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FULL SCALE TESTS ON A MINE SUBSIDENCE RESISTANT MASONRY HOUSE

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ABSTRACT

Longwall mining is a common form of coal extraction in modern underground collieries. With this process the complete coal seam is progressively removed with the consequent subsidence of the ground surface. This paper describes the development and testing of a full masonry housing system capable of withstanding the surface effects of longwall mining. The system consists of a stiffened prestressed concrete raft slab combined with a light steel framing system and articulated masonry external and internal walls. The effectiveness of the system was demonstrated by tests on a full scale prototype house which was subjected to doming and dishing curvatures and tilt effects similar to those which would be induced by a longwall mining event using a jacking system located beneath the slab. These tests are described in this paper.

1. INTRODUCTION

Underground mining is extensively carried out in many areas of the world. In the Hunter Valley of New South Wales, Australia, underground coal mining is a major economic activity. Differential ground movements produced at the ground surface by this mining can cause damage to structures located within the affected area. Newcastle has a long history of mine subsidence problems, as it is substantially undermined by early coal workings. In more recent times, the conventional bord and pillar methods have given way to longwall mining in which all the coal in a seam is extracted, causing immediate surface subsidence. There is therefore a need to develop masonry housing systems which are capable of absorbing the effects of random "pot hole" subsidence from existing workings; or ground strains, tilts, and curvatures induced by new longwall mining. If designed and detailed correctly, the same system should also be capable of withstanding the effects of the shrinkage or swelling of reactive clays (which produce similar ground curvatures), as well as the forces induced by extreme loadings from wind or earthquake.

The aim of the project was therefore to develop a residential building system of masonry construction which could withstand the effects of longwall mining, highly reactive clays, earthquakes, and extreme winds. In technical terms the system needed to be capable of withstanding the effects of severe ground curvatures, ground strains, and lateral forces, and of being lifted from the outside only after a mine subsidence event (for re–levelling), without there being significant resultant damage to either structural or architectural elements. It was also important that the system did not restrict the architectural freedom for the design.

Much of the research on masonry structures subjected to ground movement has been directed at element behaviour, e.g., footings, footing/soil interaction, or walls. This project considered the performance of the complete house as a structural system. That is, the overall performance of the structure combined with that of its components. A complete house was constructed using the system which was developed, and this house was subjected to a series of simulated mine subsidence events to verify its satisfactory performance. A more detailed background to the study has been previously reported (White and Page, 1997). This paper briefly outlines the project and describes the tests themselves in more depth.

2. EXPECTED SURFACE MOVEMENTS

The housing system was designed to withstand the effects of surface movements caused by longwall mining or reactive soil movement.

2.1 Longwall Subsidence

In a typical longwall mining situation, the ground surface, while subsiding, also undergoes a wave motion as the mine passes beneath (see Figure 1). The ground surface firstly curves downwards, in a half–crest like curve, placing the ground surface in tension. Then it curves back the other way, in a half–trough like curve, placing the ground surface in compression until it levels out. The final ground levels will be much lower than the original, with the drop in level being a function of the thickness of the seam which has been removed. The house will also often finish out of level with a residual tilt if it is located on the edges of the subsidence area. It is ground curvature that causes most of the damage to masonry walls, which are brittle. The total amount of subsidence (i.e., rigid body movement) is of little significance in this respect.

2.2 Reactive Soil Movement

Reactive soil movement is due to shrinkage and swelling of clays with increases and decreases in moisture content. The point to note is that this movement creates curvature of the ground surface due to variations in moisture content between the underside of the outside of the house, which is affected by soil moisture changes, and the underside of the middle of the house, which is relatively stable. The effects of these movements on the residence are the same as for curvatures due to mine subsidence (see Figure 2).

3. HOUSING SYSTEM

3.1 Design Parameters

The philosophy adopted in designing the system was to use a stiffened concrete raft slab-on-ground of the appropriate stiffness, combined with a steel frame and a masonry superstructure designed to accommodate prescribed degrees of ground (and slab) curvature.

The ability of the system to withstand lateral loads from earthquake or high winds can be justified by routine calculation, so that no testing was considered necessary for these situations.

