} \\
 &d = \text{dip of strata,} \\
 &\tan a = \frac{1 + \cos^2 d}{\sin d \cos d}, \text{ in which,} \\
 &\text{if } d = 0^\circ, \quad \tan a = \infty \quad \text{and } a = 90^\circ \\
 &\text{and if } d = 90^\circ, \quad \tan a = \infty \quad \text{and } a = 90^\circ.
 \end{aligned}$$

S. R. Kay suggests that for inclined strata the angle of fracture will be midway between the perpendicular to the seam and the vertical. If the angle between the perpendicular to the seam and the vertical is a , then the pillar necessary to protect a given object on the surface must be shifted, on account of the dip, from a position directly beneath the object by an amount equal to $d \tan \frac{1}{2} a \cos a$, in which d equals the depth.

Goldreich gives Table 11 showing the angle of break according to the most important theories.†

*Results actually obtained in practice confirm this theory. Thus, for supporting the glass works at Doehlen, in Saxony, a 76.8-foot pillar was left; nevertheless the surface sank considerably. The coal seam dipped 12° and was 540 feet deep. Calculated from the depth and size of the pillar, the angle of fracture was found to be 82° , or $2^\circ 20'$ less than the result obtained from the theoretical formula. In another case in the same district the value of a was found to be $82^\circ 30'$, or $1^\circ 50'$ less than that found theoretically. (Brough, B. H. Proc. Inst. Civ Engrs., vol. 135, p. 150, 1898.)

†Goldreich, A. H. "Die Theorie der Bodensenkungen in Kohlengebieten," p. 42.

TABLE 11.
ANGLE OF BREAK.

Dip	Rule of Hausse		Rule of Thiriart	German Rule		Rule of Jicinsky	English Rule
	First Hypothesis	Second Hypothesis		First Hypothesis	Second Hypothesis		
0	70	70	Toward the Dip	70	70	90	81½
10	65	67	70	75	70	85	73¾
20	60¾	64¼	67½	75	70	80	66¾
30	56	62	65¼	70	60	75	64
40	52¾	60¾	63	60	55	70	64
50	50¾	60¾	61½	55	55	70	64
60	51	61	60¼	55	55	75	64
70	54	61	60½	55	55	80	64
80	61½	65½	62	55	55	85	64
90	70	70	65¼	55	55	90	64
			70	55			
			Toward the Rise	75	70	90	81½
0	70	70	70	75	70	85	83¾
10	75	77	72½	75	70	80	88½
20	79¾	83¾	74¾	75	70	75	90
30	84	90	77	75	70	70	90
40	87½	95¼	78¾	75	70	70	90
50	89¼	99¼	79¾	75	70	70	90
60	89	99	79½	75	70	75	90
70	86	93	78	75	70	80	90
80	78½	82¼	74¾	75	70	85	90
90	70	70	70	75	70	90	90

AMOUNT OF SUBSIDENCE.

Various writers have attempted to express the amount of subsidence as a percentage of the thickness of the seam worked. In Table 12 data from various districts are assembled, showing the depth of the workings, the thickness of the coal mined, and the vertical amount of subsidence expressed as a percentage of the thickness of the material removed.

TABLE 12.
AMOUNT OF SUBSIDENCE EXPRESSED IN PERCENTAGE.

Depth in Feet	Percentage Subsidence	Thickness of Coal Required Feet	Filling	Locality	Authorities
360	70.0	5.0		England	S. R. Kay
990	64.0	3.5		England	S. R. Kay
.....	46.0	29.36	Stowing	Bully-Greenay, France, England	O'Donahue
432	44.4	30.0			O'Donahue
600	75.0	4.0			Dixon
2400	25.0	4.0			Fayol
650	68.0	5.5		England	
745	19.0	7.5	Stowing	France	Fayol
2600	00.0	13.0	Harmless depth without stowing	France	Fayol
1040	00.0	13.0	Harmless depth with stowing	France	Fayol
390	40.0	7.0	33% of seam put in gob	England	Gresley
325	87.0	30.0		England	Grazebrook
1500	30	5.0	Stowing	England	Hay
600-2400	50			Germany	Menzel

Attempts have been made to formulate rules by which the amount of subsidence may be predicted in advance. Some of the formulæ are based upon the thickness of coal and depth of workings. Most of them include factors for character of rock and filling, but few introduce factors for inclination of the beds.

The discussion of the relation between the depth of workings and the vertical amount of subsidence has brought to the foreground the question as to whether or not subsidence will result irrespective of depth. According to the formulæ of Jicinsky and Menzel there is for each thickness of coal bed a depth beyond which mining will not affect the surface. In 1884 Jicinsky suggested the following:

$$S = m + t - 1.01t$$

$$= m - .01t$$

in which S = vertical subsidence,
 m = vertical thickness of coal,
 t = thickness of overlying beds.

Menzel suggests the formula

$$S = \frac{t + 350}{350 m}$$

in which S = subsidence in yards,
 t = depth in yards,
 m = thickness of seam in yards.

The **factor** 350 must be increased to 400 for depths greater than 350 yards. This principle that there is a harmless depth has been supported by Fayol, Banneux, Thiriart, Rziha, Jicinsky, and Menzel.

Fayol formulated two rules as follows:

(1) The height of the zone of subsidence where sandstone predominates and the beds have an inclination less than 40 degrees, and where the area is infinite, does not exceed 200 times the height of the excavation.

(2) When the area is limited, the height of the dome is about twice the breadth excavated for excavations less than 6 feet and up to four times the breadth excavated for seams more than 6 feet.

In general the Germans say that the "dead point" or "harmless depth" has not been reached in Westphalia and question whether or not the term should be used. Callon said that there is no harmless depth, and the majority of the British engineers hold that the removal of all the coal over extensive areas will produce subsidence.*

*The efficiency of filling in reducing subsidence will be considered in Ch. V, see p. 138.

TIME FACTOR IN SUBSIDENCE.

In a study of subsidence it is frequently important to know (1) how soon after the movement shows in the mine workings it will manifest itself upon the surface; (2) the period during which the movement is most severe, and (3) the duration of subsidence.

Upon all of these points there seems to be a great difference of opinion, which is due undoubtedly to the great variety of conditions under which the observations have been made. Fayol wrote, "The period during which movement of the surface may continue is very uncertain. It is allowed to be ten or twelve years in Belgium and at Saarbruck. In other places it has been as long as twenty and even fifty years."*

The committee of the Mining and Metallurgical Society of Ostrau, Moravia, reported in 1881, "The land subsidence manifests itself within one to three months after the collapse observed in the mine. It manifests itself most intensely during the first half year, and then becomes less noticeable. According to our experience it may be assumed that after two years, or more safely, after three years, there do not occur any measureable land subsidences in consequence of a collapsed working."†

S. R. Kay reported that, in working a 5-foot seam at 360 feet, subsidence began about six months after the coal was removed and continued four years.‡

Elevations taken at the Bent Colliery by J. S. Dixon showed that the greater part of the subsidence took place within the first year and that the maximum subsidence came within three years. The depth to the seam was approximately 650 feet.§

In observations made by W. Hay at Shirebrook Colliery, in which mining was being conducted at 1,700 feet, the maximum subsidence appeared in two years.§

G. E. J. McMurtree reported that the mining of 8 feet of coal at a maximum depth of 800 feet caused subsidence continuing fifteen years.**

In discussing the timbering of roadways in longwall mines in Illinois, S. O. Andros says, "Permanent timbering can be extended

*Colliery Engineer, 1890, Vol. 11, p. 25, 1890.

†Goldreich, p. 63.

‡Proc. Inst. Civ. Eng., Vol. 135, p. 115, 1898.

§Trans. Min. Inst. of Scotland, Vol. 7, p. 224, 1886.

§Trans. Inst. Min. Eng., Vol. 36, p. 427, 1908.

**Proc. Smith Wales Inst. of Engrs., Vol. 20, p. 367, 1897.

only to that point where the first rapid and violent subsidence has ceased, and it is not usual to extend permanent timbering to any point until the face has been advanced beyond it for at least two years.”*

George Knox says:

“When workings advance rapidly the tendency will be for the strata to bend without fracturing; whereas if the opposite is the case, the force of the motive zone has time to break through, as is frequently shown on the working face after a prolonged stoppage.”†

*Illinois Coal Mining Investigations, Bul. No. 5, p. 32, 1914.

†Knox, George “Mining Subsidence,” Int. Geol. Congress, Vol. 12, p. 804, 1913.

CHAPTER V.

LABORATORY EXPERIMENTS AND DATA.

TESTS AND EXPERIMENTS FOR SECURING DATA.

In the laboratory various experiments and tests can be made to secure data which will be of assistance in the study of subsidence. Among these may be noted the following:

General tests of the materials entering into the problem.

Effect on superimposed material of the removal of part or all of the supports.

Probably the most extensive experiments along this line which have been described in scientific publications have been those made by H. Fayol.*

His experiments to demonstrate subsidence included a variety of materials, as iron, fibre, canvas, rubber, sand, clay, and plaster. He placed iron bars 1.9 inches by 0.19 inch (50 millimeters wide by 5 millimeters thick) one above the other horizontally, the whole being sup-

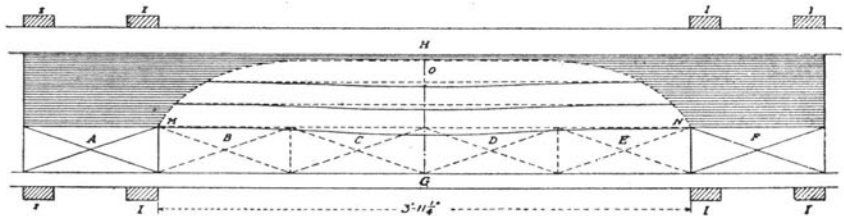


FIG. 50. SAGGING OF IRON BARS.

ported by blocks of wood, *A, B, C, D, E, F*, Fig. 50. These blocks rested upon an iron table *G*. A strong iron rule *H* was placed upon the upper bar of iron, and by means of stays *I*, and bolts, the rule and bars were fastened together and to the table. The wooden blocks *B, C, D, E*, were removed over a length of about 4 feet, and the sagging of the iron bars was noted.

It was found that the deflection of the lower bar was 5 millimeters (0.19 inch), of the tenth bar from the bottom 3.25 millimeters, of the twentieth 1.75 millimeters, and that after the thirtieth bar there

*Fayol, H. "Sur les Mouvements de Terrain Provoqués par l'Exploitation des Mines." *Bul. de la Société de l'Industrie Minérale*. II^e ser., Vol. 14, p. 818, 1885. Translation *Coll. Eng.*, Vol. 11, p. 25, and Vol. 23, p. 548.

was no more bending. The limit of the deflections is the curve *MN* shown in Fig. 49.

The same experiment was tried with flat aloë ropes and with straps of canvas and India rubber in place of the iron bars. With straps of canvas and India rubber the curve of the limits of deflection, that is to say, the limit of the zone of subsidence, had a height nearly equal to the distance between the points of support. This height was about one-third of the same distance for the ropes and one-sixth for the iron bars. Wood and rocks also bend in a manner similar to the materials mentioned.

