Modelling Surface and Subsurface Subsidence over Coal Mines

K.J.L. STONE and R.J. JEWELL
University of Western Australia
I. MISICH
Western Collieries Ltd, Collie

SUMMARY A series of geotechnical centrifuge model tests are presented in which coal extraction at depth has been simulated and surface and subsurface movements of the overlying strata recorded. The centrifuge modelling technique and its applicability to mining problems is discussed.

1. INTRODUCTION

Historically, deep coal mining techniques had the basic philosophy of maintaining a good roof and mining conditions. Under such circumstances, subsidence effects were not significant unless collapse of the roof supports occurred. However, more modern extraction techniques - total extraction methods - rely on allowing the mine roof to collapse behind the advancing mine face. The most efficient of these techniques is longwall mining where no roof support is left behind the mined face. A slight variation of this technique is Wongawilli extraction, where pillars of coal or stooks are often left to partially support the mine roof in the vicinity of the worked face, but where the roof collapses as the face advances. The use of these modern extraction methods makes sub-surface and surface subsidence unavoidable. Such mining induced subsidence can lead to the damage of surface and sub-surface structures and services. Consequently, the prediction and minimisation of subsidence is extremely important when assessing potential and existing mineral resources.

To date, the prediction of mining induced subsidence has relied on the use of empirical models and little or no attempt has been made to formulate predictive models based on the physical response of geomechanical materials - soil and rock.

In this paper, a set of centrifuge model tests are described in which a method to simulate coal extraction at depth has been devised and surface and sub-surface movements of the overlying strata have been recorded. The method incorporates a trap-door system which replicates the total extraction of panels of coal by either Wongawilli or Longwall extraction. The centrifuge model tests have been performed on the Acutronic 661 centrifuge at the University of Western Australia. The tests represent an initial study of the applicability of centrifuge modelling to simulate coal extraction beneath relatively soft sedimentary rock.

2. CENTRIFUGE MODELLING

2.1 Introduction to Centrifuge Modelling

The centrifuge modelling technique is an effective and versatile method of producing realistic small scale model test data which can be related directly to a prototype situation. This is due to the fact that the behaviour of geotechnical materials such as soil and rock is very dependent on stress level. In a conventional model test, performed in the earth's gravitational field, it is not possible to maintain similarity with prototype situations and to ensure that the stress levels in areas of interest reach prototype values.

A geotechnical centrifuge can subject small scale models to centripetal accelerations which are many times the earth's gravitational acceleration. Under this increased acceleration field the self weight of the material being tested is increased by the same proportion by which the model dimensions have been reduced. Thus, by selecting suitable acceleration levels, it is possible to create full scale stress levels in the small scale model to ensure a correct stress level dependent response of the model.

2.2 Scaling Laws

Centrifuge scaling laws have been described extensively elsewhere (1). However, if we consider a model where the prototype dimensions have been reduced 'n' times such that $d_p/d_m = n$, where d_p and d_m are prototype and model dimensions respectively, and if 'n' is chosen as the gravity scaling factor, then the basic scaling relationships associated with centrifuge modelling are as given in Table I.

TABLE I

CENTRIFUGE SCALING RELATIONSHIPS

Parameter	Units	Scaling Relationship
Gravity	m/s^2	n
Length	m	1/n
Stress	Pa	1
Strain	%	1
Force	N	$1/n^2$
Time$^+$	sec	$1/n^2$

$^+$N.B.: This relationship applies to lamina flow processes such as consolidation

If a similar material is used in both the model and prototype then the similitude of stress levels at corresponding points in the model and prototype will result in a model response directly analogous to that of the prototype.

2.2.1 Scaling Considerations for Mining Applications

The centrifuge models reported herein are concerned with modelling relatively shallow mining depths - of the order of 60 metres. However, due to the limitations in size of existing model containers the required model dimensions necessary for direct scaling was not possible. Consequently the model tests were designed to be performed at half prototype scale. This necessitates that the prototype strength parameters of the overlying sediments should be reduced by a factor of two in the centrifuge model, and thus the strength to depth ratio in both model and prototype is preserved. Figure 1 summarises the prototype and corresponding model ground profiles which were used as a basis of the model tests.

