The Application of Physical Modelling to the Undersea Mining Conditions at Kozlu Mine in Turkey

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ABSTRACT

Current problems in predicting sub-surface strata movement and fracture development due to longwall mining have highlighted the need for more accurate, dependable methods of physical modelling of rock mechanics problems which are beyond the capabilities of current mathematical techniques.

Physical model studies of the caved zone above the working faces up to the base of a water source are of importance in attempting to understand changes in mass permeability due to induced fracture zones and the resulting ground water conditions.

Turkey's most important supplies of coking coals are to be found within the hard coal resources of the Black Sea coast. Coal seams up to 9 metres thick, dipping at angles as steep as 90 degrees are being successfully mined at the Kozlu Mine. Since 1956, mining operations have been carried out under the sea in dry conditions.

The undersea mining conditions of the Kozlu Mine have been investigated using scaled physical models constructed from artificial materials which satisfied necessary scaling requirements.

Models representing the in-situ conditions were tested and the following extraction sequence was employed:

1. The Sulu Seam extraction
2. The Acilik Seam extraction (as two slices)
3. The Piric Seam extraction.

The displacement of the fixed reference points were subsequently measured using a high precision photogrammetric technique and induced horizontal and vertical strains were calculated.

The models showed the difference in behaviour of strata above longwall faces up to the seabed when the seams are either horizontal or are inclined at 35 degrees. The horizontal model of the Kozlu Mine give a more dramatic picture than the inclined model in respect of fracture development.

INTRODUCTION

A major consideration when mining under bodies of water is the avoidance of a major inrush of water. High risk reserves include those located under the sea, under surface water bodies, or under heavily water-bearing strata. These water sources constitute a potential hazard in underground mining and may be a significant operational problem. The principal hazard arises from massive inflows of water when the mine working unexpectedly intersects large water-bearing geological discontinuities or induced fracture zones. Because of the complex nature of water problems encountered during underground extraction, as yet no single method for the assessment of water inflow into mine workings has found wide acceptance.

Ideally, there should be a method of predicting the fractures and the sub-surface strata movement which would be induced by longwall mining. The flow of water is related to the width, length and direction of the interconnected fractures and fissures as they develop and change with the movement of each longwall face. Despite advances in numerical and analytical techniques, it is uncertain whether any of these can predict post-elastic deformation and the structural response of rock mass to stresses which induce fractures within the rock mass.

Field investigations can reveal actual behaviour and are essential to check the predictions of mathematical and physical models but they are generally expensive and for various reasons generally somewhat limited. Apart from some geophysical methods, information can be obtained by installing instruments in boreholes drilled from working places and access tunnels. It is thus advantageous to supplement in-situ investigations with models.

For the problem of fracture development and the associated strata movements, it is considered that physical models using model materials with appropriate relationships to the prototype rock materials can make a significant contribution to the understanding of this phenomenon. Model studies of the caved zone above a longwall face and of the strata up to the base of the source of water are one important approach to the understanding of changes in rock mass permeability and the resulting groundwater conditions.

At the Kozlu mine in the Zonguldak coalfield, mining has been carried out under the Black Sea since 1956 employing the longwall method with stowing. The conditions have been relatively dry. However, the possibility of seawater inrush has had to be reconsidered due to the recent adoption of the caving method in the under sea workings.

The development of induced sub-surface fractures and the overall behaviour of the strata in the mine have been investigated by means of scaled models constructed from synthetic rock materials which satisfied the necessary scaling requirements. Two physical models were constructed at the University of Newcastle upon Tyne: one model represented horizontal seams and the other seams inclined at 35 degrees.

In this paper some of the information derived from the models is used to assess the possibility and character of water problems which might develop in the mine.

BACKGROUND TO PHYSICAL MODELS

Physical models have been widely used in many branches of engineering; for some types of problems they have been superseded by mathematical solutions rendered feasible by the power of electronic computers. At the present time there is a lack of confidence in mathematical models which predict failure and subsequent stress redistribution.