In order to study the movement in beds of loose materials and in strata that might have been crushed by subsidence, Fayol used artificial beds of earth, sand, clay, plaster, or other materials, and constructed boxes of various dimensions having one side of glass. The box usually employed was 2 feet 7 inches (.80 meter) long, 1 foot (.30 meter) broad, and 1 foot 7 inches (.50 meter) deep. On the bottom of the box were placed, side by side, small pieces of wood of equal thickness, a few centimeters in width, and as long as the breadth of the box. Experiments were made both with one row of these little pieces of wood, and with several placed one above the other. Upon them were laid successive layers of artificial strata, varying from 1 millimeter to several centimeters in thickness. To note the movements, small pieces of paper about $\frac{3}{4}$ inch (2 centimeters) in length and $\frac{3}{8}$ inch (1 centimeter) in width, were put into the planes of stratification, and, on the glass, lines were marked in ink, covering exactly the lines formed by the paper. These lines enabled the least movement to be followed.

By withdrawing the little pieces of wood, excavations were formed and movement produced in the artificial strata.

Fig. 51 represents the movements by taking away, in the order indicated by the numbers, the upper row of wooden pieces, where there were three rows each 0.3937 inch (1 centimeter) in thickness.

The first bed (dry sand), which rests directly on the pieces of wood, falls in as each pillar is withdrawn. The second bed commences to sink only when a certain number of pillars have been taken away. The sinking is shown at first by a slight curve, which has its greatest deflection toward the center of the excavation. Then the third bed follows the second. The movement gradually extends in depth, and reaches the upper bed after the removal of the twelfth pillar. After

the removal of the seventeenth, the beds have become bent, as shown in the sketch, the limits of the deflection being the curves Z_{13} and Z_{17} . (The index figure of the curves is the number of the last pillar taken away; namely, the curves Z_8Z_4 indicate the extent of the movements after the removal of pillars 4 and 8.)

It is apparent that the zone of sinking is a sort of expanding dome, which grows in proportion as the excavation extends.

The bending of the first bed, hardly observable at first, is considerably increased. The second bed sinks rather less than the first, the third less than the second, and the sinking of each diminishes regularly

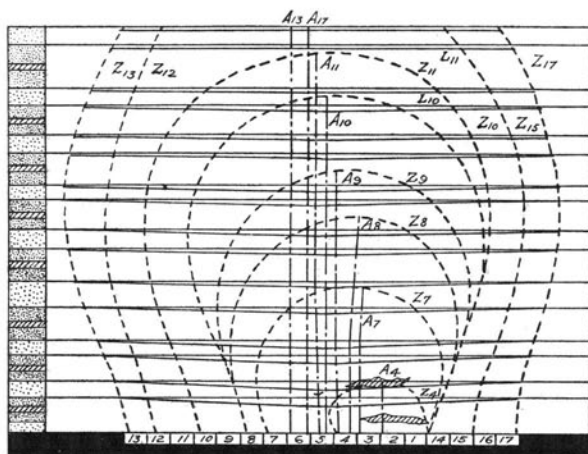


FIG. 51. SUBSIDENCE OF ARTIFICIAL BEDS.

in proportion as it is higher above the excavation. This sinking takes the form of a basin, the center of which is on the vertical axis of the excavation.

The lines A_4 , A_7 , A_8 , A_9 , A_{11} , A_{13} , A_{17} , are lines followed by the greatest deflections of the sunken beds after the removal of the pillars 4, 7, 8, 9, 11, 13, 17. These lines nearly coincide with the axes of the domes, which show the limits of the movement.

Throughout the experiments it was evident after the removal of a certain number of the pillars that the pressure of the superincumbent mass was strong at the center and weak at the circumference of the excavation.

The second row of wooden pillars was taken away and thus the depth of the excavation was doubled. The sinking of the lower beds

increased; some of them fell in; and the broken ground occupied much more space. The disturbance was greater below, but not at the surface. The line of maximum deflection did not remain vertical, and some of the limiting domes were inclined.

Removal of the third row increased the disturbance caused by the removal of the two former; the fractures of the beds and the spaces between the strata were multiplied; some opened more, others closed. As before, the movement started at the lower beds and reached the upper as the excavation extended. The removal of each row of supports results in a new state of stability, which continues if no more pillars are taken away.

Similar experiments were made with beds at various inclinations, and it was found that the line of greatest deflection was between the vertical and the normal, and that it departed further from the normal (that is, the perpendicular to the inclination of the beds) in proportion as the beds became more inclined. Whatever the inclination, the subsidence of each bed had always the form of a basin.

When horizontal beds were covered over by beds dipping at various inclinations; that is, resting unconformably on them, the zone of settlement took the direction of the inclination of the beds and its axis tended to become perpendicular to the beds affected. The lines drawn through the maximum bend of each bed were no longer continuous, but in passing from one set of beds to another were broken and shifted in the direction of the dip of the new set. In all cases the sinking of each bed and of the surface was in the form of a basin.

An experiment was made with horizontal beds, which showed that a block of coal left between two worked-out places may be of no use to protect the surface above it, because the zones of subsidence due to the excavation on either side, which, as already seen, take the form of domes, may overlap each other between the coal and the surface.

As the area of subsidence increases in proportion as the excavation is extended, it may be asked whether there is any limit in depth to the propagation of the movement when the excavation extends indefinitely. To answer this, a mass of horizontal beds was isolated round about by a space being left between them and the vertical sides of the box, and then the wooden pillars (in this case .03937 inch thick) were taken away from under the whole area of the mass. Being entirely free at the sides it might be considered to represent a mass of strata lying over the middle of a working of large extent.

On taking away the pillars, the zone of sinking was seen to increase little by little, and to stop at a certain depth; the movement did not reach the surface. The expansion of the lower beds filled the space excavated and the upper beds rested on the fallen rock. The pressure exerted by the upper strata was very much greater in the middle than at the circumference, and in this case, too, the sinking of the strata was in the form of a basin.

The effect of faults was tested by inserting in a mass of horizontal beds a thin plate of metal, placed at an inclination, and extending the whole width of the beds. This broke the continuity of the beds and represented a fault without throw. Its tendency was to stop the movement from extending above it, though the sinking occurred as usual on its low side, leaving an opening in the plane of the cut, which extended to the surface.

Fayol also made experiments upon the angle of fracture of rocks, the increase in volume of crushed rock, and the compressibility of crushed rock of various sizes.

Effect of Lateral Compression Upon Stratified Materials.

Elaborate experiments were made by Willis* in order to study the deformation of strata by compression. The substance used was beeswax with plaster of Paris to harden it and Venice turpentine to soften it so that by using different proportions of these materials, beds of a wide range of consistency could be constructed. A load of shot was applied upon the beds when constructed, in order to approximate the conditions under which strata at depth are deformed. The machine used for compressing the piles of strata endwise was a massive box of oak provided with a piston which could be advanced by a screw. The pressure chamber was 3 feet $3\frac{3}{8}$ inches long by 6 inches wide. The depth of the box was 1 foot.

T. M. Meade† made a number of experiments, and considered in detail the types of surface which may be developed. He used various kinds and combinations of bars and applied pressure in various ways. An elaborate set of experiments was made to demonstrate circumferential compression. He used for this purpose discs of clay placed within a circumferential band which could be shortened.

*Willis, B. "The Mechanics of Appalachian Structure." 13th An. Rep. U. S. Geol. Sur., Part II, pp. 211-281, 1891.

†Meade, T. M. "Evolution of Earth Structure." p. 146, London, 1903. "The Origin of Mountains," p. 331, London, 1886. Cadell. Trans. Royal Soc. of Edin., Vol. 35, part 7, 1888.

Effect of Vertical Compression Upon Beds of Stratified Materials.

Various tests upon bedded materials used for filling in mines have been made by the United States Bureau of Mines. Incidentally these tests have demonstrated the movement or flow of material in beds

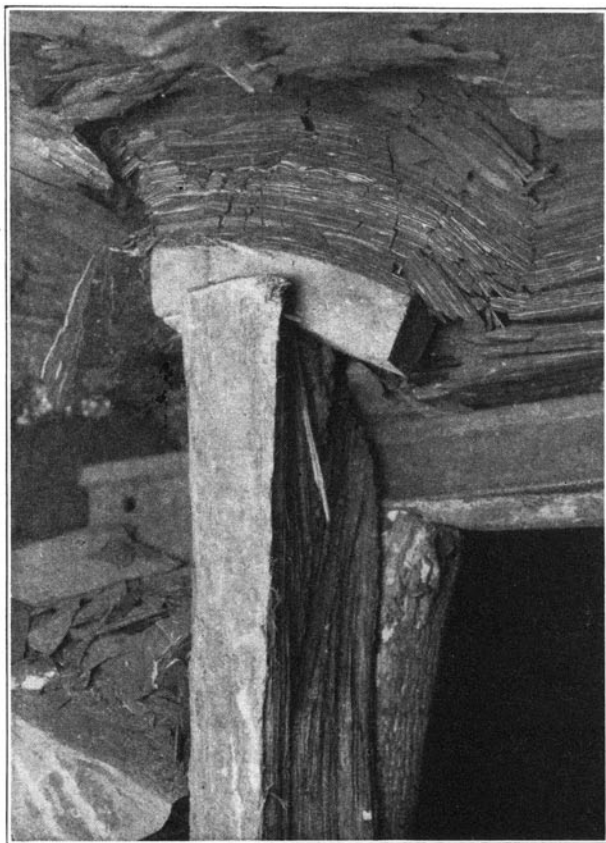


FIG. 52. BENDING OF SHALE UNDER PRESSURE.
(Photo by H. I. Smith, U. S. Bureau of Mines.)

under pressure. Fig. 52 illustrates the bending of shale under pressure in a mine. In this case, however, the bending is accompanied by fracture because of the large movement allowed by the absence of restraint on the under side.

Effect of Lateral Tension Upon Stratified Material.

Not very much work has been done to determine the tensile strength

of rocks and practically nothing has been done upon beds of stratified material.

General Experiments.

General experiments to illustrate geological phenomena and to discover the properties of rocks under conditions of pressure and temperature which may exist at great depths, have been conducted by Daubrée, Adams, and Coker, and various other scientists working at times privately and at other times under the auspices of scientific bureaus of governments and of societies.

The Behavior of Various Types of Artificial Supports.

Extensive tests have been made by the United States Bureau of Mines in various government laboratories and by various mining companies in order to determine the actual and the relative strength of different types of supports.*

SUGGESTED EXPERIMENTS AND TESTS.

(1) In order to study surface subsidence resulting from the removal of supports, it is suggested that a model be constructed, say on a 1/100th scale, both horizontal and vertical, approximating relatively the geological sequence of beds in a given district. The beds should have the same strength relatively in proportion to their weight, or the weight applied, as exists in the geological section which the model represents. The model should be of sufficient extent laterally to represent several panels of a pillar-and-room mine laid out on the panel system. Provision should be made for removing supports so that conditions such as would exist when pillars are drawn may be created.

Observations should be made upon the height of surface from time to time and, after surface movement has ceased, the model should be dissected so that the effects of subsidence below the surface may be noted. Similar models should be constructed to demonstrate working beds of various thicknesses, depths, and dips, and under other systems of mining.

(2) Strength tests of roof materials should be made. The tensile strength and the angle of fracture in bending tests should be determined.

(3) The bending power of the various materials which constitute the mine floor should be measured.

*See Bibliography on Prevention of Subsidence.

(4) In typical mines and under normal working conditions, the pressure or weight of roof should be measured and recorded over as long a period as possible at each point selected.

(5) A study should be made of the composition and physical properties of the rock strata between the beds mined and the surface and also immediately below the beds mined.

CHAPTER VI.

PROTECTION OF OBJECTS ON THE SURFACE.

The surface may be protected by the use of natural or artificial supports. Probably the most general method of preventing subsidence and of protecting objects on the surface is by leaving unmined a portion of the mineral deposit, with the idea that the pillar thus left will have sufficient strength to support the overlying rocks.