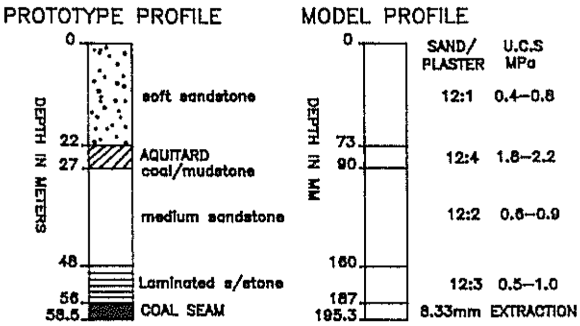

Figure 1 Approximation of model ground profile to a prototype situation.

3. CENTRIFUGE TEST PACKAGE

3.1 Actuator Assemblage for Mineral Extraction Simulation

To simulate the extraction of coal at depth, an assemblage of 18 hydraulic actuator units were designed and built. Each actuator is composed of a circular piston unit with a rectangular top cap. The plan dimensions of the top cap are 45 by 68 mm which represents a prototype area of 13 by 20 m at 150 gravities at half scale.

The actuator units are arranged three deep by six across in the centrifuge strong box to provide a simulated extraction area of 4680 square meters at prototype scale. The throw of the actuator units was set to 8.3 mm which represents an extraction height of 2.5 m at prototype scale. The strong box used for the model tests is fitted with a perspex window through which deformations of the model can be observed. Figure 2 shows a detailed drawing of a typical actuator unit and Figure 3 shows the arrangement of the actuator units in the centrifuge strong box.

The actuator units have been designed to cater for the provision of stooks by allowing pillars to remain standing to support the overlying strata as the actuator is lowered - see Figure 4. These stooks can be removed if not required - i.e for Longwall mining simulation.

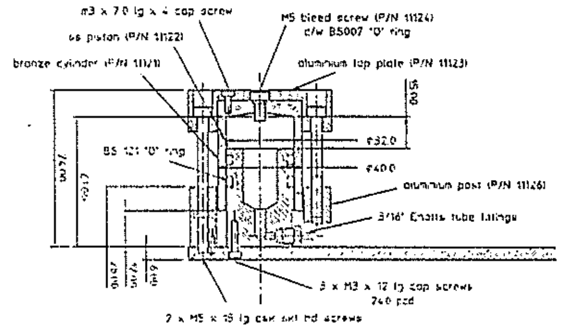

Figure 2 Assembly drawing of single actuator unit.

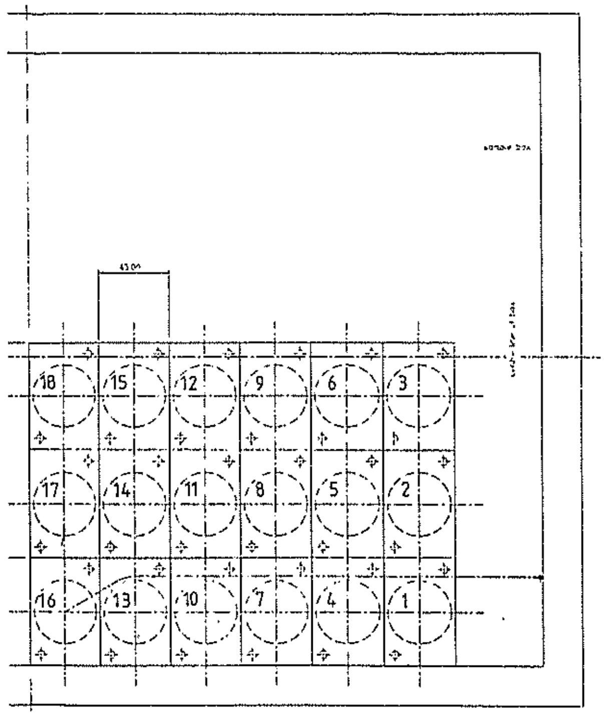

Figure 3 Plan arrangement of actuator assemblage in model container.

