

Movement of articulated buildings on subsidence sites

by

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Sir Donald Gibson, C.B.E. (President, R.I.B.A., Director General of Research and Development, Ministry of Public Buildings and Works) said that in 1959 the Institution had prepared a summary of various contributions towards the solution of problems of building on mining sites. They had had a great deal of help from the National Coal Board and from Dr Ward of the Soil Mechanics Division of the Building Research Station. Their next problem had been to find the special skill upon which the solutions to the problem partly depended, and Mr Heathcote had provided this.

85. In the current year the CLASP programme had amounted to £12 million worth of building, and since about half of these buildings were on mining sites, this meant £6 million worth of work of the type under discussion. He thought the CLASP approach was saving about 30% of the cost which would otherwise have been used to provide strong reinforced foundations. Thus on the current programme about £2 million a year was being saved.

86. He would like to feel that the method was now worthy of the Institution's approval, and that those concerned could now consider whether these methods were applicable in earthquake countries. One of the most important points to have emerged was that buildings were no longer being considered as rigid structures but as completely non-rigid ones.

87. In the original survey of buildings where precautions had been taken to avoid movement they had found for example a school hall with a heavy concrete roof with only about $\frac{3}{4}$ in. to go before collapsing onto the children; windows which had had to be strapped up while movement was going on under the building; and maintenance of such an order that it was better to pull down the whole building and begin again.

88. He was grateful for the invitation to take part in the discussion and would like to feel that after the meeting the method would have the support of the civil engineering profession as a satisfactory way of avoiding heavy expenditure on many structures which did not have to carry more than 100 lb/sq. ft and went up to about four storeys.

Dr W. H. Ward (Head, Soil Mechanics Division, Building Research Station) said that as a member of a Governmental Committee and of a Committee of the Institution which had prepared recommendations for the design of structures in mining subsidence areas,^{1, 2} he had become very conscious of the dearth of detailed measurements on the simultaneous distortion of buildings and of the underlying ground during the passage of mining operations. It was good to see this type of information in the Paper and he hoped that the further observations the Author was making on other buildings would also be published.

90. He also had a special interest in the CLASP system since Sir Donald Gibson, Mr Lacey, and Mr Swain, as successive County Architects of Nottinghamshire, had adopted his advice and basic ideas and developed a flexible system of construction that attempted to follow the changing contours of the ground surface but restricted distortion in the horizontal plane.

91. At the time this structural conception was quite a revolutionary one, directly

opposed to traditional practice. Nevertheless it seemed to be a logical development and one which might prove economical, since instead of adding material to stiffen the normal structure, it used fewer and lighter materials.

92. It was most enterprising, both of Nottinghamshire County Council and of the Author's firm, to accept a completely new structural system and to go straight ahead and put it into practical effect, when, moreover, they had to wait several years before the system became subjected to the rigorous trials of mining subsidence. Many of the CLASP school structures had been in use for several years before any of them were subjected to ground distortion. Anyone who was responsible for the structural safety of buildings containing young children must be very anxious to see a new system proven. In particular, Dr Ward was most anxious that proper measurements should be taken to demonstrate whether the buildings were satisfactory, or whether any modifications were necessary.

93. The measurements the Author had been making were simple in concept but difficult to accomplish in practice, and moreover the results were very difficult to describe simply. He knew the practical difficulties of this type of work and sympathized very much with the problem.

94. The present Paper dealt with a few special aspects of the distortion of the structure, naturally limited by the number of measurements that could be made. It said very little about the general behaviour of this and other structures which the Author's firm had built and it would be valuable in replying to the discussion if the Author could indicate, in rather more detail, the general performance of those structures which had been subjected to appreciable distortion. He had seen several of them and there seemed to be no doubt that on the whole the structures were behaving as anticipated and giving rise to far less interference with their occupation than the traditional type of brick structure.

95. Mr Heathcote was dealing with a building that moved in space and, as he had indicated, it was necessary to establish coordinates in order to describe the absolute motion. However in reading the Paper he had found at times rather loose descriptions of the motion of one part of the structure relative to another part. The descriptions were difficult to follow and he felt sure that other readers had had similar difficulties. He hoped it would be possible to provide some clarity. For example, in using the word 'twist' it was necessary to specify the axis of rotation, or the plane in which the twist occurred, and to specify the fixed plane. He also drew attention to the fact that strain was a non-dimensional vector quantity. In the lower diagram of Fig. 12 strain apparently had a dimension of inches and there was no indication whether the strain was compressive or tensile.

96. The building was sited in a very unfavourable place, over the ledge of a long-wall working—a place where many people would not advise the construction of traditional buildings. Where such an abrupt change in the ground movement occurred it was, of course, sensible to divide the three-storey block into two completely separate structural units. But if he understood the Paper correctly there were connexions at roof level capable of developing a considerable shear force transversely between the two structural units in the plane of the roof. The Author then suggested in his conclusions that similar shear connexions should be made at the floors and possibly in the foundation. In other words he seemed to be suggesting one complete structure.

97. He did not follow this argument. One must surely decide *either* to design one large three-storey block system capable of accepting the ground motions without a separation, *or* to make two completely separate structural units that were stable on their own. A casual connexion at the roof seemed to be an undesirable half-measure requiring very special structural attention that added unnecessary complication to a standardized system.

Mr L. R. Creasy (Director Civil Engineering, Ministry of Public Building and Works) said the Paper formed a very valuable contribution to the record of the behaviour of a three-storey building during a period of coal extraction. It would be helpful if in subsequent discussion the Author could, perhaps, indicate some of the details of construction, particularly of the connexions of the framework and of the braced panels which were so essential for stability.

99. It appeared that the beam-to-column connexions were of a pinned form. An essential feature of the structure was that the pin-jointed framework was constructed without breaks apart from that at the subsidence joint and that the cladding was articulated and free to move in isolation from the frame. In these circumstances it would seem that the horizontal disturbing forces were carried by the roof and floor slabs to vertical stiffening panels and thence to the foundations.

100. In the present case there had been a 4-ft seam of coal at 700 ft below the surface which on extraction had produced a slope at the surface of, at the most, 2 in. in 10 ft and generally only one half of that value. It would be important to know whether this slope was the range of deformation, which one would expect as a general rule to be affected by the type of soil overburden and the depth of the seam below the surface.

101. It seemed that the frames had tilted vertically to about the same angle, of 1 in. in 10 ft, as the slope of the soil. This seemed to imply that the floors had also tilted by the same amount of 1 in. in 10 ft. This raised problems from the point of view of appearance and use. Presumably this design of tilt had been found satisfactory by the user. From the point of view of appearance, it seemed to imply that on a three-storey building there was a lateral deformation at the eaves of 3 or 4 in. In similar circumstances it would appear that in a 10-storey building there would be a deformation at the eaves of three or four times that amount and it might then be necessary to consider masking the effect by means of projections or setbacks at appropriate positions in the height.

102. The Author had indicated an ingenious use of telescopic bracing as a measure to introduce lozenging in the cross-frames to avoid tilting of the columns. It appeared from the recorded observations that the lozenging effect was limited to only 10 minutes of arc which corresponded to about $\frac{1}{3}$ in. in 10 ft and seemed a relatively small proportion of the total tilt. On this basis the building seemed largely to have tilted squarely on the flexible slab foundation rather than to have lozenged out of shape. This suggested that the effect of the telescopic bracing was, perhaps, not so prominent as the Author had hoped. Did this mean that a solid panel instead of the telescopic bracing panel could be an acceptable alternative?

103. Turning to the subsidence joint, the impression given in the Paper was that the 120-ft long section of the building from gable-end to subsidence joint had deformed in a smooth curve which followed the deformation of the ground. In this case it was presumably the articulation of the cladding which had allowed the frame to take up the movement quite freely without damage to the cladding or to the frame. The smooth continuity was in marked contrast to the disturbance which had occurred at the subsidence joints. There were quite large differential movements across the joint, which were presumably caused by the discontinuity in the frame at that point. This seemed to suggest that, while it was desirable to reduce an irregularly shaped building into simple constituent parts, nevertheless, in a building of simple rectangular outline in plan a discontinuity joint should not be introduced at least up to the 175-ft length of the present example.

Mr A. J. Leggatt (Messrs Nachshen, Crofts, and Leggatt) said that he wished to add to the remarks made by Sir Donald Gibson on the application of these techniques to earthquake zones. He imagined that Sir Donald was referring to the dynamic behaviour of the superstructure during the earthquake shock. He believed that the design of buildings to withstand shock was fairly well understood nowadays, whether

it should be a structure based on a lightweight flexible system, as in the Paper, or whether it was one of the more conventional structures.

105. He had heard recently that a building in Japan designed on the latest methods, had in fact toppled over *en bloc*. This was due not to the dynamic shock on the building itself, but to compaction of the subsoil, a loose sand, which had been compacted by the earthquake wave to different degrees on either side of the building. In dimension and nature, the earth movement was similar to mining subsidence. Sir Donald might therefore feel that some of the buildings being discussed might be exported to Japan.

106. He suggested that the Paper might be valuable as a reference more to a qualitative measurement technique rather than to a quantitative one. The building discussed was probably unique. Certainly, the settlement pattern on the site must be unique. The actual dimensions of movement might therefore have no general relevance.