In considering the service which a pillar may render and in determining the size of the pillar or other support for protecting specific mine openings or objects on the surface, it will be necessary to consider some of the following factors, and in some cases all of them :

- (1) The unit strength of the material forming the pillar.*
- (2) The height of the mine opening.
- (3) The dip of the mineral deposit.
- (4) The angle of break of the overlying rock.†
- (5) The angle of draw or drag or pull over the pillars, as observed in the district or under similar conditions.
- (6) The strength of the overlying rocks.‡
- (7) The nature and amount of filling in the mined-out area adjacent.
- (8) The depth at which mining may be carried on without affecting the surface.
- (9) The bearing-power of the bottom or floor.
- (10) The weight of overlying materials which must be supported.

To determine the size of pillar necessary to protect mine openings of a given width, it is customary in some textbooks to assume a span of roof and overlying rock to be supported, to estimate the total weight of such a block for the depth of workings, and then, with the known or assumed unit crushing strength of the material to be left in the pillar, the cross-section may be calculated. Such calculations are seldom used in practice and they are open to the objection that they assume a pillar to be uniform throughout, while, as a matter of fact, all bedded deposits are composed of a large number of layers that may vary widely in hardness. For instance, some beds of very hard coal contain

*See p. 70-76.

†See p. 130.

‡See p. 76.

thin layers of mother coal which reduce the strength of the bed, thus vitiating any calculated results for strength of pillar based on tested specimens taken from the solid part of the bed.

SHAFT PILLARS.

Numerous rules have been formulated for the calculation of shaft pillars in flat seams. Among the best known are the following:*

Merivale.
$$S = 22 \sqrt{\frac{D}{50}}$$

in which S equals length of side of pillar in yards and D equals depth of shaft in fathoms.

Andre. Up to 150 yards deep, a pillar 35 yards square. Up to 175 yards deep, a pillar 40 yards square. Up to 200 yards deep, a pillar 45 yards square, and so on, increasing 5 yards for every 25 yards of depth.

Dron. Draw a line enclosing all the surface buildings, such as engine houses, fans, etc. Make the shaft pillar of such a size that solid coal will be left in around this line for a distance equal to one-third the depth of the shaft.

Wardle. The shaft pillars should not be less than 120 feet square, and the deeper the shaft the larger the pillars. Supposing the minimum to be 120 feet for a depth of 360 feet, 30 feet should be added for every 120 feet in depth.

Hughes. Leave one foot in breadth for every foot in depth; that is, a shaft 600 feet in depth should have a pillar 300 feet in radius.

Pamely. For any depth to 300 feet, it may be sufficient to have a pillar 120 feet square. Adopting this size as a minimum, we may fix any size of pillars for greater depths by increasing the pillar one foot for every four feet in depth.

Foster, R. J. To include the factor of thickness of seam, when conditions are normal, the following formula is suggested:

$$\begin{aligned} \text{Radius of pillar} &= 3\sqrt{Dt}, \text{ in which} \\ D &= \text{depth of shaft,} \\ t &= \text{thickness of seam.} \end{aligned}$$

Mining Engineering (London). For shallow shafts a minimum of 60 feet radius should be adopted,† and for deeper shafts this should be increased by one-tenth of the depth multiplied by the square root of one-third the thickness of the seam in feet.

*Colliery Engineer, Vol. 17, p. 538, 1897. Coal and Metal Miners' Pocket Book.
†Colliery Engineer, Vol. 18, p. 117, 1897.

$$R = 60 + \frac{D}{10} \sqrt{\frac{t}{3}}$$

Roberton, E. H. In Northumberland and Durham the practice is shown by the following formula:

$$R = \frac{D}{6} + 2\sqrt{Dt}$$

R = radius of the shaft pillar in feet,

D = depth of shaft,

t = thickness of seam.

Scotch engineers, in order to protect buildings have pillars from 1/3 to 1/5 larger than the floor plan of the building. This diversity of opinion among engineers is well shown by Fig. 53.*

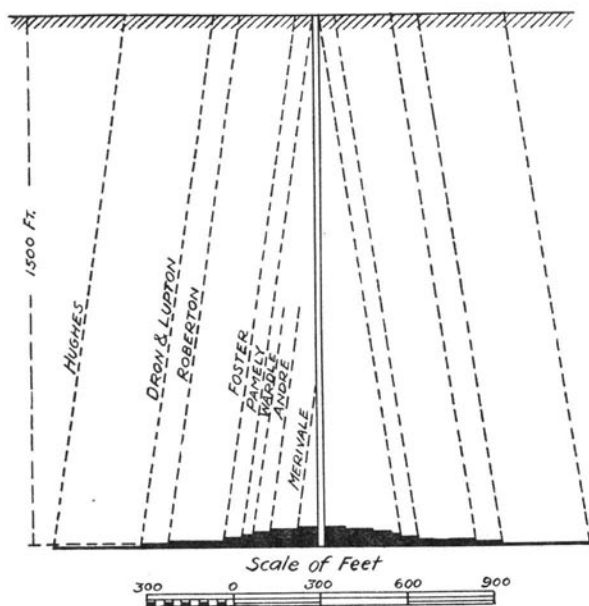


FIG. 53. SIZES OF SHAFT PILLARS ACCORDING TO DIFFERENT FORMULAS.

The Central Coal Basin Rule, presumably founded upon the experience of mining men in Illinois and surrounding states, is: "Leave 100 square feet of coal for each foot that the shaft is deep. If the bottom is soft, the result given by this rule is increased by half. For 5 or 6-foot coal beds, the Central Basin Rule may be used unless it

*Knox, G. Proc. Int. Geol. Cong., Vol. 12, p. 798, 1913.

has been shown by other operating mines in the district that a larger pillar is needed. With thicker coal a larger pillar should be left.”*

The practice of some coal companies in the Connellsville region of Pennsylvania is to leave pillars under buildings so that there is a margin of from 25 to 30 feet of coal around the building. If the tract is large, from 50 to 60 per cent of the coal is removed, the remainder being left in pillars proportioned so that they will serve in the most advantageous way to protect the building. This is the practice for depths from 150 to 300 feet.

In determining the size of the pillar necessary to protect objects upon the surface, as has previously been noted, the ability of the pillar to carry the load is not the only question to be considered. Among the most important of the other problems is that of draw or pull over the pillar previously noted, and the ability of the underlying bed to sustain the load concentrated upon it by the pillar. Quite frequently the underlying bed is less stable and has less crushing strength than the pillar. It seems logical then to proceed as follows in determining the size of pillar necessary to protect an object upon the surface:

- (1) Determine the lateral extent of pillar necessary in order to prevent damage by draw.
- (2) Determine whether the pillar thus outlined is sufficiently large to support, without crushing, the burden of the overlying beds.
- (3) Determine whether the load upon the pillar will cause the pillar to be forced down into the underlying beds, or cause a flow of the underlying material.

ROOM PILLARS.

In his discussion of methods of protecting the surface, M. Fayol referred to the use of pillars between the working places. “The meshes of the network consisting of pillars with working places between them should be made smaller as the workings are shallower. As the depth becomes greater the size of the meshes can be enlarged and dimensions of the areas worked can be increased relatively to the sizes of the pillars that are abandoned, regard being had to the height and width of the zones of subsidence so that the various zones may be kept distinct from each other. This general rule is susceptible of many combinations according to the thickness, the inclination, the number and depth of the seams worked. If the excavation is of small dimensions the subsidences which take place above them are restricted in size and become

*Illinois Miners' and Mechanics' Institutes, Instruction Pamphlet No. 1, p. 49.

enlarged both in width and height as the excavation increases in area. If each of the pillars, 1, 3, 5, and 7 (Fig. 54) be taken out singly, zones of subsidence similar to Z_1 , Z_3 , Z_5 , and Z_7 , would be produced; but when pillar 2 is taken out the line of roof subsides on to the floor, and the zone of subsidence rises to Z_2 . The same thing happens when No. 6 pillar is taken out, and if No. 4 pillar is taken out, the space comprised between the zones Z_2 and Z_6 is set in motion and determines the formation of zones Z_4 .*

It follows from this statement of Fayol that if the room pillars are properly proportioned and properly spaced, the disturbance of the strata may be limited to the volume within the zones. The material

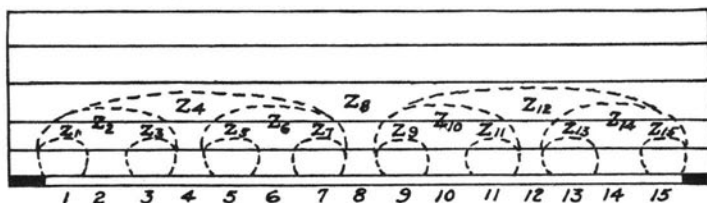


FIG. 54. EFFECT OF EXTENT OF EXCAVATION ON AMOUNT OF MOVEMENT.

outside these zones throws no weight upon the material within the zones. Necessarily, then, any vertical pressure must fall upon unmined material forming the pillars and the pillars must be large enough to withstand the pressure.

In a paper before the Pennsylvania State Anthracite Mine Cave Commission, 1913, Douglas Bunting said: "The application of a formula for determining the safe size of coal pillars for various thicknesses of veins and depths can be considered practical for depths greater than 500 feet, but it is doubtful if the same formula would be of any practical value for application to veins at less depth and certainly of diminishing practical value with reduction in depth and thickness of veins for the reasons that the variable conditions of vein, top, bottom, etc., are of more consequence with small pillars than with large pillars."†

D. Bunting‡ made a careful study of chamber pillars in deep anthracite mines on light dips. He considered the crushing strength of coal which for anthracite was found to average 2,500 pounds per square

*Proc. South Wales Inst. Eng., Vol. 20, p. 340, 1897. It should be noted that these zones outline the dome through which the movement extends, and not the limit of the falling zone, as described by Rziha.

†Bunting, D. "Pillar and Artificial Support in Coal Mining, With Particular Reference to Adequate Surface Protection." Pa. Legislative Journal, Appendix, Vol. 5, p. 5988, 1913.

‡Bunting, D. "Chamber Fillers in Deep Anthracite Mines." Trans. A. I. M. E., Vol. 42, p. 236, 1911.

inch for cubes. The ratio between the strength of prisms and cubes was taken as follows:

$$\frac{\text{Strength of prism}}{\text{Strength of cube}} = 0.70 + 0.30 \frac{b_1}{h}$$

in which

b_1 = width of pillar,
 h = thickness of vein.

The weight of overlying strata was taken at 144 pounds per cubic foot.

$$(1) \text{ Load per square foot on a pillar} = \frac{144 y z b_1}{b_1^2}, \text{ in which}$$

y = depth below the surface,

b_1 = width of pillar,

z = distance between chamber centers.

With 1,000 pounds per square inch as the safe load for a cube we obtain by substituting in equation (1):

$$\frac{144 y z b_1}{b_1^2} = 144,000 \left(0.70 + 0.30 \frac{b_1}{h}\right)$$

$$\text{or } y z = 1,000 \left(0.70 + 0.30 \frac{b_1}{h}\right) b_1$$

By making proper allowance for the crushing strength of the pillar material and the weight of overburden, this formula may be used generally for flat beds.

The relative widths of rooms and pillars are determined largely by practice. For bituminous coal of medium hardness and good roof and floor, the following rule is sometimes used: "Make the thickness of room pillars equal to one per cent of the depth of cover for each foot of thickness of the seam, according to the expression:

$$W_p = \frac{tD}{100}, \text{ in which}$$

W_p = pillar width,

t = thickness of seam,

D = depth of cover,

and then make the width of room or opening equal to the depth of cover divided by the width of pillar thus found, according to the expression:

$$W_o = \frac{D}{W_p}$$

in which W_o is the width of room.