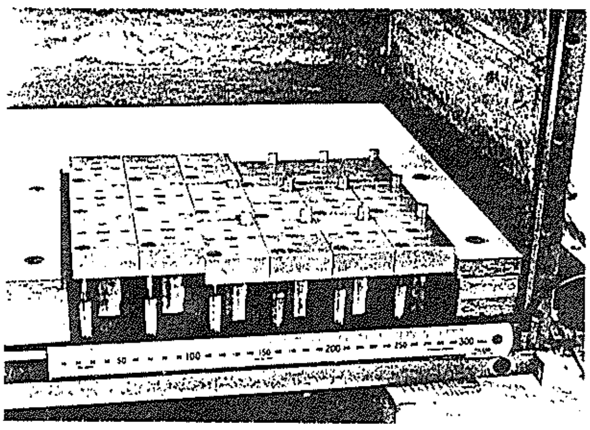

Figure 4 Actuator assemblage with stooks.

3.2 Actuator Control and Data Acquisition

Each actuator unit is connected to a miniature solenoid valve which in turn connects to a manifold on the outlet side and to a fine metering flow control valve. Thus each actuator unit can be dropped individually or collectively at controlled rates set by the orifice of the metering valve. The control of the solenoid valves is performed by a computer.

The majority of the data obtained from the model tests performed so far have been visual. Miniature CCD cameras are mounted on the package to record the sub-surface movements of the model via the perspex window and the surface disturbance of the model resulting from the dropping of the actuator units.

An imaging system has also been developed which is presently capable of monitoring the real-time motion of up to eighteen discrete points visible through the strong box window. This system is also capable of back analysing video footage of the model tests to produce displacement records of visible markers. Eventually the system will provide both strain and displacement fields of the overlying strata throughout the simulated mining process.

4. MODEL PREPARATION

4.1 Introduction

Two model tests are reported in this paper. The first test (Westcol3) was designed to simulate coal extraction by the Longwall mining style. The second test (Westcol4) was designed to simulate extraction by the Wongawilli method. This extraction technique is presently employed by Western Collieries operating the Collie Basin of Western Australia.

4.2 Tests Westcol3 and Westcol4

The model preparation of these two tests was essentially the same. The different strata were simulated using various mixtures of fine sand (250 micron average particle size) and gypsum cement. The strength of each strata was evaluated from unconfined compression tests, and by varying the mix proportions of water, sand and gypsum suitable strengths could be obtained.

One of the key elements to the success of replicating a realistic prototype situation was to develop a technique to enable the lowest strata - i.e the mine roof - to have a laminated structure - which would result in bulking of the goaf. This was achieved in the model by casting successive thin layers of gypsum/sand mixtures where each layer was allowed to dry and a small amount of dry sand was sprinkled onto the surface of the hardened mixture before the next layer was cast. The net result of this technique was to produce a 27 mm thick laminated strata with horizontal planes of weakness directly over the hydraulic actuator units.

Three more uniform gypsum/sand mixtures were then cast, in appropriate thicknesses, to represent the other layers of strata. Figure 1 shows the model profiles used in both tests, and the associated U.C.S strengths obtained for each strata. The U.C.S strengths quoted in this figure have been estimated from element tests performed on standard 76 mm diameter samples.

After the model material had been cast into the strong box the front face of the strong box was removed and a template used to spray a uniform grid of discrete marks and horizontal lines onto the model face. The surface of the models was also sprayed black to highlight any surface expressions resulting from the simulated mining.

5 MODEL TEST RESULTS

5.2 Longwall Style Extraction

The actuator units were manipulated to simulate a Longwall style extraction - i.e no stooks were provided - and the dropping order is shown in Figure 3. Two miniature CCD video cameras were employed in this test to monitor both surface deformations and deformations of the model face through the strong box window.

Video observations of the model test clearly showed that a laminated structure to the roof strata had been achieved from the model preparation process. The results of the model test are best illustrated from post-test traces of the cracking visible on the model face (Figure 5), the model surface (Figure 6) and the surface of the aquitard layer (Figure 7).