The following subsidence parameters were used in the design and simulated in the tests:

- ground curvature of 900 m radius
- residual tilt of 10 mm/m
- horizontal strains were assumed to be eliminated by suitable detailing (for example, the footings can be isolated from the surrounding soil by sand layers and flexible packing at the points of footing–soil contact).

The degree of articulation used in the design of the masonry walls was consistent with current Australian practice for the design of masonry subjected to the effects of highly reactive soils. Joints were therefore designed to accommodate an induced curvature of 900 m with maximum articulation joint spacings of 5500 mm.

3.2. Structural System

A full scale prototype house was constructed on the University campus (to be later used as the Warden's cottage for a residential college). The house was a single storey three bedroom dwelling constructed in full masonry with a metal roof. It was L shaped in plan (16 m x 12 m), with a prestressed concrete stiffened raft slab, a light steel frame consisting of rectangular hollow section (RHS) columns and roof ring beam, steel trussed roof, and masonry external and internal walls. The external walls were non–loadbearing cavity brickwork walls and single skinned autoclaved aerated concrete (AAC), with the different systems being used in different locations to check their effectiveness. All walls were articulated at 5500 mm maximum centres with appropriate control joints, supported by the RHS columns with specially developed flexible ties capable of accommodating the appropriate movements. One masonry panel in each external wall was designed to act as a shear wall, and was attached to the columns with rigid ties. All external walls were rendered externally and covered with plaster board internally. Internal walls were both brickwork and AAC, covered on both sides with plaster board. Since the internal walls were also non–loadbearing, suitable wall–to–wall and wall–to–ceiling movement joints were detailed to accommodate movements.

A series of pads and pockets were built beneath the concrete slab to allow jacking of the structure once it was completed. There were seventeen jacking positions in all, thirteen around the perimeter, and four located internally. The floor plan of the test house and the jacking locations are shown in Figure 3.

Lateral stability for the structure is provided by the shear wall panel in each external wall, combined with a rigid masonry core formed by the bathroom walls, with the two systems being inter–connected by a ceiling diaphragm. Earthquake or wind forces are transferred by all external walls in out-of-plane bending to the structural frame. The frame transfers the loads to the grounds via the ceiling plane bracing. Uplift is resisted by the frame being tied down with masonry anchors through the column base plates to the slab.

Because the structure was to be subjected to both ground curvatures and tilts, additional features were incorporated to accommodate movement and minimise damage. These included provisions for rotation between the various elements of the structural frame and roof, a ceiling system which was independent and separated from the walls, flexible joints in the plaster board lining at the wall corners, flexible adhesive between wall linings and the masonry, compressible non–masonry panels above doors, location of electrical and plumbing services in the ceiling and walls rather than in the slab, and flexible external connections of sewerage and water lines to allow for vertical movements between the slab and the ground. The house was tiled and partially rendered prior to testing so that all the brittle elements were included in the test. During a mine subsidence event the structure is designed to be flexible and follow the maximum predicted ground curvature. Sufficient gaps were left between the frame columns and the masonry infill walls as well as in the articulation joints to accommodate the relative movements induced by the slab curvature. The slab was inherently strong enough to resist ground strains. During re-leveling of a residual tilt, the slab was capable of being jacked from the outside only without inducing damage in the masonry.

3.3 Preliminary Testing

A series of laboratory tests were carried out prior to the house construction, to gain information on the performance of various components and confirm the performance of various connection details. These involved a number of racking tests on AAC and brick shear panels, tests on the flexible brick ties, and plaster board fixing. This was particularly important for the confirmation of the performance and practicality of details.

4. TEST ON THE FULL SCALE HOUSE

The task of simulating the ground curvatures on the slab of a full scale house is a difficult one, as prescribed displacements must be applied to the slab in a number of locations in a controlled manner.

After considering several options including a fully integrated hydraulic system, it was decided to use seventeen independently operated hydraulic jacks and pumps, each controlled by a separate operator. The main disadvantage of this approach was communicating effectively between operators and the need for seventeen separate people to operate the jacks. Communication problems were solved by having four supervisors on the four sides of the house in constant radio contact with the test coordinator. Operators were obtained by mobilising the help of members of staff and postgraduate students from the Department of Civil, Surveying and Environmental Engineering.