In mining, Fayol in 1885 partly based his theory of mining subsidence on small scale models. Subsequently, there have been many attempts at modelling, some using dimensional analysis in an attempt to obtain a rational relationship between model and prototype behaviour. Panek [1] employed a centrifuge to apply increased body force to his roof-bolting models. Most investigators have used 'model' materials in an attempt to obtain similarity.

Examples of the application of physical models to mining include: Everling and Jacobi 1964 [2] the stability of longwall roadways, Hobbs 1966 [3] the effect of rock strength and of roadway shape on the deformation of roadways, and Tully 1987 [4] the effect of rock bolt reinforcement of mine roadways. Roadway research has also been carried out by Whittaker & Hodkinson [5] and Brook [6]. Scale modelling has been employed in coal ploughing research by Roxborough & Eskikaya 1974 [7]. An application of an equivalent material model to the subject of subsidence was first made in the Department of Mining Engineering at the University of Newcastle upon Tyne by Singh [8] and Harwood [9], based on the technique reported by Vorobjev 1963 [10]. The model represented longwall working in a seam underlying pillars in an upper seam at an undersea mine in Northumberland, England. The resultant affect on the pillared area and the strata to the sea bed was studied.

An interesting model using blocky pre-fractured material to study the feasibility of longwall mining under strong massive roof conditions at Moura, Queensland has been reported by Wold 1985 [11].

THE PROTOTYPE

The Zonguldak coalfield extends for 50 miles along the west part of the Black Sea coast of Turkey. The coalfield is characterised by mountainous surface terrain and the highly complex geology of the coal measures which are heavily folded, with seam continuity adversely affected by severe faulting and unconformities.

The Kozlu mine is located on the coast approximately 8 kilometres west of Zonguldak. At present, mining activities are carried out under the land and under the sea. Both sets of workings are connected at the main horizons, therefore any water hazard from the undersea workings also poses a major threat to the under land workings.

The productive area of the Kozlu mine has a dome-shaped structure. The west flank dips towards the Black Sea with an inclination of 30° to 40°. The coal measures contain 17 workable coal seams. Extensive and irregular multiseam, multipanel extractions makes it difficult to predict the cumulative induced tensile strains and the fractures which may have developed.

No aquifers exist within the coal measures of the Kozlu mine. Therefore, the only possible source of water inflow into the workings would be the sea.

However, near the large North fault, which the panels are approaching, the Karadon formations which are located above the coal measures might be water bearing.

The coal measures of the Zonguldak coalfield consist primarily of sandstones, shales, conglomerates, conglomeratic sandstones, silt-stones and coals, occurring in a series of rythmic or cyclic sequences which vary throughout the coalfield.

Since the geomechanical properties have an important role in the selection of synthetic model materials for any study by physical modelling, it is important to know the pertinent properties of the in-situ formations. A comprehensive rock test programme has not yet been carried out. However, various rock tests were undertaken by the MTA (Mineral Research and Exploration Institute of Turkey) on rock core specimens obtained from the borehole of the Kozlu new shaft. These results and some from the Amasra Mine were used in order to obtain reasonably appropriate geomechanical properties for the intended model study.

THE DESIGN FEATURES

The highly complex geology of the coal measures which are also heavily faulted, would be very difficult to simulate exactly. It was thus decided to model a simplified geological section to predict the general pattern of fracture development and the increase in permeability.

The Aim of Modelling

1) An important objective of the physical modelling was to represent the wide range of dip of the coal measures in Kozlu. Horizontal coal measures are not common in the Kozlu Mine, but the layout of production faces has been influenced by the British design criteria for undersea workings. A horizontal model was employed to test the validity of the British criteria in the Zonguldak coalfield; it would enable comparison to be made.

2) To show the difference in the fracture pattern when the seams are horizontal as compared with inclined bedding.
3) To investigate the fracture development and to study the variation of sub-surface subsidence and associated bed separation and strains due to multipanel, multiseam mining.
4) To study the effects of large caving spans caused by the strong roof of the Sulu Seam on the development of fracture zones.
5) To investigate the relationship between periodic weightings and the mechanism of the opening and subsequent closing of bed separation voids.