"Frail coal and coal that disintegrates readily when exposed to the air, and a soft bottom, may increase the width of pillar required as much as 50 per cent of the amount found above; also, a hard roof may increase

the same as much as 25 per cent; while, on the other hand, a frail roof or a hard coal or floor may reduce the width of pillar required 25 per cent.”*

“As to the thickness of pillars in the Pittsburgh seam with strata 100 to 500 feet thick, the following rule should be a safe one to follow, in which the pitch is from 1 to 5 per cent:

Thickness of Surface Feet	Thickness of Pillars George's Creek Feet	Thickness of Pillars Fairmont Feet
100	25	18
150	32	20
200	40	25
250	50	30
300	60	35
350	70	40
400	80	45
450	90	50
500	100	55

These figures are based on experience in this seam, where the floor or bottom is hard and not affected by water. For a fireclay bottom somewhat thicker pillars would be necessary to withstand any extraordinary weight. Rooms should be not more than 14 feet in width in the Georges Creek region and 20 feet in the Fairmont region.”†

The average dimensions of pillars and rooms in ordinary pillar-and-room mining in Illinois are shown in Table 13.‡

TABLE 13.
DIMENSIONS OF PILLARS AND ROOMS IN PILLAR-AND-ROOM
MINING IN ILLINOIS.

District	Average Depth in Feet	Room Width in Feet	Pillar Width in Feet	Average Thickness of Coal in Feet
II	140	26	19	{ top bench 2 ft. bottom bench, 3 ft. 9 in.
III	90	22	18	4 ft.
IV	201	25	9	4 ft. 8 in.
V	243	26	16	4 ft. 8 in.
VI	270	22	18	9 ft. 5 in.
VII	227	31	30	7 ft.
VIII	174	27	8	{ Seam No. 6—6 ft. Seam No. 7—5 ft.
Average of 48 Representative mines	208	26	19	

The question of the thickness of cover is an important one in connection with the size of the room pillars and particularly when the draw-

*Coal and Metal Miners' Pocket Book, 9th Ed., p. 286, 1907.

†Reppert, A. E. "Pillar Falls and the Economical Recovery of Coal From Pillars." W. Va. Coal Min. Inst., p. 116, 1911.

‡Ill. Coal Min. Investigation, Bul. No. 13, p. 76, 1915.

ing of pillars is considered. This has been emphasized by F. W. Cunningham as follows: "The topography of the surface relative to hills and vales should be considered when starting to draw pillars and relative to this subject a question may be asked, which is an important one, viz., How many coal properties have contour maps of the surface? Suppose, for example, the rocks at the surface rise abruptly on each side of a narrow valley to say 200 or 300 feet. Would it be proper to commence pillar drawing under this valley?"*

STRENGTH OF ROOF.

In determining the limits of mining under heavy wash, D. Bunting considered the strength of slabs of roof rock supported by pillars. "In deriving a formula for computing the breaking load of a slab of stone from the formula $\frac{pI}{e} = M_m$, let W represent the distributed loading plus the weight of the beam itself in pounds, b , d , L represent the breadth, depth, and span, respectively, in inches, and R equal the modulus of rupture in pounds per square inch.

Bunting suggests that "the modulus of rupture does not express the actual stress in the extreme fiber of the beam of rock, but is a quantity useful only as a basis of comparison." He gives the following safe unit stresses for stone, recommended by W. J. Douglas as illustrative of possibly a fair average of safe stresses:

	Compression Lbs. per sq. in.	Shear Lbs. per sq. in.	Tension Lbs. per sq. in.
Granite	1200	200	150
Limestone	800	150	125
Sandstone	700	150	75

The maximum bending moment for a constrained or prismatic beam is equal to $\frac{WL}{12}$. By substituting in the formula for flexure ($\frac{pI}{e} = M_m$) we obtain the formula $W = \frac{2bd^2}{L}R$. Likewise, the maximum moment at the center of such beam being equal to $\frac{WL}{24}$, the formula becomes $W = \frac{4bd^2}{L}R$.

It is evident that failure of flexure would theoretically take place at the points of support and not at the center of the span.

*Cunningham, F. W. "Methods of Removing Coal Pillars." Proc. Coal Min. Inst. of America, p. 35, 1911.

In applying the formula $W = \frac{2bd^2}{L}R$ to the case of a slab spanning a breast or other mine opening, the weight of the overlying material will be taken at 108 pounds per cubic foot, and the depth of the opening below the surface will be designated by d' in feet.

Then, $W = \frac{108Ld'}{12}$, which would be the loading of the slab with a breadth of 1 foot. Substituting this value of W in the equation $W = \frac{2bd^2}{L}R$ and simplifying, the equation $d^2R = \frac{3}{8}L^2d'$ is obtained. If, however, the weight of the overlying material per cubic foot be represented by w , the expression becomes $d^2R = \frac{wL^2d'}{288}$.

In the use of the formula derived for determining the minimum safe thickness of rock over mine openings for various depths below the surface, consideration must be given to a number of conditions, the more important of which are:

1. Nature of the top immediately above the coal seam and its comparative strength and liability to disintegration upon exposure to the atmosphere.

2. Nature and thickness of the bed, the ability of the pillars to resist squeezing, and the liability of disturbance of the overlying strata, due to covering or squeezing in underlying beds.

3. Probable errors in relative vertical location of top of rock and mine workings.

4. Possibility of the existence of deep gorges and pot holes.*

In order to arrive at a brief solution in calculating pillars of quartzite for Rand mines, Richardson† made use of the following formulæ:

Bending

1. $F_b = 106 \frac{Kt}{l^2w}$

2. $L = 10.2 \sqrt{\frac{Kt}{w}}$

3. $W = 106 Kt^2 - l^2tw$

Shearing

1. $F_s = \frac{34.2 dk}{l^2w}$

2. $L = 5.85 \sqrt{\frac{dk}{w}}$

*Bunting, D. "Limits of Mining Under Heavy Wash." Amer. Int. Min. Engrs. No. 97, p. 18, 1915.

†Richardson, A. "Subsidence in Underground Mines." Eng. and Min. Jour. Vol. 84, p. 196, 1907.

$$3. W = (34.2 dk - l^2 w) t$$

in which F'_b = factor of safety for bending,

F'_s = factor of safety in shearing,

l = length of side of slab or distance from center to center of pillars,

L = length of side of a slab which will only support its own weight,

W = total distributed load which the slab will carry in addition to its own weight,

K = compressive strength of pillar material pounds per square inch,

t = thickness of slab in feet,

w = weight of a cubic foot in pounds,

d = diameter of pillars in feet.

He presumes that "where the slope areas are not extensive the weight of the upper masses will be supported by their own strength," and calculates the size of pillar which will support continuous slabs of rock, homogeneous and uniformly loaded. By use of the formula he prepared a table of sizes of pillars for various spaces and concluded that slabs usually break up by shearing and that the strength to resist this depends on the size and distance apart of supports.

FILLING METHODS.

Various materials and methods are employed to protect the surface if it is deemed advisable to remove all the material deposit, or if the material left in the forms of pillars is found inadequate to support the surface.

Waste material resulting from the regular mining operations or broken for this particular purpose may be stowed or packed into the excavation. If sufficient or suitable material is not available under ground it may be lowered or dropped from the surface and stowed where needed. Crushed materials may be introduced from the surface and transported through pipes and stowed by water or compressed air. Timber, steel, or various forms of masonry may be employed to support areas upon which important structures may be erected.

This entire subject has been studied by the engineers engaged upon investigations of subsidence and surface support in the Pennsylvania Anthracite field, who say:

"Most coal beds consist of interstratified layers of coal, fireclay, slate, and bony coal, the latter three composing the principal refuse material of the mine. In these beds, in which it is necessary to remove some of the roof rocks or take up some of the floor of the mine in order to obtain

height sufficient for the mules and the men to travel along the roads, much mine refuse is produced, which is stored in the chambers. In beds less than four feet thick many chambers are filled with mine refuse or gob from floor to roof. In places this gob is merely thrown in carelessly or is shoveled in; in other localities it is packed as tightly as possible by hand. When there is much interstratified fireclay or bone in the coal beds there will be larger quantities of the gob, and the thinner the bed the greater will be the quantity of mine rock raised or taken down for roads. The supporting value of stored gob depends upon the compressibility of the material of which it is composed.”*

Griffith's Method of Filling.—It has been suggested by William Griffith that worked-out portions of mines be filled by blasting up the bottom and shooting down the roof. The suggestion was made in connection with a report to the Scranton Mine Cave Commission and Mr. Griffith has secured patent (U. S. Patent 1,004,418) covering this method. W. Griffith and E. J. Conner say: “It is a well known fact that loose rock occupies from $1\frac{2}{3}$ to twice the volume of the same weight of rock in place. Your engineers have conceived the idea of taking advantage of this fact, well known to engineers, for the purpose of cheaply producing an adequate support of the rock and surface above certain classes of coal beds under the city of Scranton. So far as we know, this method, in its entirety, has never been used before in any coal mining district, and the suggestion is here made for the first time.

“The process is applicable to beds less than 6 feet in thickness and consists simply in blowing up the floor and shooting down the roof of the mine, each to a depth equal to the thickness of the coal bed. This produces a total thickness of loose rock equal to three times the thickness of the coal. The rock would be well packed together and have great supporting power, and, moreover, the desired ends would be attained in a comparatively inexpensive manner.†

The method of blasting stowing material from the hanging or foot walls is commonly used in metalliferous mines.

GOB STOWAGE IN LONGWALL MINING.

In longwall mining “the rock obtained from brushing the roof, that which remains after building the pack walls, and the clay obtained from undermining the coal are thrown behind the pack walls lining the roads.

*Griffith, Wm., and Conner, Eli T. “Mining Conditions Under the City of Scranton, Pa.” U. S. Bureau of Mines, Bul. No. 25, p. 52, 1912.

†Griffith, William, and Conner, Eli J. “Mining Conditions Under the City of Scranton, Pa.” U. S. Bureau of Mines, Bul. No. 25, p. 57, 1912.

The gob area is usually filled with rock and clay to within 2 to 5 feet of the coal face. This loose rock and clay helps to support the roof and control the roof weight on the coal face. The waste should fill the gob sufficiently to allow the roof to come down gradually without breaking off short at the face of the pack walls, but should not fill the gob so completely that it carries too much of the roof and does not throw enough weight on the face of the coal. The width of the pack wall, called 'building,' necessary to prevent the walls from squeezing out and filling the roadway when the roof weight comes on them depends upon local conditions. The Third Vein District Agreement between the Illinois Coal Operators' Association and the United Mine Workers of America provides: "The miner shall build 4 yards of wall at each side of his road, and if he has more rock than is required therefor he shall not load any of it until he has filled his place therewith." Room centers at the long-wall face (in Illinois) are usually 42 feet apart."*

GOB PIERS.

In some cases, especially when the prevention of any movement of the surface is especially desirable, gob piers are used. These are pillars of waste rock, either laid up by hand throughout, or having the outer wall carefully laid while the interior is filled with refuse shoveled in. The resistance of such supports to compression depends upon the material used and the care with which they are built.

CONCRETE AND MASONRY PIERS.

These forms of support are more expensive than those previously mentioned and are likewise more substantial. Masonry has frequently been used to support the roof below important structures and occasionally to support the walls of inclined beds and the overburden.

One of the earliest and also one of the most notable examples of the extensive use of masonry in metal mines was the construction at the Tilly Foster Iron Mines.† The total masonry constructed amounted to 20,189 cubic yards.