By using seventeen jacks as shown in Figure 3, a series of waves were simulated to pass under the house. All jacks were lifted simultaneously, but by different amounts in each row to achieve the required curvature. A number of separate stages was needed, tightening the radius of curvature at each stage, until the final radius of 900 m was achieved. A typical jacking operation is shown in Figure 4.

The sequence was the same as the house would experience during a longwall mining event (see Figure 1). Firstly the tension ("doming") curve was simulated by lifting the slab higher in the centre rows. The slab was then levelled out. A compression ("dishing") curve was then achieved by lifting the outside edges higher than the centre, and then the house was again lowered to level. This process was repeated three times – passing a wave in the north/south direction, then the east/west direction and finally across the diagonal at 45 degrees.

The final test was to show that the house could be re–levelled by jacking from the outside only. The jack spacing was increased to 6 m centres. The house was then lifted to a tilt of 10 mm per metre and then lowered. There was no damage during this process with the slab curvature being minimal. Since the slab was pivoting about one edge at this stage with the remainder being off the ground, it would not have mattered to what degree of the tilt had been imposed.

Each of these tests took several hours, so that the entire testing period extended over a 7 day period, with considerable variation in weather conditions over that time. A total of 6 major tests was performed, 5 for the wave simulation and one residual tilt test.

5. INSTRUMENTATION

As the cottage was subjected to the various wave simulations, the vertical slab movements, the roof movements and the opening and closing of various control joints were monitored. This monitoring was critical to the success of the experiment, and a range of techniques were used. This part of the project was under the control of the Surveying group of the department and formed part of a final year project for a surveying student (Boslem, 1996).

5.1. Monitoring The Floor Slab

The Water Level System

The slab movements were monitored by the use of a water level system and also by taking precise levels. A water level system was installed around the cottage to provide each jack operator with a means of measuring the lift at their jack (see Figure 4). This technique was adopted in lieu of measuring the extension of the jack which can be an unreliable method of determining movements. The water levels were backed up by a precise levels taken at critical stages throughout the testing procedure. The water level system consisted of 13 mm diameter irrigation hose, run around the outside of the cottage, with 12 mm diameter clear plastic risers located at every jacking point. A measuring scale, graduated at 2 mm intervals, was placed alongside the clear risers. The scale was attached only to the slab of the building in case the wall and the slab moved independently of each other. A large drum was used as the reservoir for the water levels, and this also had a riser and scale attached to it. A reservoir of this size was needed so that the movement of water through the system whilst testing took place would be insignificant compared to the size of the reservoir. Initial calculations indicated that if the entire building was to be raised 100 mm, then the height of water in the reservoir would rise by only 1 mm. Water levels are a traditional method of measurement going back many centuries, but despite the lack of sophistication, the method was very effective in providing a first approximation of vertical movement for the jack operators as they worked in relative isolation from each other.

Precise Levels

Precise levels were taken throughout the project to monitor the vertical slab movements. The precise levels provided a check on the water levels and also gave an accurate account of slab deformations at the crucial stage of each test. Levels were taken at each of the seventeen jacking points around the outside of the cottage, as well as the four jacking points inside. For the outside points, holes 100 mm long were drilled in the concrete slab, and steel pins fixed to the slab as benchmarks. Inside the cottage, nylon nails were placed above the four jacking points.

The levelling was carried out using a Wild NA3000 electronic level, which displayed levels to the nearest one hundredth of a millimetre. From considering the miscloses of the precise levels throughout the testing, the accuracy of the NA3000 was estimated to be ±0.1 of a millimetre.

It was important to be able to provide a high order of accuracy and precision, for some slab movements were only a few millimeters. The building did tend to move up and down slightly in-between different wave simulations. These movements were only in the order of a millimeter or tenths of a millimeter and were probably due to the building continuing to settle after each test and the expansion and contraction of the soil beneath the footings. There was a lot of rain during the testing period, which may have caused some soil movements. These residual movements were calculated by comparing the levels taken at the end of a days testing to those taken on the morning of the next day.