Similarity Requirements

All physical model studies should be based upon dimensional analysis so that the results obtained can be applied with confidence to the prototype. The design equations for the relationship between model and prototype material were derived by dimensional analysis.

The generation of the appropriate Pi terms and dimensionless equations are not presented here as they have been reported elsewhere (Obert and Duvall, 1967 [12]; Harwood, 1980 [9]; Singh, 1981 [8]. An ideal model material would satisfy all the scaling criteria. However, due to great difficulties in producing materials with all the required values, a certain degree of relaxation in similarity criteria must be adopted. It has been accepted that a longwall roof failure is due to bending tensile forces. Since the aim of the simulation of the Kozlu Mine was to investigate the failure behaviour of the rock masses and sub-surface fracture development, two strength parameters were chosen as the fundamental rock characteristics: the uniaxial compressive strength, and the tensile strength.

Model Material

Stimpson, 1970 [13] has provided an excellent literature review of the subject of modelling materials. Generally, artificial materials consist of a filler and a binder. Plaster of Paris was chosen as a binder because it has been used extensively by many investigators in physical models of underground structures. A variety of constituents were used as fillers, including dry silica sand, vermiculite, sawdust, coal dust and graphite powder. Twenty one different materials containing varying proportions of the selected ingredients were produced. In order to select satisfactory synthetic materials from these, a series of samples of each material were subjected to a number of tests: compressive, tensile and bending strengths, and density. The idealised geomechanical materials selected for the construction of the models are given in Table 1.

Size of Models

Ideally, a physical model should be large, so that movements and fractures are easily observed and measured. However, there are several constraints on size: the larger amount of materials required and the extra time to manufacture and cast them, the stronger and heavier the frame required to contain the model, the extra laboratory space required, etc.

The dimensions chosen were a compromise; the frame allowed the construction of a model 2.20m high by 2.41m wide by 0.165m thick. With the materials selected for the model only temporary supports at the front and rear face were required when the material was placed so that no problems with friction and visibility occurred during testing.

At the geometrical scale of 1 in 100 which was chosen, the maximum strata depth which could be simulated in the model frame under self-loading conditions was 220m. However, at the Kozlu Mine extraction extends to a depth of 485m below sea level. Whilst it would have been possible to apply pressure to the top surface of a model by means of hydraulic jacks, experience with other models indicated that an exaggerated failure response was provoked. Therefore, it was decided only to employ gravity loading, thus the model represented conditions at a depth of only 200m to the base.

For the selection of an idealised section from the standard Kozlu log the following factors were considered:

1) The main productive seams under the sea are the Sulu and Acilik; therefore, these coal seams would be included in each model section.
2) For the inclined model, a typical undersea section of the Kozlu Mine across to the 22926 gallery was adopted. The model inclination was 35°, the same as the in-situ situation. The strata log used was the same as that employed in the horizontal model.

MODEL EXPERIMENTS

Testing Procedure

In both models, material representing the following seams: Sulu, Acilik top seam, Acilik bottom seam and Piric was extracted successively as in the mine.

Model A

In Model A, which consisted of horizontal strata, extraction was started in the Sulu seam 40cm from the left hand side of the model and continued by small increments progressively towards the right hand side. The movement and fracture patterns represent those on a vertical plane through the centre line of a longwall face (i.e. a longitudinal section). The other seams were subsequently mined in order of depth as indicated above.

Model B

This represented longwall faces working on strike in seams inclined at 35° to the horizontal.

A pillar was left in the centre of the model and a longwall face was extracted first on the rise side of the pillar, and then a second face on the dip side, in the Sulu and Acilik top and bottom seams. Mining was simulated by removing a thin wooden lath which had been cast into the model to represent the full length of a longwall face.

The patterns of movement and fracture represented a vertical transverse section across the longwall extraction.