Whenever possible the concrete used is introduced from the surface through boreholes. An interesting example of such use of concrete is reported by Mr. Temple Chapman of Webb City, Missouri. In a zinc mine six concrete piers were constructed, 35 feet high by 16 feet wide and

*Andros, S. O. "Mining Practice in District I." Illinois Coal Mining Investigations. Bul. No. 5, p. 20, 1914.

†Engel, L. G. "Masonry Supports for Hanging Walls at the Tilly Foster Iron Mines." Columbia School of Mines Quarterly, Vol. 6, p. 289, 1885.

20 feet long. The measures were horizontal and the distance from the surface to the roof was 150 feet. First a 6-inch hole was drilled from the surface to the roof with a churn drill at a cost of \$0.90 per foot. A large pile of tailings was close at hand, consisting of crushed rock passed through a half-inch hole and containing some finer material and sand. The mixture was six parts of tailings to one part of cement, which is about equal to four parts of gravel, two of sand, and one of cement. This was mixed mechanically and discharged direct from the mixer into the drill hole. Underground two men were kept busy building up the form, which was made of 1 by 12 inch board laid on edge and 2 by 6 inches set vertically at 2-foot intervals and wired together across through the form. Worn perforated trommel screen jackets cut in strips 10 feet long by 4 inches wide were used to reinforce the concrete. These were laid east and west a foot apart and the concrete was poured. A foot higher similar strips were placed at right angles to the first, and so on. A few 60-pound rails were put into the tops of the piers, projecting from pier to pier where possible. These piers were placed between ore pillars, the plan being to remove these ore pillars. The piers were built at a cost of \$3 per cubic yard at a time when the ore in the pillars was worth \$12 per cubic yard.*

A novel method of using concrete in connection with packing or stowing was employed in France and reported by J. H. Piffaut.† The coal bed, quite thick and highly inclined, was worked in 8-foot slices in descending order. Upon the floor of a slice was spread a layer of coal dust from 1 to 1½ inches thick; then a layer of concrete from 8 to 10 inches thick; and upon this was placed the ordinary packing. As the working place had previously been timbered, the concrete surrounds the base of the posts. When the next slice is removed the concrete floor of the upper slice acts as a roof for the lower slice, which is timbered in the regular manner in order to support the concrete loaded with packing. It is claimed that this has proved satisfactory in the mining of thick beds.

COGS.

Cogs are cribs of timber filled with waste rock. They may be erected quickly and they have great strength. They find some use in the ordinary course of mining, but they are especially useful in preventing an impending squeeze, or in stopping one that has already started by

*Correspondence.

†Piffaut, J. H. "The Use of Cement-Concrete in the Working of Thick Coal Seams." *Trans. Inst. Min. Eng.*, Vol. 29, p. 274, 1904.

supplying such support that the overlying strata break through to the surface. Their strength is, of course, lost when the timber decays.

SPECIAL TYPES OF COGS AND PIERS.

William Griffith has recently developed a cog which it is expected will be many times as strong as the ordinary timber cog and both stronger and more durable than the common concrete pier. The objection to concrete cogs or piers is that when the compressive strength is exceeded the mass of concrete will go to pieces and will give no support whatever. With rock and timber piers, even though the percentage of compression may be large, the piers do not go to pieces but have some supporting power. The concrete pier will collapse suddenly while the other types of piers will be gradually deformed. Mr. Griffith says that what is needed is something that will bear up under the heaviest weight, that will "give" to a certain extent and will then withstand the continuing burden. In his new pier, concrete is the basic material with timber to reinforce it. The piers are constructed so that it is impossible for the timber to pull away and for the concrete to be crushed. "The timber should be creosoted and after the pier is constructed it should be coated on the outside with cement by the use of the cement gun."

Tests show that a cog or pier, forty days old, will sustain for each square foot of horizontal area:

- 7 tons with a compression of 1 per cent.
- 130 tons with a compression of 3 per cent.
- 140 tons with a compression of 14 per cent.

IRON SUPPORTS.

From time to time various types of metal supports have been tried in the working places of mines. Where iron props or posts have been installed in the Scranton district no subsidence occurred and it is the opinion of the local engineers that the effectiveness of such props has not been demonstrated. Rolled steel shapes are being quite extensively used as legs and collars and as beams for the support of wide openings, such as shaft bottoms. Iron supports have also been tried in metalliferous mines, but, except for the support of the shafts, stations, and passageways, they have never found extensive application. Iron props have been used in foreign mines.

HYDRAULIC FILLING.

One of the most important methods of protecting the surface above

mine workings is by filling the workings with fine material carried by water through pipes. In his report upon this method as used in the Pennsylvania Anthracite fields, Charles Enzian says: "Heretofore the process has been termed and even at present is known in the Pennsylvania Anthracite region as 'slushing,' 'flushing,' and 'silting.' As a result of various suggestions from men of long experience in this work, the name 'hydraulic mine filling' was adopted for the use of the report."* The process has been used in (a) extinguishing mine fires, (b) arresting mine squeezes, (c) supporting the surface, (d) reclaiming pillars and increasing the yield of coal, (e) disposing of spoil banks, and (f) in lessening stream pollution.

According to the *Colliery Engineer*, Vol. 33, p. 537, flushing was first used August, 1884, by John Veith, General Inside Superintendent of the Philadelphia & Reading Coal and Iron Company, who employed it to extinguish a fire in the Buck Ridge slope near Shamokin, Pennsylvania.

The second use of flushing and its first use to support or control overlying strata is credited in the same reference to Frank Pardee of Hazleton, Pennsylvania. In 1886 F. Pardee used the system to stop a squeeze which threatened the slope and breaker of the Laurel Hill colliery at Hazleton. He accomplished this by flushing adjacent breasts with culm. The breasts were steeply pitched. The squeeze was stopped by means of natural pillars, each 10 yards wide, and two breasts filled with culm, each 10 yards wide, and the subsiding rock broke off.

The most extensive early use of flushing was at the Kohinor colliery at Shenandoah, Pennsylvania. When this colliery was taken over by the Philadelphia & Reading Coal and Iron Company, January 1, 1884, it was found that because of workings in the thick Mammoth seam a large part of the town of Shenandoah was likely to be affected by a subsidence of the surface. The Mammoth seam was from 40 to 60 feet thick, thus making timbering impossible. The coal was about 400 feet from the surface. After various methods had been suggested, the officials of the company decided to flush culm into the workings, none of those engaged in the enterprise knowing of the previous use of culm for roof support by F. Pardee.

A very detailed description of the method used in flushing the culm into the workings can be found in the above reference in the *Colliery Engineer* and in Bulletin No. 60 of the U. S. Bureau of Mines.

The materials that have been used or may be available for hydraulic

*Enzian, Charles "Hydraulic Mine Filling." U. S. Bureau of Mines, Bul. No. 60, 1913.

mine filling include culm, ashes, crushed refuse from coal washing plants, sand, gravel, clay, loam, granulated slag, and crushed rock.

The methods employed and results accomplished have been described by Davies, Griffith, and Enzian.*

The process consists of conveying culm, sand, ashes, etc., to the desired place by means of water, the method used depending upon conditions. If the pipe line can be laid on a steep grade from end to end, the material will flow easily and little water will be required. On the other hand, if the grade is light or if it must be reversed over part of the line a larger quantity of water is required and, of course, a larger pipe. There must always be sufficient velocity to prevent settling of the solids and this can be obtained only by having sufficient head. Naturally the whole operation is easiest when the grade is steep, the pipe short, and the curves and connections few.

To avoid blockage of the pipe, clear water should be allowed to flow for a few minutes before filling is added, in order to establish a current throughout the pipe and when the flushing is to be interrupted, the addition of filling should be stopped some time before the water is shut off, so that the solid matter may be washed out of the pipe.

The proportion of water required depends upon the velocity of the current and the nature of the filling material. In general practice about 90 per cent of the material carried by the line is water.†

Good practice requires absolute control of the filling until it is deposited at the desired place. This necessitates carrying the pipe line to the place of deposit, no allowance being made for flow in chambers.

As the filling should be interrupted after 200 to 400 cubic yards have been deposited and the material be allowed to settle for fifteen to eighteen hours, it is desirable that branch lines be laid to different points, so that the process, as a whole, need not be interrupted. During the period of settling, water seeps out and the material shrinks from 1 to 10 per cent in volume. It is necessary that the drainage be so controlled that the least possible solid matter will be carried away. The finest part of the filling has an important part in the cementation of the mass.

The process requires careful and continuous attention, though the number of men employed need not be large. Generally, there should

*Davies, J. B. "Flushing Culm." *Mines and Minerals*, Vol. 18, pp. 342, 389. 1898.
Griffith, William. "Flushing Culm." *Mines and Minerals*, Vol. 20, p. 388. 1900. Enzian, Charles "Hydraulic Mine Filling." U. S. Bureau of Mines, Bul. No. 60, pp. 58-60.

†Wilson, H. M. "Irrigation Engineering." Pp. 61-69, 338, 344, Revised edition, 1910.

be one man for the surface, one to patrol each 1,000 feet of pipe line, and one to inspect the filling.

The results obtained have been very satisfactory and a large amount of material formerly deposited on the surface is now washed back into the mines.

In discussing wastes in Illinois coal mining, G. S. Rice commented upon the feasibility of employing hydraulic fillings. He noted the use of culm for filling in Pennsylvania and stated that "In Illinois, the substitute would have to be surface sands and gravel. That this would be impracticable in the great majority of cases throughout the State is self-evident, particularly if water, the usual vehicle for transportation, is employed, inasmuch as the majority of the thick seams in Illinois have clay under them which water would soften, and thus tend to cause a 'squeeze.' Aside from this, much farm land would be destroyed in getting the filling material."*

In longwall mining the application of hydraulic filling under present practice does not seem to be generally feasible. Hydraulic filling in flat seams worked on the longwall plan was inaugurated near Liege, Belgium, in 1913, but has not been employed on a sufficiently large scale to justify a statement that it is practicable for flat seams.†

Over a hundred collieries in Upper Silesia have employed hydraulic filling‡ in seams varying from 4 to 40 feet in thickness. Subsidence has been reduced from 30 to 70 per cent to 0.3 to 7.8 per cent of the height of the seam. In 1914 twenty-seven collieries, employing forty equipments, used hydraulic filling. The sand commonly used in Silesia for filling is mined with steam shovels and then transported by railroad, sometimes for considerable distance, to the mine, where it is dumped on a grizzly to remove the boulders and then mixed with a suitable amount of water to flush it into the mine. At one mine, at least, the boulders are crushed and mixed with sand filling. A detailed description of the methods used in Upper Silesia will be found in the reports of the Upper Silesia Mining Association. In the Saarbrücken district there are on state-owned lands more than twenty independent hydraulic-filling installations, costing \$350,000. This method is employed for iron and potash mines as well as in the coal mines.

"The only fairly extensive installations at work in Britain is that

*Rice, G. S. "Mining Wastes and Mining Costs in Illinois." Ill. State Geol. Sur., Bul. No. 14, p. 220, 1909.

†See Trans. Inst. Min. Eng., Vol. 46, p. 439, 1913-1914.