An automatic level was set up inside the building independent of the floor slab, in the hole in the slab providing access to the internal jacks, to monitor the movement of the four inside jacking points. This was necessary as it was impossible to site to all four inside jacking points from any one point outside the cottage. Hence, when levels were being taken, a level was transferred to one of the points inside the building by the outside instrument, and then the other three points were levelled from the inside.

To monitor possible movements of the jacking pad on which the inside level was located a tripod with a small scale, graduated to one millimeter, was set up outside the building. Levels were continually read to this tripod throughout testing to check for any subsidence. The maximum observed movement of the footing was one millimetre.

Precise levels were taken before inducing a wave, at the peak deformation of the slab, and after the building had been lowered. From these levels, movements were able to be calculated for each jacking point. Graphs were then produced showing the slab deflection.

5.2. Monitoring The Roof Structure

The roof structure was monitored by the use of short range electronic distance measuring devices (EDM) to thirteen targets located around the outside of the building. Two Leica TC1100 total stations were used to monitor movements of the roof structure. These were positioned at opposite diagonals of the building so all thirteen targets could be monitored simultaneously. Single bearing and distance measurements were recorded to each of the targets, thus allowing the movements of the target in the three dimensional space to be determined.

The targets were mounted on steel brackets which were bolted to the top of the columns around the outside wall of the building. Six targets were used to pick up the corners of the building, with seven other targets being used to pick up the movements of the external shear walls.

The horizontal control consisted of four stations, and comprised three loops. Stations two and four were placed so that the thirteen targets could be radiated from these two points, with station one and three being used to tie all the measurements together. Stations one and three were placed outside the area of construction to ensure they would not be disturbed. Observations from each station consisted of three rounds of readings, in both face left and face right. The distances were measured from both ends of the line with the averaging option selected on the instrument. The averaging option allows the distance to be repeatedly measured, with the instrument displaying the number of readings taken, the average distance, and the standard deviation of the distances. The standard deviation was normally around 0.2 to 0.4 of a millimetre. From stations two and four, observations were also taken to two distant reference objects to check for any movement of the stations in between tests.

5.3. Monitoring of The Opening and Closing of The Control Joints

A separate monitoring system was developed to electronically monitor the opening and closing of the control joints and the movement between different elements in the structure. This system consisted of 29 potentiometric displacement transducers connected to a data logger which was connected to the computer. Of the 29 displacement transducers, 14 monitored displacements during the north-south wave, 15 monitored displacement during the east-west wave, and 16 monitored displacements when the diagonal wave was simulated. All transducer movements were reproduced on the computer screen in bar graph form during the test, so that any unusual behaviour could be noticed and that location immediately inspected.

5.4. Recording The Test Observations

As mentioned earlier, 'real time' results were required throughout the testing. These results were displayed in a table as ΔX, ΔY and ΔZ movements at each point during testing. This was achieved by interfacing the total stations with a computer which continually supplied the results for each monitoring position.

There were four pieces of information needed in this string: point number, bearing, vertical angle and slope distance. From this information, coordinates can be calculated for each observed point radiated. Before a lift was commenced an initial round of readings were taken, then further readings at the required stages throughout the lift. From these readings ΔX, ΔY and ΔZ movements were calculated and displayed in a table enabling the results to be assessed before the testing proceeded further.

In all, the monitoring systems which were installed worked well and gave an excellent picture, in real time, of the deflection of the slab, and the movement of the various components of the structure.

6. RESULTS AND DISCUSSION

Despite the difficulties associated with testing a full scale structure, the tests worked well, with no major problems being encountered. The most difficult task was the coordination of the large number of people involved in carrying out each of the tests. The jacking system was able to reproduce the required slab curvature well, as can be seen from some typical comparisons of induced versus required curvatures for both the dishing and doming cases at various stages of the jacking process shown in Figure 5. It is significant to note from the "doming" case that the slab lifted off the outer rows of jacks and cantilevered from the three central rows, indicating that the slab stiffness was actually greater than that required.