Observations and Measurements

The movements and fractures which developed in the models were recorded photographically. The dynamic effects were recorded on video tape by means of a video camera.

Photogrammetric cameras were used to obtain high quality still photographs of the model at critical stages of extraction. With Model A the camera was a Wild P31 using cut film, and for Model B, an Officine Galileo camera with glass plates was used. From these still photographs it was possible using high precision photogrammetric equipment to determine, with respect to fixed targets on the frame, the position of targets fixed to the surface of the model. Consequently, movement vectors, vertical and horizontal displacements, and strains could be calculated from the changing values of the target co-ordinates.

Model A

During the extraction of the Sulu seam, three major caving events occurred. As expected, the largest span developed prior to the first fall, which happened at an extraction span equivalent to 128.5m. Two periodic cavings occurred after further advances of 33m and 30m in the Sulu seam.

In the Acilik top seam, five periodic cavings occurred. Unlike the Sulu seam extraction, the first caving event occurred after an advance of only 40m. As the face in the Acilik bottom seam was advanced, no periodic cavings were observed. The goaf of the Acilik top seam caved as the face advanced. However, the previous fractures in the overlying strata became more severe and bed separation cavities opened up between fractured layers. The final extraction of the Piric seam did not cause significant additional fracture development.

The progressive development and migration of bed separation was clearly displayed as each seam was progressively mined in small increments. After the first roof fall, the bed separation occurred in the beds overlying the seam, particularly near the face and the face start point. As the face advanced, the beam fractures and bed separation penetrated into the higher strata. Some readjustment of the fractured beds occurred and some of the bed separation cavities closed fully or partially as the face moved forward. Above the goaf, most of the bed separation closed up and most fractures 'healed' without significant relative displacement. As further seams were mined, the greater was the relative displacement between the strata over the side and over the goaf. The progressive changes are shown in Figure 1.

Figure 1 : Fracture and Bed Separation Model A

2) After total extraction of the Sulu seam.

4) After caving of roof after equivalent advance of 86m of Acilik top seam.
6) Caving after partial advance of Acilik bottom seam face.
8) After total extraction of Piric seam.

The size of the model constrained the location of the face starting and finishing points and thus intensified the fracture pattern. In the mine, the disturbance could be reduced by appropriate locations of the longwall panels in the various seams.

Model B

Owing to the method used to extract the longwall face as one unit (rather than progressively as in Model A), the periodic cavings as a result of face advance did not occur.

In all seams but the Piric, a small coal pillar was left near the centre of the model with a face extraction on each side of the pillar. Consequently, the faces were narrower than in Model A, and the fracture zones associated with the two face ends intersected within the model. Bed separation eventually developed in the higher strata centred around the perpendicular to the seam through the centre of each face. These higher bed separations closed up when the Piric seam was worked under the pillar. Although the strata supported by the pillar in each coal seam is not fractured it does show a small amount of movement. In both models the principal movement is directed perpendicular to the coal seams; this is illustrated in Figure 2.

Figure 2 : Movement Vectors

Model A : Total movement vactor due to extraction of the Sulu seam and the Acilik top seam.
Model B : Movement vector caused by the extraction of the right hand panel of the Acilik top seam (after previous extraction of the right and left hand panels of the Sulu seam).

The fracture and bed separation at various stages of extraction are shown in Figure 3.

Figure 3 : Fracture and Bed Separation Model B

11) After extraction of both Sulu seam panels.
13) After extraction of both right hand side panels in Acilik top and Acilik bottom seams.
15) After extraction of both left hand side panels and Acilik top and Acilik bottom seams.
17) After extraction in the Piric seam and extraction of the Sulu pillar.

Figure 4 : Model B

After extraction on both sides of a pillar in the Sulu seam and in the top and bottom Acilik seams and after complete extraction of the lowest seam, the Piric.