‡Trans. Inst. Min. Eng. Vol. 46, p. 534, 1912. Report of British Consul-General, Westphalia, p. 25, 1911.

of the Wishaw Coal Mining Company, Motherwell. There are other installations in a small form, or under consideration, but nothing yet has been adopted on an extensive scale. A small trial outfit has been installed at one of the Fife pits, and there is a proposition to use hydraulic stowing where the seams run under the sea. There is a small installation at the Crowgarth iron-ore mine.”*

“In France it has been used, especially at the collieries in the Department of the Pas-de-Calais, and also in the coal fields of St. Etienne. In Belgium it is used at several collieries. In Spain the Penarroza Colliery is erecting a plant, and several collieries in Austria, as well as Poland and Russia, are employing the system. It is used also at lignite mines in Manchuria and in the gold mines of Australia and the Transvaal.”†

Gullachsen reports that in order to avoid the great expense of pumping to the surface the water used in hydraulic filling the Cinderella Deep mine introduced a system by which sand is sent into the mine in a dry condition. A wooden box-laundry was constructed measuring 12 by 11 inches in inside cross-section. This laundry was carried down the vertical shaft to a depth of 3,900 feet to the level at which the filling material was required. The sand, which should not contain more than 7 per cent of moisture, is stored in a surface bin, from which it is taken on a conveyor belt to the top of the shaft and there discharged into the laundry. On reaching the bottom of the laundry, it falls on a steeply inclined iron plate, at which point jets of water are turned into the sand, which is then carried away as a pulp. The great objection to this system is the difficulty of securing a constant supply of dry sand. As soon as the sand contains more than 7 per cent of moisture, it is inclined to adhere gradually to the sides of the laundry, which in time becomes choked. The laundry was connected to a Roots blower and jets of compressed air introduced, the idea being to assist the drying of the sand and to increase the velocity of the falling stream, but this device was found to result in only a very slight improvement.”

PNEUMATIC FILLING.

The stowing of crushed rock by means of compressed air has been successfully employed in the Lake Superior copper district at several

*Paton, J. D. “Modern Developments in Hydraulic Stowing.” *Trans. Inst. Min. Engrs.*, Vol. 47, p. 468, 1914. See also *Trans. Inst. Min. Engrs.*, Vol. 48, p. 134, 1914, and *Iron and Coal Trades Review*, Vol. 89, p. 454, 1914.

†Gullachsen, B. C. “Hydraulic Stowing in the Gold Mines of the Witwatersrand.” *Trans. Inst. Min. Eng.*, Vol. 48, p. 122, 1914. See also *Trans. Inst. Min. Eng.*, Vol. 41, p. 586, 1910, and *Trans. Inst. Min. Eng.*, Vol. 43, p. 632, 1911.

mines, having been developed at the Champion mine of the Copper Range Company by F. W. Denton. Stamp sands or tailings from the concentration plant are hauled in railroad cars a distance of eighteen miles and discharged through pipes into the worked-out stopes. It is claimed that by the use of this material a saving is made over the method of support formerly used. In order to provide sufficient material for filling the stopes, waste rock secured from sorting in the stopes was supplemented by rock blasted out of the walls. At present the sand is used in addition to the waste material discarded in the stopes.*

SUPPORTING POWER OF FILLING.

The problem of support of surface by filling suggests two important points, in addition to the controlling factor of the cost of filling. When the worked-out portions of the mine are filled by the natural process of caving, the factor of increase of volume of material should be known. Moreover, as the overlying beds sink upon this filling the factor of compressibility of the filling must be considered. Fayol made extensive and careful investigations along these lines, and his determinations of the increase of volume are shown in Table 14.

TABLE 14.
INCREASE IN VOLUME OF MATERIALS IN FILLING.

Nature of Rock	Relative Volumes					
	Unbroken	Crushed to Powder	Grains .078 to .118 inch (2-3 mm.)	Grains .393 to .59 inch (10-15 mm.)	Grains .59 to .787 inch (15-20 mm.)	Mixtures, Grains and Fine Dust
Clay	100	196	209	226	225	216
Shale	100	213	210	221	224	229
Sandstone ...	100	219	214	211	310	214
Coal	100	207	224	199	223	202

The mixture of large and small pieces of sandstone and shale commonly used for stowing increases in volume about 60 per cent. The greater the increases in volume, the more easily is the crushed material compressed. Fayol's results of tests of compression upon crushed material are given in Table 15.

The pressures noted in Columns I, II, III, and IV correspond to depths of strata of 1,638, 3,276, 8,190, and 16,380 feet, respectively.

*"Sand Filling at Champion Copper Co., Painesdale, Michigan." *Min. and Eng. World*, Vol. 41, p. 1194, 1914.

TABLE 15.

RESULTS OF TESTS OF COMPRESSION UPON CRUSHED MATERIAL.

Nature of Rock	Space Occupied Before Being Broken	Rocks Having Been Previously Crushed or Broken, the Space Occupied under Pressure of			
		I. 1422 lb. per sq. in. 100 kgm. per sq. cm.	II. 2844 lb. per sq. in. 200 kgm. per sq. cm.	III. 7110 lb. per sq. in. 500 kgm. per sq. cm.	IV. 14,220 lb. per sq. in. 1000 kgm. per sq. cm.
Clay	100	100	90	75	70
Shale	100	128	116	110	97
Sandstone	100	136	125	120	105
Coal	100	130	125	118	109

Fayol concluded that the material which ordinarily fills the goaves of mines always occupies a larger space than it did originally, and after an expansion of about 60 per cent it appears to undergo in workings of from 300 to 900 feet in depth a compression of about 30 per cent, which leaves a volume about 12 per cent larger than the volume of the unbroken rock.*

The supporting strength of dry filling as studied in connection with the problem of surface support at Scranton, Pennsylvania, is shown in Table 16.†

Anton Frieser reports that in coal mining in Bohemia hydraulic filling has been carried on extensively and that, with such filling at depths of from 60 to 200 feet, the roof pressure compresses one volume of ordinary stone-and-sand packing to 0.6, clay packing compresses to 0.5, and puddled sand and ashes to 0.8 or 0.9.‡

In the Ruhr coal district of Germany, filling has been used extensively and the amount of compression has been noted carefully.§ This has been possible as new openings were driven through workings which had been filled from two to eight years previously.

Dr. Niesz has found that gobbing, under pressure, may lose four-tenths of its height, small-grained pit-heap material 25 per cent, and pure loose sand 8 per cent.§

The commission reporting upon the slide at Turtle Mt., Frank, Alberta, Canada, commented upon the efficiency of various kinds of filling in mine workings. The general statement was made that under

*Colliery Engineer, Vol. 33, p. 548, 1913.

†U. S. Bureau of Mines, Bul. No. 25, p. 59, 1912.

‡Oestrr. Zeit für Berg- und Hüttenwesen, Vol. 43, p. 253, 1895.

§Oberhausen, J. "Compression of Slope Fillings," Glückauf, p. 1146, Nov. 22, 1902.

Translation in Columbia School Mines Quarterly, Vol. 26, p. 271, 1904.

§Zeit für Berg-, Hütt-, u.-Salinew., Vol. 58, p. 418, 1910.

TABLE 16.
SUPPORTING STRENGTH OF VARIOUS FORMS OF DRY FILLING.

Kind of Material Comprising the Artificial Supports	Approximate Depth, in Feet, of Column of Coal Measure Rock, 1 Foot Square, Necessary to Compress Artificial Roof Support					
	1	3	5	10	20	30
Per Cent. of Compression						
1. Rectangular gob piers, ordinary construction	Feet	Feet	Feet	Feet	Feet	Feet
2. Circular piers of mine rock, well constructed		10	12	36	125	*306
3. Timber cogs filled with gob, average construction		46	75	146	292	*512
4. Loose pile of broken sandstone through 1¾-inch ring, 40 per cent. voids		8	65	182	270	*419
5. Pile broken sandstone, 40 per cent. voids, voids filled with sand			20	53	124	*298
6. Loose pile large size broken sand rock, 45 per cent. voids			21	53	186	*465
7. Mine room filled with large broken sand rock, 50 per cent. voids		48	66	121	351	*492
8. Mine room filled with broken sandstone, 40 per cent. voids	12	27	45	117	434	a615
9. Mine room filled with broken sandstone, 40 per cent. voids filled with sand		44	74	177	619	1,310
10. Mine chamber filled with dry coal ashes, 64 per cent. voids		46	77	325	6,000	b8,860
11. Mine room filled with dry river sand		13	25	70	143	332
12. Mine room filled with river sand flushed in with water	12	40	70	442	1,715	6,640
13. Mine chamber filled with coal culm flushed in with water	111	522	891	2,310		c8,860
14. Concrete pier, 1 part cement, 7 parts sand and gravel; 5 months old	32	118	190	472	1,822	5,905
	117	1,092	(e)			
Resistance of flushed culm	1.0	1.0	1.0	1	1	†.....
Resistance of flushed sand	3.5	4.4	4.7	5	4	†.....
Concrete pier	3.6	9.0	(d)	(d)	(d)	†(d)

a 27 per cent. settlement.

b 23 per cent. settlement.

c 20¾ per cent. settlement.

d Worthless.

e Gradually cracked to pieces under continuous load equal to 600 feet of rock.

*Free to expand laterally.

†Comparative.

average conditions the settlement would be 5 per cent of the thickness of the bed if ordinary sand were used; an inappreciable amount if granulated slag were used; 10 to 15 per cent with loam, sandy clay, and ashes; and 40 to 60 per cent with dry packing. Under the conditions at Frank the coal pillars left merely serve "to delay the process (of movement) for under the great pressures due to depth, shales, such as here constitute the hanging wall, will 'flow' and seal all openings."*

*Daly, R. A., Miller, W. G., and Rice, G. S. "Report of Commission Appointed to Investigate Turtle Mt., Frank, Alberta, 1911." Can. Dept. Mines, Geol. Survey Branch, Memoir No. 27, p. 30.

TABLE 17.

EXTENT OF FILLING IN RUHR COAL DISTRICT, GERMANY.

Per Cent. of Compression Referred to Original Thickness	Area Worked Out Square Metre	Average Depth from Surface	Age of Workings at Time of Reopening	Composition of Filling
29	14,400	370	8	Waste rock, slates, and sandstones from surface.
28	20,800	450	2	Granulated slag and waste rock (clay and slate).
37	104,000	360	5	Waste from seam and from roof and footwall.
39	26,400	300	4	Waste from seam and from roof and footwall.
60	36,000	270	5	Waste rock from bottom of gangways.
21	21,000	380	2	Waste rock from surface, granulated slag and clay slate.
28	25,000	440	2	Same as preceding.

CONSTRUCTION OVER MINED-OUT AREAS.

When a building is threatened by subsidence resulting from mining operations, or when it is planned to erect a structure upon land which has been undermined and which does not offer sufficiently stable material for a foundation, various steps may be taken to prevent damage to the structure erected or proposed.

Owing to the danger of surface subsidence, the Central Railroad of New Jersey introduced sand into the old mine workings beneath the site of a proposed depot in Scranton in 1911. The Diamond and the Rock seams had been worked and after investigation of the workings it was decided that it would not be necessary to fill the entire area of the workings, but only to reinforce sufficiently the smaller pillars in both seams and fill the wider areas in the Diamond seam so as to prevent any further caving of the roof. In an 8-inch borehole, drilled for this special purpose, a 6-inch pipe was placed. The depth to the lower seam was 80 feet. Sand was brought in railroad cars and flushed into the workings, a total of 9,400 cubic yards being placed at a cost for labor of 29 cents per cubic yard of sand filling.*

*Bunting, D. "Pillar and Artificial Support in Coal Mining." Penn. Legis. Jour., Appendix V, p. 5989, 1913.