107. It was interesting to see the approach to the design of the building. He realized that the CLASP system was not primarily a means of overcoming mining subsidence, but was eminently a building system. The ability to cope with mining subsidence was valuable, but it was nevertheless a side-attribute. Lightweight steel had been used and he wondered whether the Author would care to comment on its suitability for building in an area of mining subsidence. One of the obvious advantages of lightweight building in normal circumstances was the saving in foundations.

108. The relative settlement of foundations was the design criterion more often than the actual fear of soil failure. In the case of mining subsidence differential movements of over 1 ft might be expected, and the 2 to 3 in. of differential settlement which would occur due to the natural consolidation of the soil were not of great concern. Greater ground pressures than were normally the case could perhaps be used and in that event the attractions of lightweight construction diminished.

109. Perhaps the Author could say more about ground strain. His own firm was engaged in the design of the foundations, basement, and sub-basement for a factory, and therefore problems of ground strain were very much in their minds. Such strains were far more difficult and expensive to combat than the vertical movement. A slip plane or continuous plane under the foundations was often suggested, on which the building could move, or, strictly speaking, under which the ground could move, leaving the building above it unsplit. Mr Heathcote had not mentioned if he had included the slip plane under his slab, and he would like to know if this had been done, and if so, had it slipped. Was it possible to compare the measured strain in the ground floor slab with the corresponding strain in the soil beneath. If it did not slip, did the slab crack? If it slipped, was there any coefficient of friction or some factor of that nature which was used, and what was the value?

110. He had been disappointed to discover that Mr Heathcote had not brought along the model which was shown in Fig. 3. He had, however, discovered that the mattress of one's bed formed a most useful subsidence model. What one did was to put books of representative sizes and stiffnesses on the mattress. By pressing a walking stick across the mattress but under the books, subsidence waves in any direction and of any magnitude could be simulated. One could observe some of the effects which the Author had found in his prototype.

111. The investigations had made clear the fact that a rectangular floor slab was not compatible with arbitrary differential movement of the four corners, and if these occurred the slab would warp, crack or lift at one corner. This problem could be solved by forming the floor slabs into triangles by creating a joint across the diagonal. A more practicable way was to use narrow strips, or one of the proprietary concrete floor systems, covering a rectangular grid of columns which could be made to work as independent beams, producing a warped effect and limiting cracking to the surfacing.

Mr R. J. Orchard (Chief Subsidence Engineer, National Coal Board) said that while he was very pleased to welcome a Paper on the CLASP type of construction he was not too happy as to whether the CLASP structure could be used during the actual movement of the ground while mining was taking place. In the case of a new town in the north-east where the requirement was to build as many dwellings as possible and the N.C.B.'s requirement was to work the coal, the local authority could not wait for housing until after the coal had been worked. Perhaps Mr Heathcote would say what he thought about the chances of building without damage on ground which was moving all the time.

113. He suggested a reversion to the rigid type of construction as a possible alternative. A factory-made structure, either dwelling house or small block of flats, could be bolted together rigidly at whatever angle the ground happened to be, on a foundation which might at that time be sloping. The superstructure could however be levelled after the movement had stopped. There might be more scope in the rigid structure than in the flexible one in this respect.

114. Dr Ward had raised the question of the word 'strain' as used by mining engineers. To his mind, strain was the result of stress. A building of 100 ft length suffering from mining subsidence could change by 0.1 ft. This could be described as a strain of 0.1 ft, providing the 100 ft was mentioned, or as a strain of 1 in 1000 or 0.001.

115. Since his organization had recently done a great deal of work on slope and curvature in mining areas perhaps he might answer the point made by Mr Creasy. Slope, was, of course, affected by the depth of the seam and the amount of subsidence. It was not noticeably affected by the type of strata provided that one was on something firm. The latest value which they had been able to find for maximum slope was 2.75 times the maximum subsidence over the depth—and this was the worst slope that one could get in a mining area.

116. With regard to the triangular foundations suggested by Mr Leggatt, he was afraid that these had just as much chance of cracking as rectangular ones. However, provided that the triangles were big enough or subsidence and curvature severe enough, curvature in a particular place could be fairly accurately calculated, and the amount of space to be left in a subsidence joint could be assessed for design purposes in regard to a CLASP or any other structure. This joint was necessary because there was horizontal extension or compression, and because allowance had to be made for the curvature which took place. A joint which could open at ground level under the horizontal strain could also open further at the top because the ground was suffering from convex curvature. In the case of compression, one had to allow for closure at ground level due to concave curvature and to provide the building with a bigger compression gap. This could be calculated fairly accurately now for any type of mining which might take place.

Mr Kenneth Wardell (Partner, Durnford, Lee, and Wardell, Consultant Mining Engineers) said that since he was not a structural or a civil engineer, he would not comment on the structure itself or its behaviour, but would simply make one or two points which seemed relevant to him looking at the problem as mining engineers usually did, from the bottom upwards rather than from the top downwards.

118. It was fairly clear from the observations of ground movement, as opposed to the observations on the structure itself, that the building was almost wholly in a zone of ground extension. Approximate calculations indicated that the maximum strain in the ground at the southern end of the small block was about $2\frac{1}{2}$ parts in 1000, running out to about zero at the northern end of the block. He wished to make the point that, in terms of ground movement caused by mining, this was not a particularly violent movement. Greater movements might be expected to occur in about 30 or 40% of cases where mining was taking place. One must not, therefore, draw too wide conclusions from this particular experiment, not simply because the intensity

of the movement would be exceeded in a fairly large number of sites in other mining areas, but also because the movement was wholly tensile. For his part he was still very anxious and interested to see exactly what would happen to one of the CLASP structures when it was affected by compression in the ground rather than tension.

119. He would like to stress, as a peculiarity of the mining situation, that the maximum compressive strain which could be developed over mine workings was twice as great as the maximum tensile strain. If the particular structure in question had for instance been situated directly over a more or less horizontal seam and the dimensions of working had been appropriate for the same seam at the same depth, it might have been subjected to a maximum compressive strain in the order of five or six parts per thousand. He wondered what might be the reaction of the structure to a compressive movement of that intensity.

120. If the building had been designed for a unique mining situation and no further mining was to take place at all he would have thought that it was quite unnecessary to have a 2-in. subsidence gap, since the whole of the structure was in tension. The building could presumably accommodate its shape to the changed ground contour along the whole of a subsidence slope, provided that this slope was all convex or all concave. He was rather puzzled about the possible effect where a building was affected by both.

121. He wondered why it was decided to locate the subsidence gap at a point 120 ft from one end and not in the middle. If one were building a more traditional structure and it was necessary to make a division, the logical thing to do would be to make the separation in the middle rather than towards one end. Perhaps there was a structural reason for this.

122. He felt sure that the Author had been able to demonstrate that a CLASP structure behaved quite admirably and exactly as it was intended in tension, and in tension up to quite a severe intensity. Provided that the building would behave just as admirably in compression, he thought that it was a very fine achievement.

Mr K. Severn (Leslie Turner and Partners) said that the amount of damage caused by subsidence in the coalfields of the North Midlands had not readily been appreciated by people living in other parts of the country. As an engineer he had always been intrigued not so much by the damage done and the causes thereof, but by the unpredictable behaviour of old buildings, and the remarkable resilience which many of them showed to movements in the ground.

124. In 1957 the chairman of the subcommittee considering the effects of mining subsidence on behalf of the Institution, Mr Leslie Turner, had visited Nottingham to observe tests on the prototype CLASP structure. The system had appeared to Mr Turner to be evolved from a consideration of why buildings did not crack rather than why they did, and the inherent flexibility of brickwork in lime mortar, of timber joints, and of overlapping slates had been reproduced in the CLASP system with modern materials.

125. In spite of Sir Donald's criticisms, he thought that the rigid foundation was still a reasonable solution for many structures other than buildings, but where it was adopted for buildings there was frequently evidence of a lack of co-operation at an early stage between architects and engineer. In pre-CLASP days his firm had done work for the Derbyshire County Council in which a rigid articulated foundation had been adopted because the superstructure material, either the Derwent timber system or traditional bricks and mortar, had been chosen beforehand. It would be interesting to know whether any survey of the behaviour of structures designed according to these alternative principles had been made or was contemplated.

126. Mr Severn believed the Paper would have a long-term value because of its excellent review of possible methods of measurement. The Author had referred to the recording of the progress of movement on the time basis, and also to the more sudden movements of the smaller stiffer part of the building. It was clear that more

frequent readings during the critical stage of movement would have been desirable. He was particularly interested in the question, as in the design of rigid foundations subject to subsidence he had generally adopted a point or line bearing on the ground in order that the bearing pressure should always be a maximum, thereby inducing sudden rather than prolonged settlement. He would like the Author's views on whether sudden settlements were detrimental to structures.

127. The intention in the design of the structures described in the Paper had been to allow for movement of 2 in. A maximum of $1\frac{1}{4}$ in. had been recorded leading to some slight damage. An examination of the graph from which the figure was taken suggested that it might have been greater, as the peaks of the two graphs showed the roof bending at the subsidence joint had been arbitrarily chosen. He wondered whether Mr Heathcote was satisfied that 2 in. was adequate. Would not the movement have been greater had the mining works passed more directly under the building?