ASSESSMENT OF THE RESULTS OF MODEL TESTS

Photogrammetry

During the various testing stages of the models, photogrammetric pictures were taken; they were successfully analysed. The co-ordinates of the photogrammetric targets derived on the unworked model were compared with the co-ordinates determined after the extraction of successive seams. Displacement vectors were plotted for each excavation sequence by using the plotting facilities of the mainframe computer at the University.

Strain Calculations and Fracture Development

Horizontal and vertical displacements were calculated from the photogrammetric co-ordinates. In order to assess the effects of the strains on the fracture development, horizontal and vertical strains were calculated using the displacements of adjacent targets. After the extraction of Acilik top seam, fractures were induced at the seabed and these calculations were concluded. The horizontal strain values at the seabed for the first two stages of extraction are presented in Table 2.

It is interesting to note that the main fracture occurred at the seabed (surface of model) between the targets 9 and 10 at a tensile strain of 10.9mm/m, which is in agreement with the British Code of Practice which prescribes less than 10mm/m.

However, it has been found that, by using the SEH [14] for the same geometrical dimensions, the Sulu seam extraction should induce 13.23mm/m tensile strain and Acilik top seam alone would produce 9.5mm/m, giving a cumulative tensile strain of 22.7mm/m.
The calculations from the model experiment give less strain. This may be due to having strong model materials not representative of British Coal Measures and because the SEH values are the result of the averaging or smoothing effect of boulder clay overlying the rock head.

The calculated vertical strains in the model were often much higher than the horizontal strains, reflecting the development of bed deformation at various heights above the seams extracted.

DISCUSSION AND CONCLUSIONS

The results of these physical model studies have provided further evidence of the formation and movement of bed separation cavities and the development of fracture zones and their probable influence on the character and quantity of water inflow.

It is believed that the qualitative results for the models are more realistic than the quantitative results. Due to the lack of field measurements of strata movement in the Kozlu Mine, it is not possible to make any comparison with the model results. The quantitative results for the models are not in agreement with those obtained from the SEH for the same geometrical conditions. The strain analysis for the models indicates that the development of the sub-surface fracture zones are associated mainly with high vertical strains which are not considered in the SEH since it is primarily for the prediction of subsidence at the surface.

As expected, the strong and massive conglomerate strata above the Sulu seam played a dominant role in the caving behaviour of the roof. Such a strong roof allowed a very large initial span to develop and when this collapsed, the fracture zone induced was much larger than with extractions in the other seams.

The horizontal model of the Kozlu Mine gave a more dramatic picture than the inclined model with respect to fracture development.

It was observed during the various extraction stages of the models that once a fracture pattern had developed it was extended and modified by the extraction of the successive seams or another panel within the same seam, suggesting that the order of seam extraction could be significant in determining the location of fracture zones.

Many of the pertinent variables of this physical model study are related to the synthetic model materials. Despite the difficulties in developing artificial model materials which would satisfy all the scaling requirements based on dimensional analysis, the investigation and development of new model materials and their subsequent application should enhance the validity of physical modelling.

The fracture pattern obtained from physical Model B shows that the fractures above the faces and near the surface induced by the panels worked down dip of the central pillar are not connected to those induced by the first faces. This model simulates approximately 200m of depth. It can, therefore, be concluded that on this evidence the 90m caving faces can be extracted safely below -425m level without causing major water inflow from the Black Sea. However, it is essential that the locations and properties of the major faults be carefully studied. It is also recommended that in future the quantity of water (m^3/ton) should be continuously monitored for each panel worked.

The results from the physical models will be of assistance in determining the location of boreholes to be drilled in a major in-situ investigation to be undertaken at the Kozlu Mine.
A comprehensive project, somewhat similar to the investigations of Malone [15] and Dowdell [16] is being initiated in order to study sub-surface subsidence and the associated strata strain and deformations. All water inflows into the mine will be subjected to frequent chemical analyses.