No significant damage was observed in any of the tests described above, indicating that the masonry housing system was capable of withstanding a subsidence event. Some minor cracks in the masonry occurred in a couple of isolated locations, but these closed up once the imposed curvatures were released. There was some minor damage to the internal plaster board (as expected), and no damage to tiles or render. For the system to have performed successfully it was necessary that the only residual damage be cracking of the plaster board joints. This would mean that, after a subsidence event, the only repairs required by the Mine Subsidence Board would be re-setting these joints and painting. The testing was therefore 100% successful.

There was damage to the plaster board above the lounge room openings but this was as expected. Joints were designed for these areas, but it was decided to omit them to see if the flexibility of the plaster board adhesive was enough to avoid having joints. It is of interest to note that there was no damage to plaster board at all until half way through the compression wave.

All the articulation joints performed satisfactorily with the observed movements being as predicted. A longitudinal crack was observed in the prestressed floor slab in the "doming" configuration, but this crack closed once the slab curvature was removed.

7. CONCLUSION

This paper has described tests on a masonry housing system which is capable of withstanding the effects of a longwall mining event ("doming" and "dishing" curvatures as well as residual tilt). The curvatures induced were of the same order as those produced by the differential drying effects of reactive soils, indicating that the system would also be suitable for reactive soil areas.

The housing system consists of a prestressed concrete raft slab, and a light steel framing system, combined with masonry external and internal walls. The system is detailed so that the movements between the articulated masonry elements are accommodated by the flexible attachments to the supporting frame. Lateral stability is provided by masonry shear walls in conjunction with a ceiling diaphragm system.

The series of tests simulated a range of surface curvatures and tilts with a range of techniques being used to create slab curvature, movement of the frame and movement of control joints. No tests produced any significant distress in the masonry or other walling components. The system therefore has the potential to provide a full masonry housing system for use in subsidence areas in which only flexible, lightweight construction would normally be allowed.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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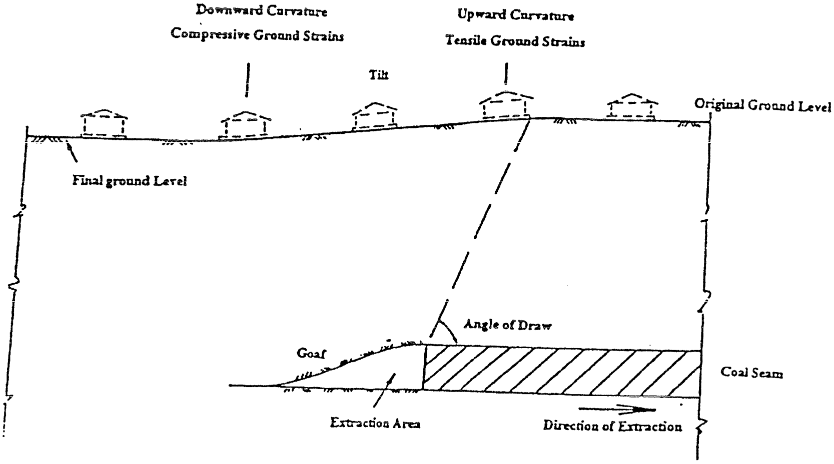
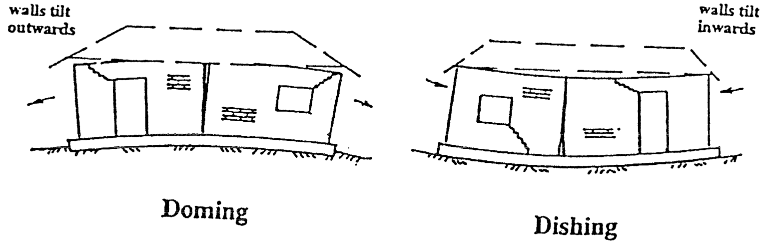