128. The information about the slip of the structure along the ground seemed scanty. The position and direction of the underground working suggested that the whole building might move progressively in a southern direction. He wondered if such a movement was totally resisted by friction on the ground, and if there was any evidence in the bridge, of which they had heard nothing, of relative movement between the three-storey block and the adjacent building.

129. He would be pleased to hear the Author's answer to Mr Creasy on the matter of the subsidence joint. He had been left with a feeling that the behaviour of this particular structure would not have been very different had the subsidence joint been omitted.

Mr H. T. Swain (County Architect, Nottinghamshire County Council) said that he might try to answer one or two of the speakers.

131. Firstly he would deal with the terms of reference for the design. When the project had been started, an average bad case of mining subsidence had been assumed rather than the worst possible case. For the normal shallowest case of mining 250 yards had been taken. In addition a maximum seam thickness of 3 ft 6 in. was also allowed for. The standard system had been designed to withstand without damage mining subsidence caused by extraction of such a seam. In fact, the depth of the seam on the site referred to was 230 yds, so it was shallower, and the thickness of the seam was 4 ft rather than the 3 ft 6 in. which had been assumed. The subsidence therefore was outside the limits set by the standard design and this accounted for the slight damage.

132. He would also like to say something about the method of designing the standard systems. This had some bearing on the 120-ft length. At the back of his mind were some simple rules which had been devised as practical rules to help architects in using a standard system like CLASP. One of these was that a three-storey block should not be longer than 120 ft without a joint. Most of the jobs were designed by young architects in offices without engineering help. It had to be remembered that the system was being used on a national scale with a new CLASP job opening every half week throughout the year. The 120 ft really produced the biggest building unit which would hold together with a tension reinforcement in the slab without getting an uneconomical amount of steel. The copper strip on the roof had caused trouble. The trouble here was that the copper was too strong, and instead of the two halves of the roof operating independently it had operated as a single plane, although it was in fact hinged round one corner. He mentioned this because it raised one of the real problems. There had never been any doubt that the main structure would behave properly but one of the problems was to make sure that everything was weak enough. Most of the trouble at Heanor Gate was due to lack of practical experience. Clearly, the experience showed that copper expansion joints had to be made a lot weaker than had previously been thought.

133. He thought that Mr Wardell had not been quite fair in saying that the building did not prove the compression aspect. Heanor Gate was only one of five buildings which had stood up to severe subsidence. Of these five only two had even superficial damage. Nowadays his department really took no note of whether jobs were being subjected to subsidence or not.

134. Mention had been made of the collaboration between Mr Heathcote and the architects. He would like to say something about this. Why was it possible to build up such good teamwork? He had noted down one or two points which he thought might be of interest. First of all it was because both the engineer and the architect were looking at the problems and trying to identify them, not trying to rush out with the answers. This was very much better than when an architect encountered a problem in his building and then went to the engineer to ask him for a solution in the structure. The second reason lay in Mr Heathcote's own character, which made him extremely easy to work with. He seemed to be able to combine a thoroughly English empirical attitude to engineering with a great knowledge of scientific research. At the same time he could explain quite complicated things extremely simply and at no point were the architects left behind or frightened by mathematical equations which looked like barbed-wire entanglements. A third point that made the collaboration work was really the business of communication. Mr Heathcote used drawings and mathematics extremely well but the really complicated ideas he communicated with three-dimensional models which made moving structures understandable.

135. Perhaps the last point was that the collaboration involved engineering in its widest sense. As could be imagined, devising big structures deliberately designed to move with the ground was sometimes quite worrying. It seemed like a frontier of engineering. What gave one confidence was looking all the time away from traditional structural engineering towards other things. Mr Heathcote's experience had included all kinds of mechanical engineering and they had often found themselves looking at the structures of lorries, ships, grid pylons, and so on. It was encouraging to realize that about the only things that by their inherent rigidity would not stand up to mining subsidence were brick and concrete buildings.

136. To conclude he had to mention that this sort of solution was difficult for a one-off job and was only practical because of the mass production approach of CLASP. He would like to say that this applied to every other problem of building. Everybody who worked on CLASP believed that the future of building anyway was one of prefabrication and no major problem could really be solved today on a one-off basis.

137. This really brought him to his last point which was to refer to Mr Heathcote's knowledge of mass production. Behind everything that had happened at Nottinghamshire in the first place and then in the CLASP development was the concept of mass production technology.

Dr J. D. Geddes (Dept. of Civil Engineering, University of Newcastle upon Tyne) said that several years ago the Department in which he worked had embarked on a programme of research into the performance of structures in areas of mining subsidence. In 1962 as part of that work they had been able to participate with Brockhouse Steel Structures Ltd and the National Coal Board in a study of the behaviour of a CLASP system school. Observations were completed in 1964 and would be presented in detail in a Paper in the near future. The school in question was similar to that described in the Paper. It had two three-storey blocks and a number of smaller buildings of single-storey construction. The seam being worked was 3 ft 6 in. thick at a depth of 1045 ft.

139. In the Paper it had been pointed out that at certain times quite frequent readings were required. This was also apparent from some of the curves illustrated (e.g. Figs 12 and 13). From his experience of observations on several sites he considered that readings should take place at intervals of not more than three weeks and

this period should be reduced to 10 days or so at critical periods. Figs 19–21 showed clearly how the distribution of vertical movements, gradients, and slope directions could change completely over short time intervals. This feature meant a considerable amount of effort, with its attendant cost, but it was only by systematic observation that the design of structures for mining areas could be improved.

140. The school illustrated by him eventually subsided a total amount of 2 ft. The maximum differential on one of the three-storey blocks was 5 in. and the total differential over the whole group of buildings was about 13½ in. The school had also been subjected to tensional and compressive effects. The maximum ground strains were of the order of 0.12% tension and compression.

141. The design was successful in that it withstood these movements which were in excess of those acceptable to a conventional building. Some damage had occurred. It was of a trivial nature except for a severe crack in one of the foundation slabs. This was not dangerous to the structure and was easily repaired but it happened unfortunately on one of the slabs on which no measurements were being taken. A nearby brick-built school constructed in the early 1930's had been subjected to significantly lesser movements and was relatively badly damaged in some areas.

142. He had three other points to raise concerning the Paper. First of all he felt that it would have been improved by the inclusion of further information concerning the mining movements. From the point of view of learning more about the relationship of damage or behaviour to ground movement (horizontal and vertical), as much information as possible about movement patterns as a function of time was needed. He also objected to the way in which the subsidence curve had been obtained in Fig. 10 by plotting the settlements at the corners of buildings as though they were in the same vertical plane. This could lead to confusion and ambiguity since the resultant curve would depend on which of the buildings was being observed.

143. Secondly he wondered whether any measurements had been made to date on the spring bracings in any of the schools. He regarded the spring bracing as the essential feature of the system and it would be interesting to see what amount of movement, if any, had been recorded.

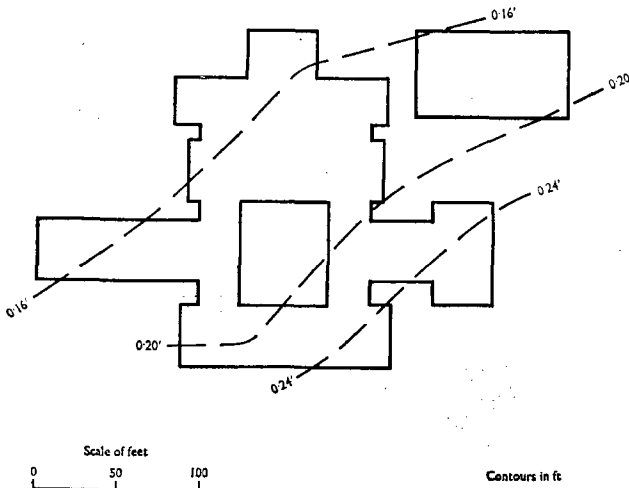


FIG. 19: SUBSIDENCE CONTOURS: 5 May, 1962

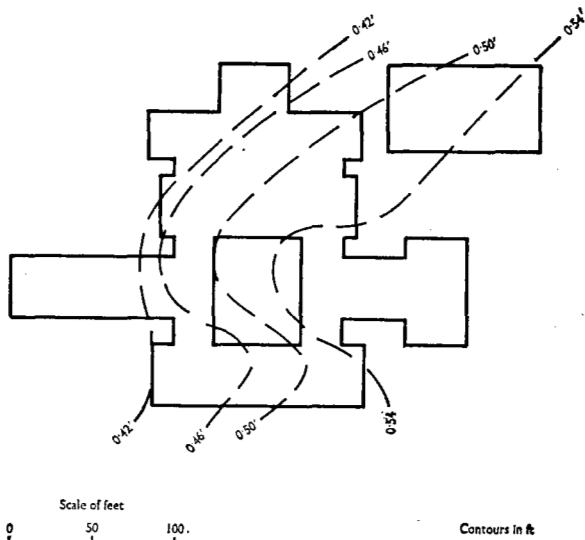


FIG. 20: SUBSIDENCE CONTOURS: 24 July, 1962

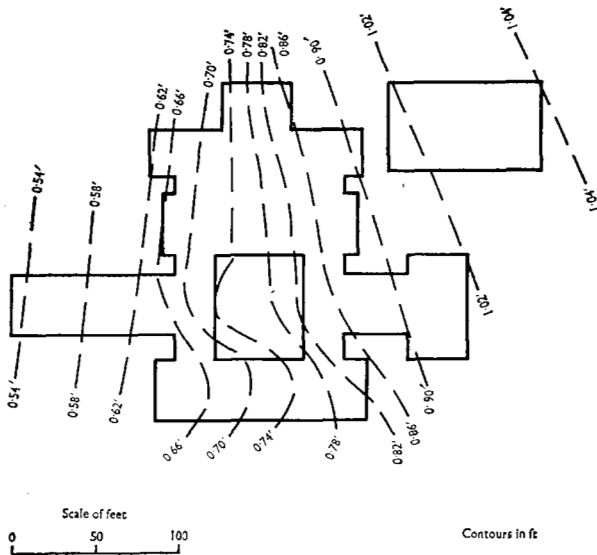


FIG. 21: SUBSIDENCE CONTOURS: 6 December, 1962

144. Thirdly, with regard to § 72 of the Paper, he wished to disagree to some extent with the Author. He felt that the programme of measurements should be as comprehensive as possible even though it involved extra time and labour. It had been suggested that it was desirable to concentrate on particular features with checks on related movements. One could not always be sure in advance which were the related movements and if one merely made checks on those selected some very important features might be missed. Experience in this field had taught him that opportunities lost were gone forever.