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Rock Type	Idealised Properties		Equivalent Material Composition-% Volume						Properties of Equivalent Material	
	Uniaxial Comp. Strength (MPa)	Tensile Strength (MPa)	Mix No.	Plaster	Sand	Mica	Wood Dust	Graphite	Uniaxial Comp. Strength (MPa)	Tensile Strength (MPa)
Shale	14	1.99	8	15	45	-	40	-	0.80	0.099
Sandstone	98	12.28	4	15	50	35	-	-	2.66	0.515
Conglomerate	104	12.23	14	15	70	35	-	-	4.80	0.492
Conglomer-atic Sandstone	103	11.0	15	15	60	25	-	-	3.54	0.442
Siltstone	100	14.24	3	15	45	40	-	-	2.96	0.345
Coal	43	4.0	11	15	40	20	20	5	2.09	0.359

TABLE 1 : Idealised goemechanical properties of Kozlu Mine for the models and the equivalent materials selected

Observation Line	Face Position	Strains induced by the Sulu Seam (mm/m)	Strains induced by Acilik top Seam (mm/m)
5-6	-200	-0.51	0.00
6-7	-185	-1.62	-2.2
7-8	-170	+4.44	+2.2
8-9	-155	-2.16	-2.74
9-10	-140	+1.08	+10.86
10-11	-125	-0.96	-4.54
11-12	-110	-1.62	-3.84
12-13	-95	+2.25	+0.53
13-14	-80	-1.12	0.00
14-15	-65	+2.89	0.00
15-16	-50	+3.31	-6.27
16-17	-35	-6.21	+3.47
17-18	-20	+1.72	-2.84
18-19	-5	+0.53	+2.86

(+) Tensile Strain

(-) Compressive Strain

TABLE 2 : Induced horizontal strains at the seabed due to successive seam extractions from the Model A.