Figure 1. Surface Effects of Longwall Mining



Doming

Dishing

Figure 2. Effect of Reactive Soil Movement on Masonry Structures

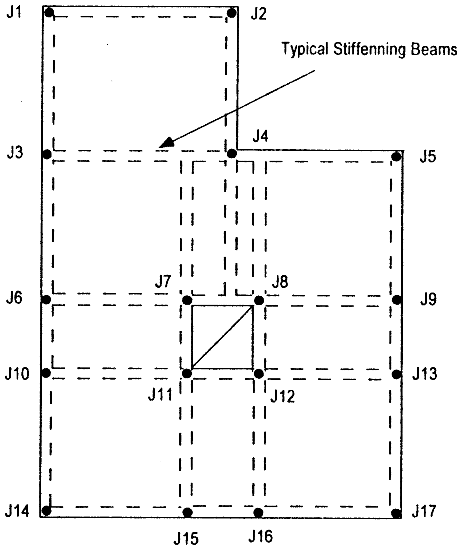


Figure 3. Slab Plan and Jacking Points

Figure 4. Typical Jacking Location

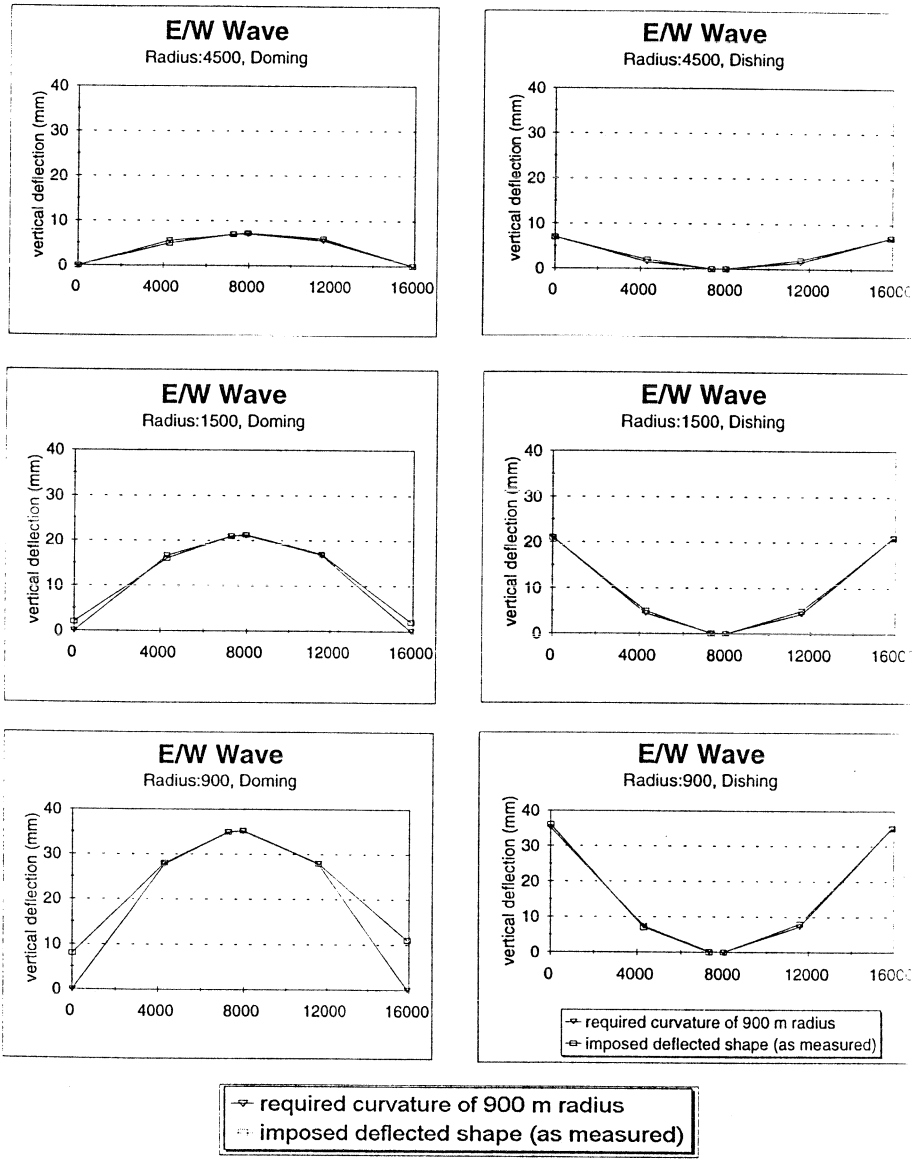


Figure 5. Typical Comparisons of Induced Versus Design Curvatures (E-W Wave)