Mr Stefan B. Tietz (Consulting Engineer) said that he had always understood that a sand layer was desirable under foundations as the ability to slide was essential, and that flexibility of foundations was important. The early CLASP buildings he had seen achieved these qualities by means of a thin concrete slab with a flat level soffit. Unfortunately, the type of problem which he had to deal with normally required higher, heavier buildings of longer spans. It was however suggested by the Author that CLASP could apply to multi-storey buildings. As this entailed heavy concentrated loads on column foundations, what were the solutions suggested for such foundations to achieve the two desirable properties of sliding and flexibility?

The following contributions were received in writing:

Mr C. J. F. Jones (Assistant Engineer, West Riding County Council) wrote that the Author had restricted his survey to what he termed 'really necessary' measurements on a three-storey block divided into two structural units by a subsidence joint, so that the majority of 'conventional' CLASP structures remained unconsidered. His measurements fell into three main categories: (a) movement of the foundation; (b) movement of the roof; (c) behaviour of the subsidence joint. Perhaps it would be preferable, in view of the large number of these structures, to have a measuring programme giving coverage of all possible subsidence effects.

147. For such a programme it would seem necessary to include the following observations: (1) measurement of the subsidence wave and the ground strains traversing the building; (2) relative movements between the major building units occurring at the construction joints; (3) change in vertical level throughout the buildings; (4) horizontal slip between the foundation slabs and the underlying material; (5) tilt measurements on the superstructure; (6) possible changes in stanchion loads; (7) changes in loading of the spring bracing; and (8) internal strain measurements in the floor slab. A programme of this nature had been undertaken by the University of Newcastle upon Tyne and the following points had arisen with regard to instrumentation and procedure.

148. In order to have the observation lines and triangulations in the correct positions for measuring the subsidence wave, it was advisable to make an estimate of the effects of mining subsidence based on an accurate plan of the proposed workings. Where possible, an allowance for unexpected mine developments would also be desirable. The measuring stations needed to be rugged, especially if the site under investigation was a school.

149. The method suggested by the Author for measuring relative movement between foundation slabs was effective unless the foundation slabs failed. Movement across the expansion gaps in the superstructure could be measured using special gauges. A suitable set, measuring the three components of displacement (two horizontal and one vertical) at any number of positions on an expansion joint, had been designed at the University of Newcastle upon Tyne.

150. A water level suspended from suitable stands could be used to measure the change in vertical level throughout the buildings. The following reasons made it particularly effective for this type of measurement: (a) it was unaffected by temperature; (b) sight lines were not required, so it could be used anywhere in the building; (c) levelling points could be cast into the floor slab in unobtrusive places; (d) the

accuracy was ± 0.01 in. and levels could be reduced to OD by levelling between any loading point and any station on the observation lines (obviously the external and internal levelling should be taken within a short time of each other); and (e) it could be used both inside and outside.

151. Horizontal slip between the foundation slabs and the underlying material could be ascertained by direct measurement between the foundation slab and a fixed ground station using a simple gauge fitted with extension pieces. A system recently introduced at Newcastle University using a short fixed measuring bar on a triangulation of marker points was better, as it had the advantage of giving the direction of strain.

152. Measurements for changes in stanchion loads could be made using a Demec Gauge if the stanchions were uncovered; otherwise strain gauges had to be used. A steel rule or micrometer was effective in measuring changes in the load in the spring bracing, provided access was available.

153. Internal concrete strain gauges would measure internal strain in the floor slab. These gauges could be produced as very rugged devices capable of maintaining stable characteristics over long periods of time and of measuring strain in any direction. The electrical parts were potted, all openings being sealed to prevent ingress of moisture, and the structural materials were such that when the gauge was set in concrete it was matched to the elastic modulus of the slab, and the temperature effects became negligible.

154. Each set of readings should be taken in the shortest possible time, no longer than a few days for the whole programme. In general, it would be found necessary to repeat the readings about every three weeks to record all movements, but during the period of critical movement, more frequent observations should be made. It was important to keep a plan of mining development so that the performance of the structure in relation to the position of the mining could be seen.

Mr G. A. Booker (Senior Engineer, Sheffield Corporation Waterworks) asked if the Author would comment on the following points.

156. Was there any special significance in the slab sections not exceeding 300 sq. ft? He would have thought that the dimensions should depend on the siting of a building relative to expected workings, on the seam, and on extraction characteristics.

157. Did cottering the braced stanchions to the rocker base limit their movement to one plane? It would appear that this would reduce the excellent articulation afforded by the rocker base.

158. Was the building under study oriented in relation to the working panel with a view to limiting the effects of subsidence?

159. Did the theoretical assessments of effects agree with the actual findings?

160. In § 32(c) unpredictable movements were mentioned; what were these? Modern subsidence engineering allowed the calculation of effects to a high degree of accuracy by the use of simple formulae, substituting seam and extraction characteristics.

161. Which slab of those mentioned in § 40 moved relative to the other, to produce the $\frac{1}{4}$ -in. difference?

162. He noted that the Author had excluded slab strain from detailed discussion, but would like to make the following comments on this aspect. The rapid relaxation of strain at the end of June would appear to be caused by the opening of the subsidence gap, and the subsequent increase during July and August to be caused by the subsidence gap remaining constant over this period. An evening-out of strain would occur if frictional resistance between the slabs and the ground in contact was limited to ensure an even movement of all joints.

163. Referring to Mr Heathcote's comment in § 71, measurement of slab strain might be facilitated by the use of photo-elastic stress meters as developed by the Post Graduate School in Mining of Sheffield University.

Mr N. Rayman (Deputy City Engineer and Surveyor, Coventry) wrote that he had followed Mr Heathcote's Paper and the discussion with great interest in the light of his association with the development of the CLASP system. The observations described were perhaps the most important ones that had so far been made on the effects of actual mining subsidence on a substantial building in this system. The fact that the Paper appeared to be an interim report (since it described movements as a result of extraction of one panel of coal by observations extending over a relatively short time scale) did not detract from its value. The basic concept of the system was to provide a building that by articulation and the limitation of imposed disruptive forces 'rode' and survived the subsidence wave whatever its amplitude or direction. Any observations made on the effects of subsidence of this type of building would be valuable in assessing the validity of design criteria and the results of prototype and experimental testing.

165. The measurement programme needed in a complex building which became susceptible to complex movements, in order to derive from these measurements the information necessary to underwrite or modify the processes of design, must necessarily be extensive, and meticulous planning of measuring procedures and the provision of reliable measuring devices were essential. A full scale investigation of the type described was much more onerous and difficult than one of a prototype or in a laboratory, since non-reversible or non-repetitive processes were involved and it was often impossible to observe movement—or lack of movement—as extensively as might be desirable.

166. Some four years ago, in collaborating with the Author in carrying out in situ tests on a full scale four-storey structural frame in the same articulated system, under induced loadings, he had been impressed by the variety of instruments which Mr Heathcote had gathered together to carry out a somewhat similar series of readings to those described in the present report. Some were standard test equipment, others he had devised and made himself. The drill needed to get all the readings done in time even in controlled loading conditions was quite arduous and it must have been even more difficult in the investigation described in the Paper. While the Author and his helpers must be complimented on recording the extensive series of measurements given, he was surprised that automatic recording equipment had not been used to the fullest extent.

167. The Author showed some hesitancy in commenting on the design of the foundation slab for the building and the implications on the design concepts of the observed movement which he described in some detail. It should be explained that the design considerations for the foundation slab were to provide (a) a foundation which, under normal conditions, was adequate for the support of the building, having regard to the allowable ground bearing pressure and the imposed loading from the building; (b) a flexible slab which would take up the contour of the subsidence wave, and sustain the transmitted ground strains without failure or disintegration, and (c) support for the feet of the articulated frame about which the structure could lozenge without instabilities developing. To these ends, the slab was designed as a rectangular-section reinforced concrete slab of uniform thickness, the latter depending on the imposed loading. Reinforcement was placed beneath each column to deal with local loading and disposed generally over the slab to resist the flexural forces of normal conditions and the horizontal tensile forces transmitted through the sub-base as a result of ground strain during subsidence. The presence of the latter reinforcement was the prime factor in providing flexibility to the whole of the foundation slab and it was doubtful whether the bitumen-coated daywork joint had more than a hypothetical value in this respect. Tests had shown that this joint, in fact, did not act as a good hinge and as actually constructed was capable of achieving almost complete continuity.