5.3 Wongawilli Style Extraction

The actuator units were dropped in the same order as for test Westcol3 (see Figure 3). Again the majority of the information obtained from the test was visual, with observations being recorded on video. Figure 8 shows the sketch of the crack pattern visible on the model face and Figures 9 and 10 show the respective crack patterns for the model surface and aquitard surface.

5.4 Comparison of Model Responses.

By comparing the traces obtained of the front faces of the models after testing, it is possible to determine slightly different responses of the two types of extraction procedure employed. For example , Figures 5 and 6 show that a large tension crack develops in the near surface almost vertically above the trailing end of the Longwall extraction. This cracked zone is much less significant in the corresponding traces for the Wongawilli extraction (see Figure 8 and 9), and is an indication that greater tensile strains had developed in the near surface in the absence of stooks at the onset of the extraction. This observation can be linked to the deformation response of the underlying strata where comparison of the cracked aquitard surfaces show a more significant deformation of the aquitard has occurred in the Longwall (Figure 7) than for the Wongawilli extraction (Figure 10). The effect of the stooks is clearly seen by the "wavey" appearance of the goaf in Figure 8 (test Westcol4) where intermittent partial support is provided to the overlying strata. The dotted lines in Figures 5 and 8 show the interface between the goaf and the overlying strata.

The degrees of subsidence resulting from the two types of extraction were obtained by comparing the pre and post-test surface and aquitard surface profiles. These data, obtained by laser transducer profiling, are best represented by the absolute settlement values at discrete points on

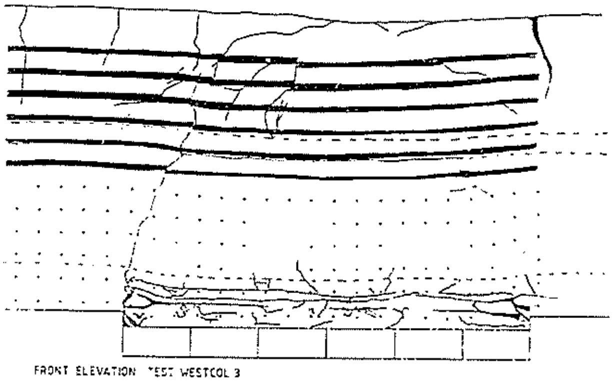

Figure 5 Trace of crack pattern on model face after test Westcol3.

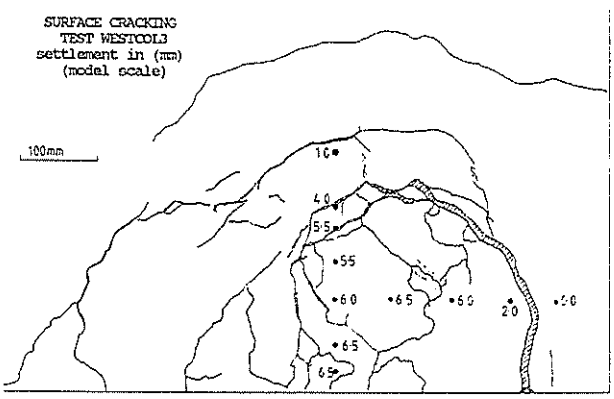

Figure 6 Trace of ground surface crack pattern after test Westcol3.

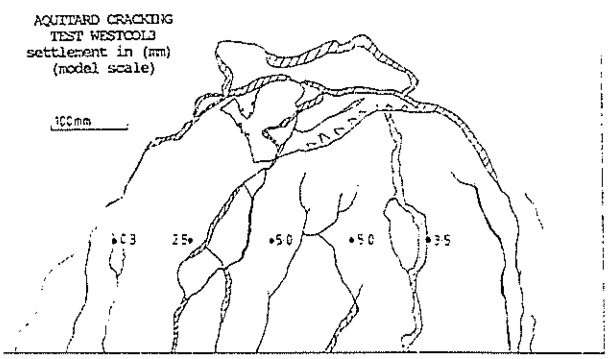

Figure 7 Trace of aquitard crack pattern after test Westcol3.