The problem of constructing a six-story building, 60 feet wide by 157 feet 7 inches long, on Wyoming Avenue, in Scranton, Pa., was solved by constructing a series of concrete columns. The Big, or 14-foot, bed was close to the surface and had been mined beneath the property, but no maps were available to show the exact location and size of the pillars, and the old workings were inaccessible. Beneath the 14-foot bed other thinner beds had been worked. Five lines of holes were drilled to the rock under the 14-foot bed, the average depth being 40 feet. They were spaced 14 feet 10 inches in one direction and 16 feet 4 inches in the other. Twelve-inch steel pipes were driven into the holes and filled with concrete and, on the top of these, reinforced concrete beams were built.*

The Scranton Electric Company flushed ashes into the old workings under its new power house on Washington avenue. At the present time it is sinking a shaft to be used for dumping ashes into these workings, thus avoiding the expense of hauling them away.

In Pittsburgh, Pennsylvania, the residence section of the city extends over areas from which coal has been mined and it has been thought advisable to construct special foundations under buildings which might be endangered by surface subsidence. Exploratory holes at Beacon Street and Shady Avenue showed that the mine workings were 35 to 55 feet below the surface. Some of the roof had fallen, but some pillars had been left and it was anticipated that subsidence might not be uniform. A pillar of coal extended under one corner of the site for a house. Holes 10 and 14 inches in diameter were drilled to the rock below the coal and six concrete columns were constructed in order to provide support for that part of the house which would be unaffected by caving over the rooms in the mine. No column was constructed under the corner of the house where the coal pillar was located. The concrete columns were 8 inches and 12 inches in diameter inside the galvanized-iron lining which was placed in each hole. The lining was slightly smaller than the hole so that the rock might sink without disturbing the columns. Each column was reinforced and upon these columns were erected reinforced concrete girders which served as a foundation for the house.†

When it is proposed to remove all the mineral in a horizontal bed beneath a structure, it is advisable to mine out the coal in advance in a direction at right angles to the longer axis of the structure and to

*Stevenson, G. E. "Founding a Building Over Coal Mine Workings." Eng. News, Vol. 71, p. 791, 1914.

†"Concrete Column Foundation for a Building Over Coal Mine Workings." Eng. News, Vol. 117, p. 632, 1912.

advance the face at a uniform rate as rapidly as possible so that the structure may be subjected to stress for as short a period as possible.

Reference has previously been made to the special types of construction employed in buildings* and bridges† when surface movement is anticipated. Foundations may be reinforced, long buildings may be divided into units, joints permitting expansion and contraction may be provided, expansion pieces may be placed in railroad tracks, pipe line, cables, etc. In cities in German coal mining districts gutters and curbing are laid with elastic and waterproof joints. Asphalt, cement, and concrete pavements are not used because they are not easily repaired.

RESTORING DAMAGED LANDS.

When subsidence causes breaks and pit holes in agricultural lands, the surface may be rendered temporarily almost valueless for certain kinds of tilling. When the land is of great value for farming, these holes may be filled with waste rock from the mine, cinders, and other refuse, to within four feet of the surface. The remainder of filling necessary to restore a regular surface slope should consist of good soil. At a number of mines in Illinois where such surface damage has resulted from mining operations, the mining companies cooperate with the farmers in filling the pit holes with mine rock.

When subsidence does not break the surface but simply causes shallow basins below the general drainage levels, large ponds form during the spring and may result in the permanent flooding of valuable land. In Northern Illinois, in the longwall field, the topography is such that tile drains have been laid to permit the use of the land. Longwall mining frequently causes a surface movement sufficient to destroy the usefulness of such artificial drainage systems. Referring to the problem in Northern Illinois, G. S. Rice said: "It may be solved to a certain extent through draining the sunken lands by pumping, but even with such a method, aside from the expense, there is a serious difficulty from storm water. When the subsidence is from 2 to 4 feet it will render previously level lands of little use for raising crops until the particular area has come to full settlement and has been retiled. If it were possible to systematize mining so that the land nearest the water courses was first undermined and then in succession the land further away, the damage done to farming would be minimized."[‡]

*P. 68.

†P. 60.

‡Rice, G. S. "Mining Wastes and Costs in Illinois." Geol. Survey, Bul. No. 14, p. 48.

CHAPTER VII.

LEGAL CONSIDERATIONS.

RIGHT OF SUPPORT.

The title to the minerals, and the right to work them may be held separately from the surface. Under the common law the owner of the surface is entitled to surface support, even though the owner of the minerals finds it impossible to remove them without disturbing the surface. Moreover the owner of the surface is entitled not only to vertical support, but also to lateral support from his neighbors even to the extent that minerals upon adjoining lands cannot be removed in such a manner or to such an extent that the surface of adjoining properties is disturbed.

Leases of coal rights often state distinctly that the lessee shall not be liable for damage to the surface, and where surface rights only are sold, the deed often states that the title to the surface does not include the right to surface support if the owner of the mineral rights mines out the mineral. In spite of such clauses in deeds and in leases suits are of common occurrence when surface and mineral rights are owned by different parties.

MINING UNDER MUNICIPALITIES.

The problem of the claims of municipalities in the coal districts has aroused considerable discussion. In many instances coal mines have been opened upon lands remote from towns and upon which no buildings other than the mine structures were erected at the time. Later mining villages have grown up near the mines and residences and other buildings have been constructed upon the land which had previously been undermined. In many instances, owing to the importance of locating near an abundant fuel supply, industrial plants have been erected in these mining villages or in other towns in the coal district. Eventually large cities have grown up on the lands on which coal mining was the pioneer industry. Similarly mines have been opened outside the limits of important cities and mining operations have been confined to the area which was outside the limits of the city when the mine was opened, but in the course of years the city has extended its limits to include the mine and the area undermined.

The claims of the municipality upon the mining interests, which may have a right by contract and under the law to mine all the coal and to be exempt from liability for damages to the surface, were forcibly presented by Mayor B. Dimmick of Scranton before the Pennsylvania Anthracite Mine Cave Commission, as follows:

"I am of the opinion that there is no constitutional barrier against the inclusion in the general police power of a state or a community of the specific power to declare as null and void and as against sound public morals any and all contracts that waive the right to a reasonable support of the surface which is to be occupied and used for community purposes. I would recommend submitting to the Legislature an act that would declare null and void and as being contrary to public policy any and all contracts that waive the right to, or release from responsibility for, reasonable support of the surface wherever such surface is actually devoted to community life.

"Fortunately this problem has been attacked at a period in which public opinion is slowly but surely crystallizing in favor of acceptance of two general principles, the first being in the direction of such qualifications to the ownership and use of property as are exacted through the increasing interdependence of modern life, such qualifications being in no sense a redistribution of property, in no sense a taking away from one and giving to another, but simply such restrictions and regulations as are demanded, not only in the carrying out of the ancient rule, 'So use your own as not to injure another,' but also for the general welfare of the community. The second principle is that Society must accommodate itself to such costs as are incident not only to fair return to both capital and labor, but also to all the accidents and burdens that result from any activities that Society desires or is compelled to enjoy, and this principle is being regarded as so clearly equitable that its enforcement is being demanded, all private contracts to the contrary notwithstanding. If this principle can and should be enforced when the health of the community or individual is at stake, surely it can and should be enforced when, as in the case of support of the surface, the very lives of men, women, and children are jeopardized.

"The maintenance of the surface, upon which are located the communities that extract the coal, should be regarded as a necessary factor in the cost of mining and should be paid for by the consumer. Such inclusion of the cost of the support of the surface in the general cost of production will be fairer than any fixed tax to be imposed by

the State and then paid out, say to municipalities, to be expended in securing such support.

"It is possible that even under the existing welfare clauses of the acts governing municipalities of Pennsylvania, the proposed exercise of police power might be upheld, but certainly the hands of these municipalities in the anthracite region would be greatly strengthened by such proposed legislation.

"In contemplating this exercise of police power, I realize that there is possibly no exact precedent therefor, yet such exercises would clearly fall within not only the modern but even the ancient definition of the power. So eminent a judge and publicist as Jeremiah S. Black once said that "the police power of the State, of which she cannot disarm herself if she would, enables her to regulate the use even of private property in such manner that neither the general public nor particular individuals can be made to suffer by it unjustly."

With these claims of Mayor Dimmick many eminent lawyers have taken issue.*

Opinions upon a number of the points under discussion are given in the following citations:

"In the natural state of land one part of it receives support from another, upper from lower strata, and soil from adjacent soil." (Per Lord Selborne in *Dalton v. Angus*, 6 A. C. 791.)

"Where the surface belongs to one and the minerals to another, no evidence of title appearing to regulate or qualify their rights of enjoyment, the owner of the minerals cannot remove them without leaving sufficient support to maintain the surface in its natural state." (*Wilms v. Jess*, 94 Ill. 464, 1880.)

The same principles hold between the owners of different minerals lying in separate beds. If one bed lies above another the owner of the lower bed must give support to the upper bed. (*MacSwinney* p. 301.)

A coal mine operating beneath a clay mine is liable for injuries to the upper mine caused by failure to leave sufficient pillars in the coal mine. (*Yandes v. Wright*, 66 Ind. 319, 1879.)

The right of support is not affected by the nature of the strata nor by the difficulty of propping up the surface. (*MacSwinney* p. 292.)

The right of support is wholly independent of the comparative

*For a complete statement of American cases on the various points of discussion between surface and mining rights, see Lindley on mines, Title IX, Ch. II and III, 3d Ed., 1914. For British cases, see MacSwinney, R. F. "The Law of Mines, Quarries and Minerals," Ch. XIV, 4th Ed., 1912.

values of the substance receiving and the substance giving support. (*Op. Cit.*, p. 292.)

The right of lateral support is an absolute one. The obligation to respect it is in no way affected by the question of negligence. (50 Mo. App. 525.)

“Every owner of land in its natural state has a *prima facie* right to support, lateral as well as vertical; and the adjacent or subjacent owner has no right, *prima facie*, in order to win his minerals, to withdraw such support. The burden, both in pleading and in proof, is upon him who asserts that the position is different from that existing as of common right.” (*Op. Cit.*, p. 299.)

EXEMPTION FROM LIABILITY FOR DAMAGE TO SURFACE.

A conveyance of the right to mine all the underlying minerals implies that in so mining such minerals the surface land shall be sufficiently supported and that so much of such minerals may be mined as can be obtained without injury to the surface. A waiver of the obligation to support the surface must be made by the owner of the surface land by language clear and unequivocal. Such a waiver does not follow a conveyance of all such minerals, nor from the use of language in such a conveyance to the effect that the mining operations shall be “conducted with as little damage to the surface as conveniently may.” (*Seitz v. Coal Valley Mining Co.*, 149 Ill. App. 85, 1909.)

Where a land owner sells the surface, reserving to himself the minerals with power to get them, he must, if he intends to have power to get them in a way which will destroy the surface, frame the reservation in such a way as to show clearly that he is intended to have that power. (*Wilms v. Jess*, 94 Ill. 464, 1880.)

When an instrument excludes the right of the surface owner to support, the mine owner may be liable, if he works negligently, or contrary to the custom of the country. (*MacSwinney* p. 311.)

The right of support by land in its natural state may also be excluded, wholly or in fact, by statute. Examples of this may be found in various English Acts. (See *MacSwinney* p. 312.)

In an investigation of the surface damage in a section of Scranton, Pennsylvania, it was found that 48 per cent of the titles contained a clause completely waiving surface support, in the following language: “All the coal in, under and upon said lot, together with the sole right and privilege to mine and remove all the coal under said lots without

incurring in any event whatever any liability for injury or damage done to the surface of said lots or improvements thereon or that may thereafter be put thereon caused by mining or removal of said coal."