168. The basis of the design for the subsidence reinforcement assumed that the transmission of forces due to ground strain through the sub-base to the foundation

slab was limited by the forces which the frictional co-efficient between the base and the sub-base could transmit without relative movement of ground and foundation slab. This limiting frictional force was clearly directly proportional to the loading of the building on the ground and since the foundation slab was designed to spread this latter load uniformly, the forces acting on subsidence were a function of the plan area of the slab and varied directly with its dimensions. The magnitude of these forces was dependent on the value chosen for the co-efficient of limiting friction, which, from prototype testing and general experience, some years ago was taken as 0.66. There would be confidence in the validity of this basis of design if uniform loading between the slab and the sub-base was certain, if there were no doubts that the co-efficient of limiting friction itself was a constant value and if there was no mechanical locking between the underside of the slab and the sub-base and within the sub-base material itself to affect this value. In three- and four-storey buildings of this type, the loading of peripheral columns could be so high as to disturb the concept of uniform distribution of normal loading all over the slab and the flexures in the slab under this loading, together with the erratics of construction, inevitably appeared to introduce a lack of uniformity both in contact and in normal loading. Additionally, on a long slab where a variation of ground strain over the length of the slab occurred, irrespectively of the location of the edge of the working panel relative to the slab, such variations would tend to create differential forces giving rise to horizontal couples which could clearly slew the slab in a horizontal plane. The movements of the sub-structure in relation to the subsidence joint, which the Author had observed, seemed to be a tangible expression of this effect. The latter had long been suspected and had been quoted as an argument against the use of buildings with slabs having re-entrant angles and rectilinear polygonal shapes. As the Author had said, these considerations were at the moment under investigation for CLASP by the Cement and Concrete Association at their Wexham Springs Research Laboratories. Included in these investigations were experiments designed to provide data for slabs of erratic shape and to investigate the value of the co-efficient of limiting friction, related to normal loading and to the distributional effect of incident normal point-loading from heavily loaded columns through the slab to the sub-base.

169. The movements displayed in the superstructure were said on the whole to conform to the general tolerances built into it and it was encouraging that no damage rendering the building unfit for occupation had been encountered during subsidence. It would be interesting to know from the Author whether the general tolerance for deformation built into the structure and its cladding was exceeded locally by the lozenging and torsional movements.

170. While the Author's comments on the effect of the subsidence and the desirability of making all elements of the building at the subsidence joint compatible in strength could not be too greatly emphasized, it was clearly much simpler to reduce the strength of the superstructure at this point than, in fact, to increase that of the slab subsidence joint. Considerably more attention should, in fact, be devoted to the question of the location of the subsidence joint within a single building and to whether it was really necessary to provide one. The acceptance of a continuous and more heavily reinforced slab and the avoidance of a subsidence joint would undoubtedly give better subsidence control of the building. The subsidence joint should be a straightforward, clear and simple discontinuity and, although the basis of the design foreshadowed a recuperative effect after passage of the subsidence wave, joints did tend to become mechanically locked within a framework of composite construction. One could never rely on the complete recuperation of horizontal concrete slabs under sub-grade restraints.

171. Finally, one could not avoid a comment on the phenomenon which had given rise to the Paper and he would like to ask the Author how far the observed movements corresponded with predicted movements of ground in the area of influence of the panel of extraction shown in Fig. 10, and, further, what subsequent workings

were expected in adjoining panels and to what programme were they to be carried out? The location of the buildings relative to the direction of the working panels did not appear likely to provide any great probability of inducing compressive stresses within the foundation slab to counteract what must be quite high tensile forces at present locked in the subsidence reinforcement. This might create an important issue in the design of the foundation slab, i.e. the superimposition of horizontal tensile forces due to successive working panels with an interval between panels in which equilibrium between slab and ground was reached. In these circumstances, each successive panel could build up horizontal tensile forces and impose on the slab forces greatly in excess of those allowed for in the design. Similar considerations applied in the building itself and the tolerances allowed might not be adequate to avoid damage where the working face did not embrace the full extent of the building.

172. The Author was to be complimented on an interesting Paper and on the great part he had personally played in the development of a sensible form of building construction on sites susceptible to mining subsidence.

Mr D. S. Miller (Chief Structural Engineer, Derbyshire County Council) wrote that the Author had mentioned that he wished time had been available to cover certain points raised during the discussion. In relation to some of these he provided some notes on the history of the building of the school and also answers to some of the questions.

174. Construction of the school had started in March 1962 and was completed in March 1964. The site, comprising approximately $19\frac{1}{2}$ acres, was formerly an opencast coal site, which was finally restored during 1960.

175. The school, to accommodate 600 pupils initially, was built in the CLASP form of construction and comprised (1) a single-storey block containing assembly hall, gymnasium, kitchen, changing rooms, and art room; (2) a two-storey block containing administration, youth, and further education rooms; (3) a three-storey classroom block; (4) a single-storey practical block; and (5) a detached single-storey boilerhouse.

176. The assembly hall, gymnasium, and ground-floor administration block had the same floor level and were detached from each other by subsidence joints through the building. The second floor of the administration block was connected to the ground floor of the three-storey block by a non-standard bridge link, which was again detached from both buildings by subsidence joints. Both the three-storey block and the practical block had subsidence joints across the width of the building to reduce their overall effective lengths and, it was hoped, to minimize the effects of movement due to mining operations. Provision had been made in the planning of the school for extensions to an ultimate capacity of 900 pupils.

177. Siting of the school buildings was restricted by the recently restored coal mining operations and also by the presence of a geological fault crossing the site in the north-east/south-west direction, its position in the Piper Seam being approximately 150 ft north-west of the north-west corner of the three-storey block and on the surface approximately 350 ft from the same corner of the three-storey block. The buildings were located on the part of land used for storage of overburden during the opencast mining operations and as a result were not subject to settlement due to incompletely compacted ground.

178. When construction of the school started, coal workings in the Piper Seam were advancing towards the site in a south-east direction and scheduled to terminate at the fault in September 1962, but due to difficulties encountered underground the workings were stopped short of the fault and consequently no movements were recorded in the vicinity of the school buildings. The rate of extraction of Panel 3 (Fig. 10) had, however, increased during this time to an extent far in excess of the National Coal Board's projections and it soon became apparent that the face of this panel would pass under the south-west corner of the three-storey block and the practical block some six months before originally intended. This resulted in the

general contractor having to install furniture and fittings in a building which was continually moving in different directions.

179. The position of the subsidence joint across the three-storey block was fixed in the position indicated for two reasons. Firstly, it was agreed that the centre of the length of the block would be the ideal position for the joint, but planning requirements on the location of rooms meant that the joint in this position would cross the centre of the classrooms and library and if differential settlement between the two units took place, this would have led to unsatisfactory floors. Secondly, the necessity for having the joint at all was partly as indicated by Mr Swain and partly for economic considerations. The amount of reinforcement required to accommodate the tensile forces induced in the slab by the subsidence wave was directly proportional to the length of the foundation slab (in the rectangular building) and by introducing the joint into the building the total amount of reinforcement was considerably reduced.

180. Since the Paper had been presented a second panel of coal, also in the Piper Seam and immediately adjacent to the east of Panel 3, had started to affect the buildings. Measurements of the movement would continue to be taken and it was hoped to record the effect on this type of building when subjected to the compression zone of the subsidence wave.

181. In the discussion Mr Severn had queried the use of rigid foundations on sites liable to mining subsidence. He might be interested to know that at a further school in Derbyshire, where the rigid type of foundation had been used, measurements and records of movement due to coal extraction beneath the school had recently been taken.

182. Dr Geddes referred to measurements taken on a similar type of CLASP building at Gateshead, but he thought it should be pointed out that the foundations to that building were not constructed in accordance with standard CLASP conventions and it would not therefore be fair to the system to compare the effects recorded at Gateshead with those experienced at Heanor.

The Author, in reply, wished to thank the speakers for their stimulating comments, and in many cases for making long journeys to attend what had turned out to be a very representative gathering of collaborators. In particular he expressed his appreciation to the leader of the team, Sir Donald Gibson, for opening the discussion.

184. Several of the contributors to the discussion had suggested the publication of other results, including the further effects of subsidence on the buildings at Heanor Gate. Since the publication of the Paper the extraction of the remainder of the Piper Seam affecting this site had been completed and the additional information obtained formed a very useful extension of the Paper. The Author therefore proposed to commence by describing these results in answer to Dr Ward (§ 89), Mr Creasy (§ 100), Mr Wardell (§ 118), Mr Swain (§ 133), Mr Jones (§ 146), Mr Rayman (§ 164), and Mr Miller (§ 160).

185. The first phase of subsidence described in the Paper was completed in 1963 and stable conditions prevailed during 1964. The second phase, due to the extraction of panel 4, took place during the first half of 1965.