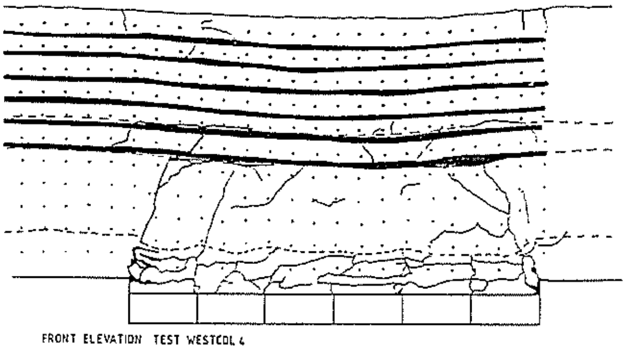

Figure 8 Trace of crack pattern on model face after test Westcol4.

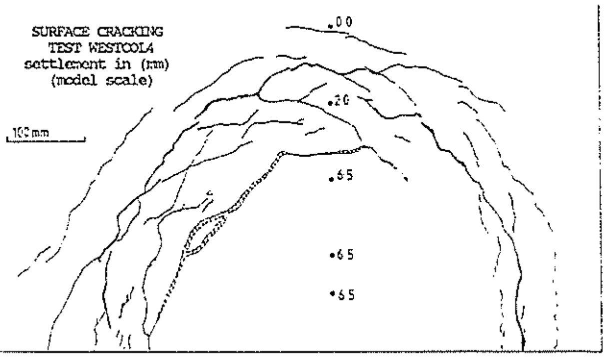

Figure 9 Trace of ground surface crack pattern after test Westcol4.

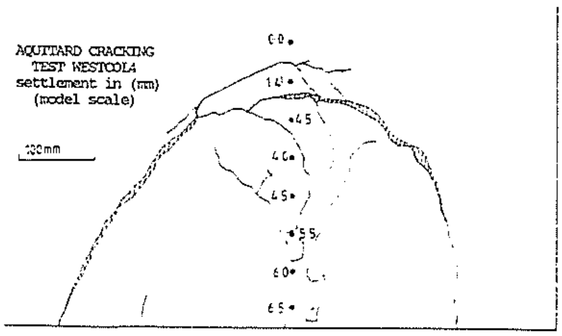

Figure 10 Trace of aquitard crack pattern after test Westcol4.

the sketches of the surface and aquitard surface crack patterns, as indicated in Figures 6 and 7 and Figures 9 and 10 for the respective Longwall and Wongawilli cases. This data show that the maximum surface and aquitard settlements recorded for both tests was fairly similar - about 70% of the extraction height. However, the traces of model face and surface crack patterns (Figures 5 and 6, and 8 and 9) illustrate that the areas affected by the extraction process is somewhat greater for the case where Longwall extraction has occurred, and although the general shape of the subsided region is similar for both tests the surface expressions (i.e visible cracks) are more pronounced for the Longwall case.

Similar observations can also be made concerning the aquitard crack patterns. In this case the differences are more pronounced with more abdundant cracking occurring and extending over a larger area in the Longwall case than in the Wongawilli case. These observations can again be attributed to the intermittent support offered by the presence of stooks in the goaf.

6. DISCUSSION AND CONCLUSIONS

The centrifuge model tests reported in this pilot study have clearly demonstrated that the centrifuge modelling technique offers a powerful tool in investigating subsidence problems resulting from mineral extraction processes in stratified deposits. A versatile mechanical system has been developed and proof tested which enables a variety of mining methods to be studied.

Whilst only a limited amount of work has so far been undertaken on the feasibility of modelling site specific strata, it is clear that the use of artificial rock of any required strength can be reproduced by careful design of gypsum/sand/water mixtures. Model making techniques have also been developed, which indicate that as well as meeting strength criteria, the structure of the overlying strata can also be replicated. This was clearly illustrated by the laminated nature of the model mine roof in test Westcol3.

The magnitudes of the maximum surface settlements - about 70% of the extraction height for the model tests - compare favourably with values measured in the field where the properties of the overlying strata is similar to that used in the scale model - i.e the Collie Basin of Western Australia.

7 ACKNOWLEDGEMENTS

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8. REFERENCES

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