Fourteen per cent of the titles contained waivers which are more or less conditional in their nature: "All the anthracite coal lying underneath, also half the width of streets adjoining. It being understood and agreed that at least one-fourth thereof, properly distributed, shall be left for surface support and the coal shall be mined in a workman-like and skillful manner, it being understood that all the coal is to be mined and paid for except so much left thereof as may be necessary to be left for pillars to support the surface thereof, and it being possible that there may be a difference of opinion relating to the fulfillment of this provision it is agreed that the matter shall be submitted to a board of competent and skillful engineers, each party to select one and, in case of failure to agree, said engineers are empowered to call in a third mining engineer and the decision of the majority shall be final."

Ten per cent of the titles contained the following clause: "All the coal and minerals under said lot, together with the right to mine and remove all of said coal and minerals, provided also that in removing the coal the second party shall leave one-fourth thereof in place for the protection of the surface."

The remainder of the titles examined by the investigators contained the following clause: "All right, title, etc., to all coal in and under said lots, also the coal under the surface in front of said lots to the center of the street."

In the report of the Pennsylvania State Anthracite Mine Cave Commission excerpts of 42 deeds are given showing the various forms in which reservations have been made when the title to the surface has been severed from the mining right.*

In the bituminous fields a customary form of exemption clause in deed for coal, separate from the surface, is as follows: "All the coal underlying and within the described lands together with the right to take the entire quantity, or a less quantity of said coal, without leaving any support for the overlying strata, and without liability for any injury or damage which may result from the breaking of said strata." Another type of exemption clause employed in Illinois is as follows: "Releasing and surrendering any and all claims for dam-

*Pa. Legislative Journal, Appendix, Vol. 5, p. 5953, 1913.

ages and all liability by reason of damages either to person or property which may in any way be caused or occasioned at any time hereafter, directly or indirectly, by the mining or removing of coal or other minerals.”

PROTECTION OF SURFACE BY GRANTS AND BY LEGISLATION.

The right of support for land in its non-natural state may be acquired by express or implied grant.* Where land is severed from adjoining land for a particular purpose, and such purpose is known at the time the mineral right is severed from the surface, there is, *prima facie*, an implied grant of a reasonable degree of support for carrying out the particular purpose under consideration.

In order to protect railways, canals, waterworks, sewers, etc., the British Parliament has enacted legislation which guarantees that such structures shall not be undermined, if liable to be damaged, without notice. In accordance with these acts, the mining company may be required to leave a pillar, but the mining company is compensated for the coal left in the ground and for any damage that may be sustained by the interruption with the system of mining. In the case of the Railway Act, it is specified that “the (railway) company shall from time to time pay to the owner, lessee, or occupier of any such mines, extending so as to lie on both sides of the railway, all such additional expenses and losses as shall be incurred by such owner, lessee, or occupier by reason of the severance of the lands lying over such mines by the railway, or of the continuous working of such mines being interrupted, or by reason of the same being worked in such a manner and under such restrictions as not to prejudice or injure the railway, and for any minerals not purchased by the company which cannot be obtained by reason of making and maintaining the railway; and if any dispute or question shall arise between the company and such owner, lessee, or occupier as aforesaid, touching the amount of such losses or expenses, the same shall be settled by arbitration.†

Similar sections are included in the Wat. Cl. Const. Act, 1847; the Pub. Health Act, 1875 (Support of Sewers); Amendment Act, 1883; the Local Government Act, 1894; the Small Holdings and Allotments Act, 1908; and the Housing and Town Planning Act, 1909.‡

Under these acts, as noted, the intention of a mining company to

*MacSwiney Pp. 315, 316.

†Railway Clauses Consolidation Act, 1845, Sec. 81. 8 and 9 Vict., c. 20.

‡MacSwiney P. 370.

remove the mineral beneath any of the legally specified structure must be announced through a regular "notice of intention to work." This notice is given in most cases thirty days in advance of the intended working. If, after notice has been given, the owner of the structure does not agree to negotiate with the mining company, it is lawful for the mining company to proceed in the regular manner of working. If damage results, it shall be repaired by the mining company.*

Gas works and gas mains are not within the British mining code excepting in so far as they are vested in local authority. Private gas companies are not entitled to support if the mineral right has been severed, but the colliery company would be liable for damages to gas pipes and leakage of gas. In the absence of special provisions, owners, lessees, and occupiers of mines are not liable for damage caused to tramways by working mines or minerals in the usual and ordinary course.† This mining code of Great Britain is not applicable to burial grounds, school sites, public highways, bridges, nor canals.

In several states of the United States there are statutes in regard to support, particularly in western states in which the lode mining law permits extralateral mining. The statutes of Colorado, for example, prescribe that "when the right to mine is in any case separate from the ownership or right of occupancy to the surface, the owner or rightful occupant of the surface may demand satisfactory security from the miner, and if it be refused, may enjoin such miner from working until such security is given." No person shall have the right to mine under any building or other improvement unless he shall first secure the parties owning the same against all damages, except by priority of right."‡

Other states, such as Idaho, North Dakota, South Dakota, and Wyoming, have similar laws. In commenting on this type of legislation, Lindley says, "We are not aware that this class of legislation has been the subject of judicial investigation. It seems to us that such legislation is not altogether free from constitutional objections."§

Arkansas has a law, approved Feb. 28, 1907, forbidding the mining of coal or any other mineral substance from beneath a cemetery or burial place. No openings whatever may be driven under or through

*Cockburn, J. H. "Minerals Under Railways and Statutory Works." Trans. Inst. Min. Engrs., Vol. 39, p. 104, 1909.

†Op. cit. P. 128.

‡Rev. Stat., Colorado, p. 4213, 1908.

§Lindley "American Law Relating to Mines and Mineral Lands." Vol. 3, p. 2016. 3d Ed.

the mineral directly beneath the cemetery under penalty of a fine of \$5,000 or imprisonment of from one to five years.*

In Pennsylvania the Davis Mine Cave Act, approved July 26, 1913, provides regulations governing the mining of coal and other minerals and the "support underlying and beneath the surface of the several streets, avenues, thoroughfares, courts, alleys, places, and public high-ways within the limits of the several municipal corporations, and authorizing the creation of a Bureau of Mine Inspection and Surface Support," by any municipal corporation within the anthracite coal fields. Members of the Bureau of Mine Inspection and Surface Support have the right and power to enter, examine, and survey any mine within the limits of the municipality. Mining companies are required to furnish accurate and complete maps of the workings and to keep the same up to date.

The mining companies are required to "maintain, uphold, and preserve the stability of the surface" of the various streets, etc. The officers of mining companies are made responsible for the violation of the provisions of the act and for violation are subject to a fine of \$1,000 or imprisonment for ninety days, or both.†

An ordinance was enacted by the Borough of Plymouth, Luzerne County, Pennsylvania, forbidding mining within 200 feet of the street lines and as the borough is platted in 400-foot squares, this prohibited any mining whatever. The county courts in Borough of Plymouth v. Plymouth Coal Co. restrained the coal company from mining under the streets.

REMEDIES.

In the event that the owner of the surface is entitled to surface support and is sustaining damages by the mining operations beneath or adjacent to his land he may recover damages or if the damage is irreparable or immeasurable he may apply for an injunction to restrain mining operations. If the mining operations are being conducted by parties whose financial resources are not adequate to insure the payment of damages in case such are assessed, an injunction may be issued.

The right of support is not infringed by excavation, but by subsidence and damages do not exist until subsidence has actually occurred. (Catlin Coal Co., v. Henry Lloyd, 109 Ill. App. Rep. 122, 1902.) The Pennsylvania court now holds, however, that the cause of action

*Arkansas Acts of 1907, Sec. 566 d-f.

†Pa. Acts of General Assembly, 1913, No. 857.

accrues when the support is removed and is barred after the lapse of six years from such removal. It is said by the Pennsylvania court that the adoption of any more onerous rule "would encourage the purchase of surface over coal mines for speculation in future law suits." (Noonan v. Pardee, 200 Pa. 474, 86 Am. St. Rep. 722, 55 L. R. A. 410.)

"The owner of the subsidence estate is not liable to the surface proprietor for a subsidence caused by excavations made by his predecessor in title, although damage does not occur until after such owner came into possession. This results from the fact that, while the subsidence gives the cause of action, the responsibility therefor attaches to him whose acts and omissions have brought about the mischief."*

If the owner of real estate which has been injuriously affected or damaged by a permanent structure has not brought an action to recover damages and conveys the land to another, the cause of action does not pass with the title nor inure to the benefit of the depreciation in value in the price paid. (La Salle County Carbon Coal Co. v. Sanitary District of Chicago, 260 Ill. 423, 1913.)

Depreciation in the value of the surface caused by the mere apprehension of future damage gives no cause of action.† Only damage which has actually occurred may be considered by a court, but each fresh subsidence constitutes a basis for a new claim for damages. (Catlin Coal Co. v. Henry Lloyd, 124 Ill. App. 394, 1906.)

"The right of support is not infringed unless the subsidence is substantial. There must be some real sensible interference with the land. The right of support in ordinary cases is infringed where the subsidence is substantial, but the damage is inappreciable; and it is now settled that an injunction may be obtained where the subsidence is substantial, although the damage is inappreciable. The right of support is analogous to a right of property, and is a right to have the surface kept securely at its ancient and natural level."‡

A mine owner cannot avoid liability by showing that his workings have been proper and in the customary manner. "The act of removing all support from the superincumbent soil is, *prima facie*, the cause of its subsequently subsiding." (Wilms v. Jess, 94 Ill. 464, 1880.)

Where land has been artificially burdened by a building and no contract or prescription is available to regulate its right to support, no right to support, lateral or vertical, exists for the building. In an

*Lindley P. 2021.

†MacSwinney P. 294.

‡MacSwinney P. 297.

action for removing support from land artificially burdened, the plaintiff has always been obliged, as a matter of pleading, to show that he is entitled to have the weight supported.*

Where the injury to the surface would have resulted from mining operations if no buildings existed upon the surface, the act creating the subsidence is wrongful and renders the owners of the mine liable for all damages that result from mining to the buildings as well as to the land itself. (*Wilms v. Jess*, 94 Ill. 464, 1880.)

As a general rule, the measure of damages in actions for injuries to real property is the difference in market value before and after the injury to the premises. But to this rule there are exceptions, and it has been held that the cost of repair or of restoring the premises to their original condition is the true and better rule to apply. The valuation should be adopted which will be most beneficial to the injured party, for he is entitled to the benefit of the premises intact. (*Donk Bros. Coal and Coke Co. v. Slatá*, 133 Ill. App. 280; 135 Ill. App. 633.)

A bill in equity to restrain the mining of coal was dismissed as there is a remedy at law in case damage is done to surface by subsidence. (*Henry Lloyd v. Catlin Coal Co.*, 109 Ill. App. 37, 1902.)

What amount of coal may be safely mined and what amount must be left for necessary support of the soil are largely engineering questions, and it is only in rare cases, where the remedy at law is so inadequate as to render such course necessary, that a court of equity will direct the work by injunction. (*Henry Lloyd v. Catlin Coal Co.*, 210 Ill. 460, 1904.)

As previously noted† considerable damage has resulted in England from the pumping of brine. Under the Brine Pumping Act of 1891 (54 and 55 Vict. c. 40), upon application, compensation districts may be formed within the pumping fields. For every compensation district, under the act, there is established a compensation board. This board is incorporated and consists of representatives of the various interests concerned; one-third shall be persons not interested in the brine business and appointed by the county council; one-third elected by the brine pumpers; and one-third (not interested in brine pumping) appointed by the local sanitary authority. A compensation fund is maintained in each district; upon each pumper is levied a tax not exceeding 3 pence per 1,000 gallons pumped for a twelve-month period. Out of this fund damages allowed by the compensation board are paid.

*MacSwinney P. 304.

†Ch. I.

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