186. Another measuring programme was undertaken to continue the records made during the first phase. Also, in order to predict the effect on the three-storey block, levelling was carried out along the approach road parallel to the block. The rate of advance was such that the road was affected about a month before the building, leaving time to take action if the nature of the subsidence warranted it. The roof joint had already been open to its design limit so it was important to know whether further opening was to be expected or whether it would close. Closure was predicted so it was not necessary to re-make the joint in the roof.

187. The effect of the second phase was very different from that of the first, because the direction of the approaching wave was different, and it stopped whilst passing across the site. This was due to the location of the building in relation to

the edge of the workings and the presence of a geological fault lying obliquely in relation to the direction of advance of the workings.

188. The plan in Fig. 22 showed these relationships. It would be seen that the full subsidence due to panel 4 only just reached the buildings. The subsidence contours show that the wave approached the east face of the three-storey block almost at its centre.

189. Details of the three-storey subsidence were shown in Fig. 23, drawn in a similar way to Fig. 11, but with the second phase shaded. The first phase, with maximum subsidence at the corner indicated by the arrow, had left the slab convex, but the second phase, with maximum subsidence at the centre of the other side, had now left it concave. The arrows also showed the positions and directions of the maximum slopes caused by each phase. The mean subsidence in the first phase was 9 in. and in the second 17 in., while the maximum subsidence was 2 ft 9 in., the amount for which the system was designed.

190. Since the maximum subsidence occurred near the centre of the building during the second phase, the effect was to draw the ends of the building together, closing the subsidence gap. This had opened in the first phase, when the maximum subsidence was at the end of the building. The details of the closure at each level

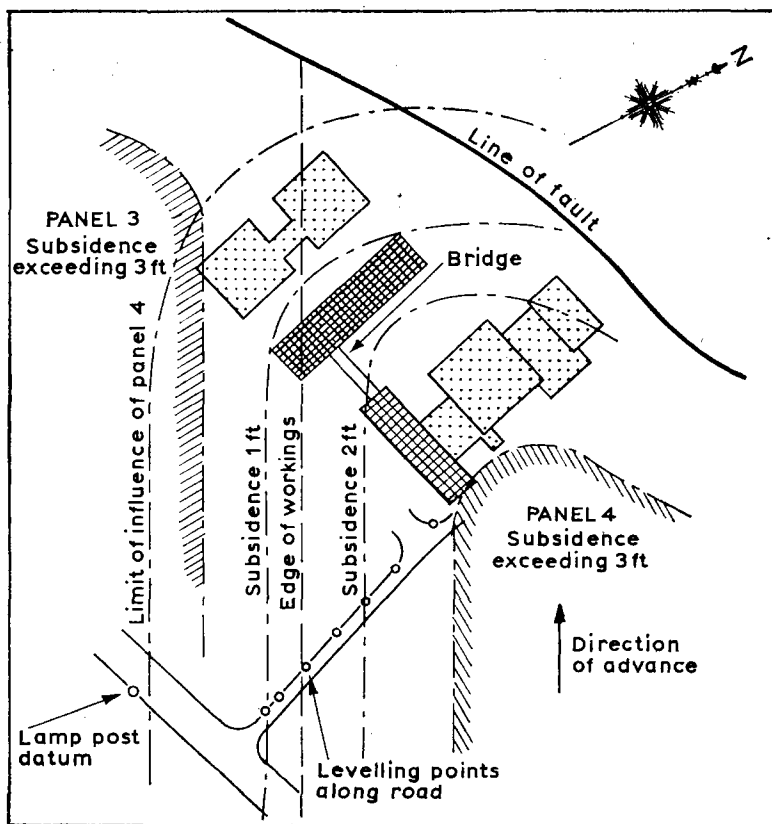


FIG. 22: PHASE 2: APPROXIMATE CONTOURS DUE TO EXTRACTION OF PANEL 4

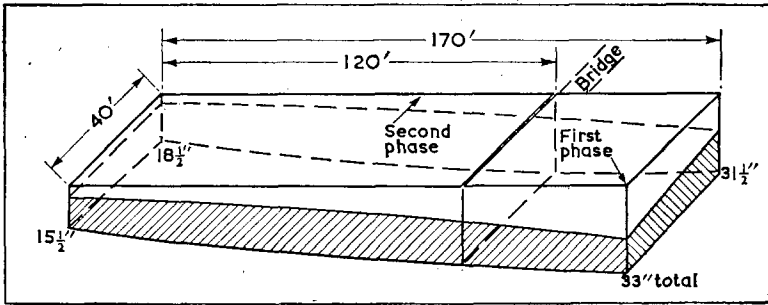


FIG. 23: PHASE 2: DIAGRAM OF VERTICAL SUBSIDENCE

were shown in Fig. 24. The roof has returned to its normal position with very little difference between the two sides; the first floor has closed and twisted slightly, while the foundation gap has closed to half its normal width of 2 in. The openings after the first phase are shown on the left and it will be seen that there has been a closure of the order of $\frac{1}{4}$ in. at each level before the more rapid closure during May 1965.

191. This closure of the subsidence joint took place without causing any distress to either the roof covering or the wall cladding. Minor repairs were carried out to the floor screed and partitions near the subsidence joint, but nothing occurred to stop the continuity of normal activities in the building. Thus the design intention had been fulfilled.

192. The school has been in occupation since September 1964, and was officially opened by Mr George Brown, the Deputy Premier, on 19 June, 1965 when he unveiled a commemorative plaque to mark the occasion.

193. The Author now proposed to deal with other interesting points raised in the discussion, without going much beyond the performance of the particular building which was chosen as a basis for this Paper. Although other buildings had been investigated, some perhaps in greater detail, the results at Heanor in 1963 and 1965 had been sufficient to prove the system for the mining conditions set out in Sir Donald's Paper to the R.I.B.A. in 1957.

194. Dr Ward, who had been an unflinching collaborator throughout the development, mentioned restriction of distortion in the horizontal plane. This had been checked by diagonal measurements on the floors of a three-storey block at Gateshead, during two phases of subsidence, so the measurements were not repeated at Heanor. Regarding the general performance mentioned in § 94, it had been found that the individual structural units and their cladding had accepted the distortion without damage. Repairs were required at subsidence joints, and to certain kinds of partitions, but these did not interrupt the use of the buildings and it was felt that rigorous designs to allow for three-dimensional movement might well be more expensive than a limited amount of repair work. Mr Rayman had given some very wise advice on subsidence joints in § 170.

195. The Author would like to apologise for his loose descriptions, particularly regarding strain, which really were most unworthy of an old student of Professor Lamb. He had merely plotted the difference in gauge readings on the instrument described in § 36 (d). Fig. 12 really showed variations of elongation related to the 5-ft reference bar.

196. Twist in the slab (§§ 38 and 39) meant differences of transverse slope along its length, i.e. 6 in. in 40 ft at the south end minus 1 in. in 40 ft at the north end gave a twist of 5 in. in 40 ft over the total length of 170 ft or 20 minutes per 100 ft about a horizontal axis.

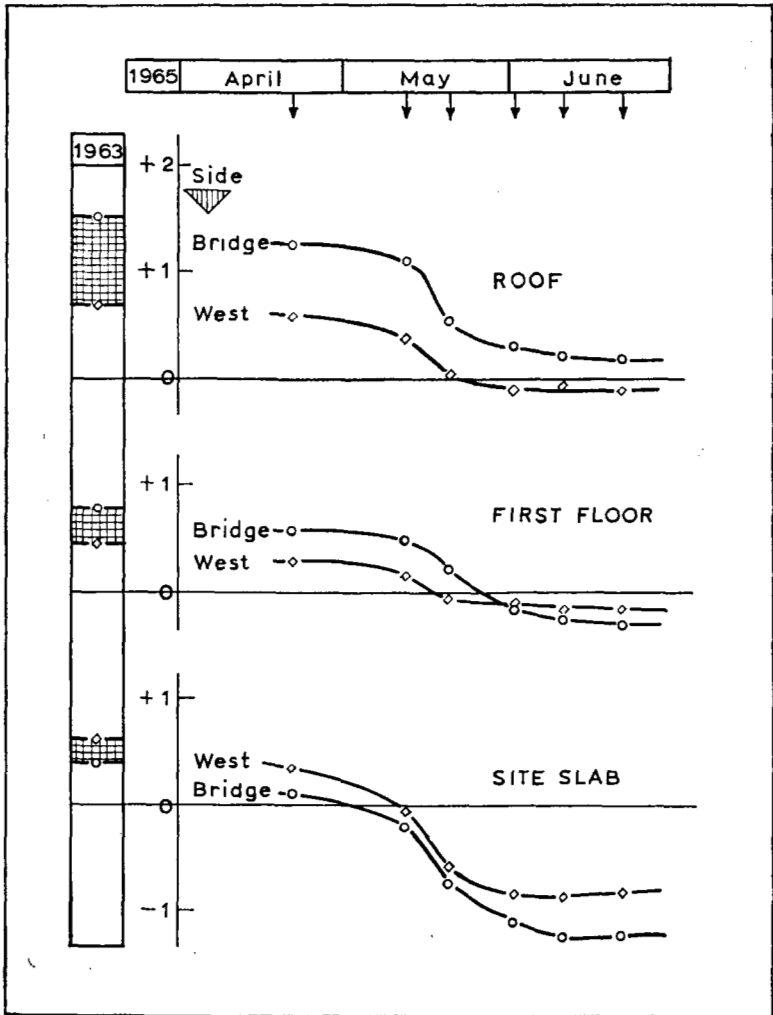


FIG. 24: PHASE 2: CLOSING OF SUBSIDENCE JOINT AT EACH LEVEL

197. Twist in the smaller part of the three-storey block at the south end (§ 52) referred to angular displacements of the diaphragms in relation to the larger part of the block at the north. Thus there was an angular difference between the foundation and the roof of 8 minutes measured about a vertical axis.

198. Regarding § 97 the Author believed that there was an economical compromise between a large complete block and two separate structural units, as suggested in § 68. If a satisfactory connexion could be made between the two foundation slabs to prevent lateral and vertical movement, as by sliding dowels, the subsidence joint could open or close and the two parts of the slab could vary their angular relationship. Additional reinforcing steel would thus be saved and the movements in the superstructure

would be more determinate. In other words it would be useful to have expansion without side-slip in diaphragms at all levels, foundations, floors, and roofs. It was not intended to imply, of course, that dowelling would be a satisfactory basis for design.

199. The Author was grateful to Mr Creasy for acceding to his request for a contribution to the discussion because it was under Mr Creasy's chairmanship that the Addendum to BS449 concerning cold-formed sections had been drafted (BSI Committee B 20/6). The system under discussion did not rely entirely on mechanical joints for its flexibility. Some of this was derived from the flexibility of the components themselves which were fabricated from a mixture of hot-rolled and cold-rolled sections. It was Mr Creasy who had said that 'maximum efficiency in many projects was achieved by a judicious blending of hot-rolled and cold-formed fabrication'.³

200. In general short beams were actually pin jointed, while long beams, requiring less angular movement, relied on elastic deformation in the joints. This problem had been quantitatively examined in tests referred to by Mr Rayman. The results were satisfactory and the sprung bracing operated at the correct loading, but to do justice to the results as a whole would require a paper in itself. It had been suggested to the Author that descriptions of systems were to be avoided in papers to the Institution but it might be mentioned that some details appeared in the Author's Paper for the coming Symposium on Industrialized Building (Institution of Structural Engineers). The articulated cladding was designed to follow movements of the frame and was controlled by a multiplicity of connexions rendered economic by the extensive use of presswork, fixed by hardened hexagon-headed self-tapping screws. These cladding movements were demonstrated at one of the Building Exhibitions at Olympia, on a frame which the Author designed to lozenge continuously, by means of a motorized mechanism concealed between the ceiling and the floor.

201. It was not true that all subsidence buildings needed sprung bracing; nor was it always used. The planning of the building was examined to see to what extent the use of sprung bracing to avoid interference was necessary.

202. The necessity for the subsidence joint in the example in the Paper was admittedly controversial, especially when judged from results while in the tension zone. However, the compression phase caused a closure of about $1\frac{1}{2}$ in. and the Author was inclined to think that this has made it worth while. Another feature which had not been discussed was the change in direction of ground movement during the first phase which would have required considerable perimeter reinforcement to avoid opening of daywork joints. An example of this on another building was shown in Fig. 25.

203. Mr Leggatt's comments on earthquake damage were very interesting to the Author, because some consideration had been given to this matter, but the project did not mature. He had apparently appreciated, from the photograph of the model, that something of this kind had been under investigation. The model was motorized to vary the slope of the building while the various dynamic loads were being applied. The Author had an interesting experience of the effect of shock on a light steel framed prototype building after a V1 bomb exploded in front of it. The cladding fixtures were totally inadequate, but some of the joints in the steelwork showed remarkable ductility, and the general result was very encouraging.

204. Concerning § 106 it seemed very desirable to make a thorough qualitative appreciation when tackling new problems. This was considered an essential prerequisite of quantitative investigations and much of it was done on other buildings.

205. The Heanor site was rather unusual, but in spite of this, characteristic results were obtained on the three-storey block in the first phase and on the two-storey block in the second phase. The questions in § 109 were largely answered by Mr Rayman's written contribution.

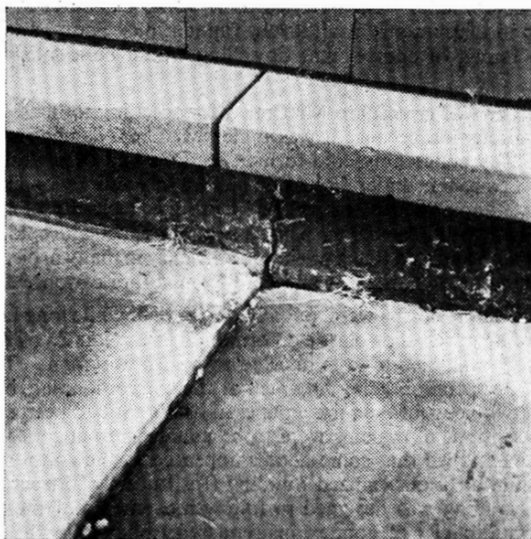


FIG. 25: OPENING OF JOINT IN LONG SLAB DUE TO GROUND STRAIN

206. It was interesting to reflect that the first-off building from which the system was developed was on a non-subsidence sloping site and had to be prevented from slipping. Mr Nachshen was the Ministry's consultant on foundations and the Author well remembered accompanying him to inspect the excavation about fourteen years ago.

207. Mr Orchard raised a very topical problem regarding building on ground during subsidence movements. The Author had recently been requested by architects in Lancashire to examine the plan of a proposed building together with particulars of the extraction programme, and he had agreed that, subject to certain planning limitations, it could be built on a moving site.

208. For relatively small buildings the rigid approach, perhaps with light construction on a steel frame, had much to commend it. However, in order to obtain the requisite density, the Ministry seemed to favour an articulated terrace which appeared to be another viable approach, subject again to suitable planning.

209. The Author was pleased to have Mr Orchard's figure for maximum slope and was interested to find that the two-storey block in phase 2 had a slope of about 85% of this maximum (Fig. 26). In an early CLASP building in Coventry a greater allowance was made at the top of the building to allow for curvature; but this was never taken up and for the sake of economy the standard 2-in. allowance was used at all levels in the Heanor buildings.

210. Mr Wardell's explanation of the greater influence of compression than of tension was most important and he would, no doubt, be very interested in the results during phase 2 when compression predominated (Fig. 24). Lifting of slabs, a characteristic of compression, was shown in Fig. 27. This occurred in the single storey in phase 1 and in the three-storeys in phase 2. His very reasonable comment on the location of the subsidence joint was answered by Mr Miller in § 179.

211. Mr Severn referred to a general lack of appreciation of the subsidence problem in the north, and mentioned unpredictable behaviour. However, the Author had found a reasonably predictable pattern on the sites he had investigated and Mr Orchard confirmed that this could be expected with modern methods of mining.

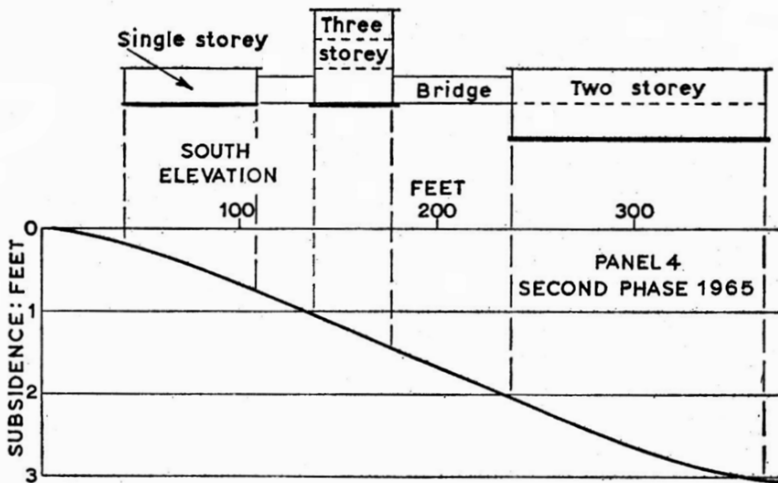


FIG. 26: APPROXIMATE SUBSIDENCE CURVE AT RIGHT ANGLES TO THE THREE-STOREY BLOCK

212. Mr Severn also raised the question of sudden movements, which the Author thought it better to avoid when possible. In dry technique buildings based on an assembly of steel units there were necessarily slight deflexions and clearances in components which gave rise to a progressive take-up as distortion proceeded. If a portion of the building was stiff it was liable to move suddenly causing greater local strains than if the movement had occurred gradually. This appeared important where

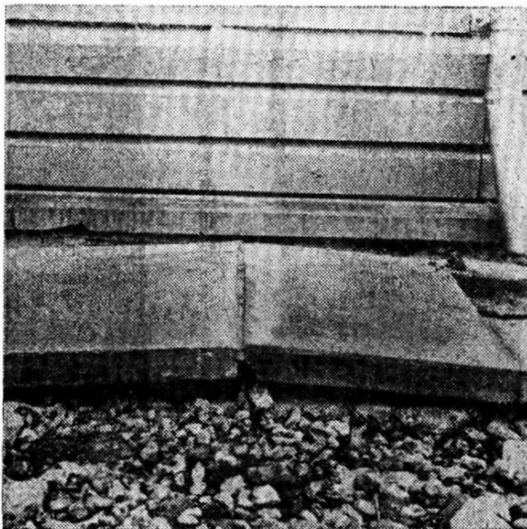


FIG. 27: LIFTING OF SLABS DUE TO COMPRESSIVE GROUND STRAIN

semi-flexible jointing materials were used between dry components. Regarding § 128 the Author agreed that the whole building moved to the south but he had decided to confine his measurements to relative movements of the buildings. If absolute movements were required further analysis could be done using the offsets which had been recorded between the foundations and the Coal Board markers. The Paper dealt with the three-storey block, but as a matter of interest, Fig. 28 was included to show movement between the bridge end and the two-storey block.

213. Mr Swain, who might be described as the founder architect of the system, had stressed the fact that the design was related to a carefully chosen degree of subsidence and this had been a very valuable factor in setting a precise design problem and thus avoiding the extravagancies of over-design. The buildings did not have to be rigid; neither was complete flexibility needed. There was a practicable compromise and time had proved that this had been well chosen.

214. The very fact of a clear understanding between architect and engineer, on the basic terms of reference, was the surest way of beginning a collaboration likely to bear fruit. Under the guidance of Sir Donald this essential preliminary was firmly established.

215. The Author appreciated Mr Swain's remarks on the details of personal collaboration in § 134. When members of different professions were involved in a complex project it was often difficult to ensure mutual understanding when using technical methods peculiar to each profession. This raised the need for finding common ground by using non-technical language and demonstrating one's ideas by sketching and making models, before making decisions. This was something beyond the normal practices of the individuals concerned and might be called supraprofessional collaboration. Educational building was so important and required such a big team that any difficulties in communication between the professions had to be overcome in the national interest.

216. Dr Geddes with whom the Author had collaborated in Durham, raised the question of frequency of measurements and the Author felt that still more frequent

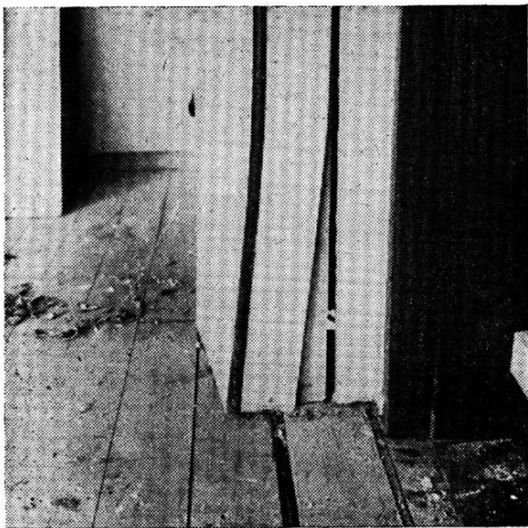


FIG. 28: OPENING OF JOINT AT EAST END OF BRIDGE

readings, even at two-day intervals, were required at critical periods. Automatic recording to detect sudden movements at these times would be very useful and possibly practicable if the school were on holiday. The arrows under the time scales on the graphs showed when measuring took place and it would be seen by their spacing that short-term decisions had to be made as to when measurements would be most useful.

217. The suggestion about greater detail on mining movements was very true, but space had not permitted the inclusion of much additional data which had been recorded. This explained to some extent the treatment of Fig. 10 where the shape and continuity of the ground profile over the edge of the workings depended on other data. The sprung bracing had not been checked at Heanor but this was done at a test in Coventry referred to by Mr Rayman in § 166. The Author's remarks about concentration on particular features referred to industrial development, without a research programme, which could lose force by attempting too much and failing to produce any conclusive results.

218. An explanation of the meaning of 'checks' was evidently required. In this context it meant additional investigation to prove the validity of readings in a pre-determined series which were not following the anticipated pattern. In other words, the selected basic work must be beyond reproach and where anything unexpected happened it must be checked by examining other features which would be consequential to such unexpected movements, or lack of movement. For example, if movement stopped at one point, it might be taking place at another, and this other point must be found, otherwise the results became suspect.

219. The Author agreed wholeheartedly with Dr Geddes that in this field 'opportunities lost were gone forever'.

220. In reply to Mr Tietz, the Author explained that the use of the system was limited to four storeys and that planning information had been issued so that stanchion loading could normally be restricted to come within the scope of the standard foundation tables prepared by Mr Rayman.

221. When using industrialized methods of building it was highly desirable to select a system and study its scope to determine its suitability for the proposed building before embarking on detailed planning and design.

222. With regard to the written contributions the Author wished to make the following points.

223. Mr Jones, who had collaborated in the work at Durham, made a plea for more extensive investigations, but desirable as these were, the Author felt that time must be conserved in industry and opportunities taken as they arose. Ten years' work in this field had convinced the Author that opportunism was more fruitful than planning. Proving the system by preplanning started in 1956, by choosing a suitable site for the first school. An extensive measuring programme was started but the workings were discontinued. As Mr Jones knew, a programme on the lines of his § 147 was carried out in Durham but the amount of subsidence was inadequate for the evidence required. The opportunity to prove the system to the limit of its design came suddenly, following the extraction of the Piper seam at Heanor. Hence a quick decision had to be taken to prepare the equipment and obtain the essential readings in the time available.

224. There was little opportunity for collaboration and the whole of the readings on which the Paper was based were taken by the Author and one assistant.

225. Mr Booker asked a number of specific questions to which the Author would reply as follows

(§ 156) The 300-sq. ft limit to slab sections was arbitrary but it had been found convenient in use and not too large for articulation. The system did not vary for individual buildings and under one of them there were seven seams.

(§ 157) The method of cottering did not restrict the movement to one plane. A stanchion could be dropped on its dowel and cotted, then swung round to generate a cone.

- (§ 158) The building was not oriented to minimize the effects of subsidence and as could be seen from Fig. 23 the direction of maximum slope in the three-storey block moved round by about 135°. The building was liable to influence from four workings.
- (§ 159) The theoretical expectations were in general agreement with actual findings; except perhaps that the tunnel between Panels 3 and 4 did not have as much effect as might have been expected.
- (§ 160) Examples of unpredictable movement were:
- (a) side slip at subsidence joints, particularly at changes of level;
 - (b) local irregularities in change of slope;
 - (c) building movement due to differences in stiffness between various components.
- (§ 161) Both slabs were moving but the smaller portion tilted slightly (about 2 minutes of angle) whilst settling down on the wave, presumably because it had greater stiffness than the larger portion.
- (§ 162) The Author still felt that the major factor contributing to increase of strain at the centre of the larger slab was horizontal ground strain acting differently on opposite sides of the slab causing horizontal movement: tension on the bridge side and compression on the west side.
- (§ 163) Probably stress meters would be useful if they could be installed when required (see § 74 which referred to Durham and led to the use of simpler equipment at Selston and Heanor).

226. Mr Rayman's contribution to the discussion was much appreciated by the Author, especially for its philosophical additions to the technical data presented in the Paper. It was a pity that time did not permit him to deliver it at the meeting.

227. Automatic recording equipment as suggested in § 73 would have been very useful, but there was little time to prepare it in view of the circumstances explained by Mr Miller in § 178 and, as the building was under construction, conditions of access were continually varying.

228. Regarding the daywork joint referred to at the end of § 167 the Author felt that the bitumen should be thick enough to make it work. In a recent test to destruction of a small experimental slab the bitumen had been omitted and a tensile failure occurred in the concrete instead of in the steel. The crack referred to by Dr Geddes in § 141 did follow the daywork joint and fracture the steel, but as pointed out by Mr Miller in § 182, this was non-standard, having been designed at an early stage. In § 168 Mr Rayman referred to horizontal couples slewing the slab, and in the Author's experience this had always been a contributory factor in any high slab stressing. This emphasized the need for additional perimeter reinforcement, especially at, and opposite to, re-entrant corners (see § 44 to 46 and Fig. 25).

229. The tolerances for lozenging did not appear to have been exceeded in practice because windows were not usually out of square by more than $\frac{1}{4}$ in. or not more than 1 in. in 10 ft, whereas the original window tests were taken to 3 in. in 10 ft, and other types of cladding were tested to 2 in. in 10 ft. The worst lozenging was probably to be found in single-storey blocks at Heanor and Selston. The torsional movements had been of a very low order, compared with anything likely to cause trouble, in spite of the great changes in direction of maximum slope, both in Derbyshire and Durham.

230. Mr Miller had amplified the Paper by further useful details of the buildings, and of the extraction programme, together with an explanation of the location of the subsidence joint. It was fortunate that the adjacent panel of coal referred to in § 180 had been extracted in time for the results to be included in the written discussion. In addition to the compression effects on the three-storey block, the two-storey block had also put up a very interesting and satisfactory performance in reaching the position shown in Fig. 26.

231. In conclusion the Author wished to thank all those who had written contri-

butions to the discussion. These, together with detailed observations made by speakers at the meeting, indicated a deep interest in the subject and justified the Institution's announcement that papers on mining subsidence would be welcome.

REFERENCES

1. NATIONAL BUILDING STUDIES, Special Report No. 12. *Mining subsidence: effects on small houses*. London, H.M.S.O., 1951.
2. INSTITUTION OF CIVIL ENGINEERS. *Report on mining subsidence*. London. Institution of Civil Engineers 1959.
3. CREASY L. R. In discussion on CHILVER A. H. Structural problems in the use of cold-formed steel sections. *Proc. Instn civ. Engrs*, 1962, 23 (Oct.), 271.