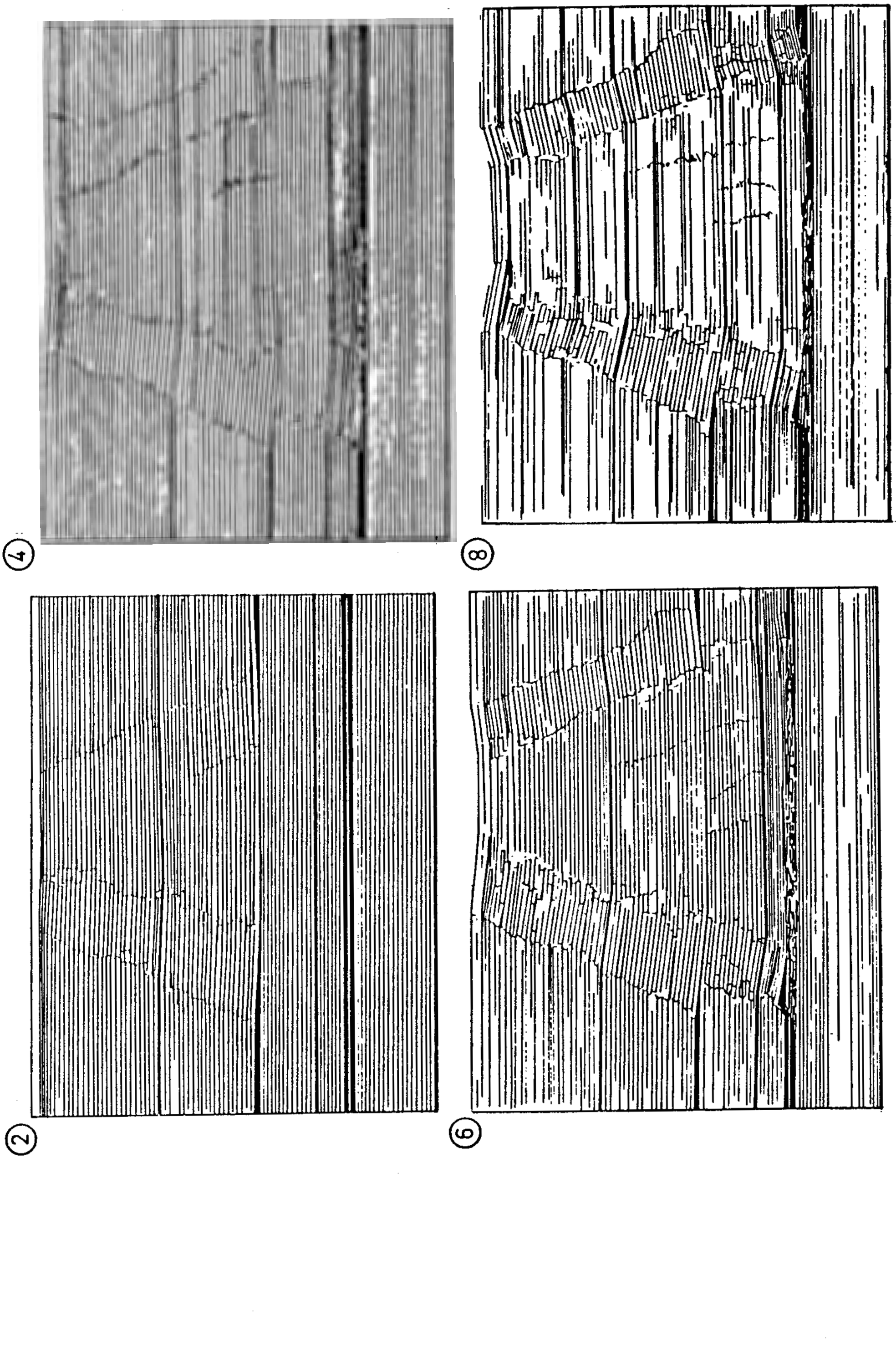
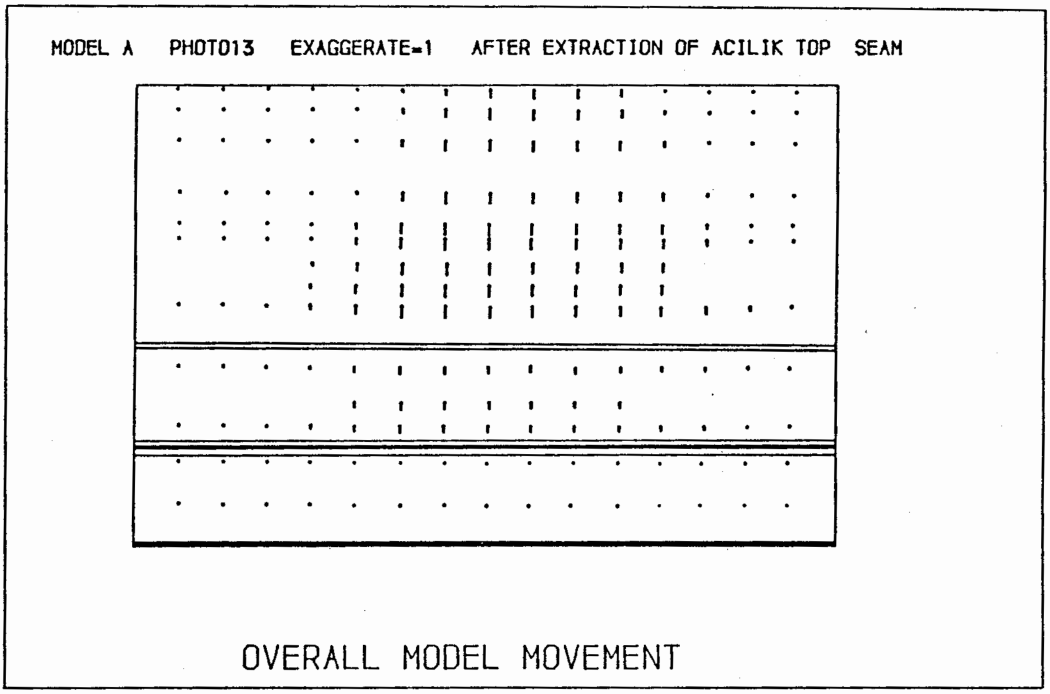


FIGURE 1 : Fracture and Bed Separation Model A



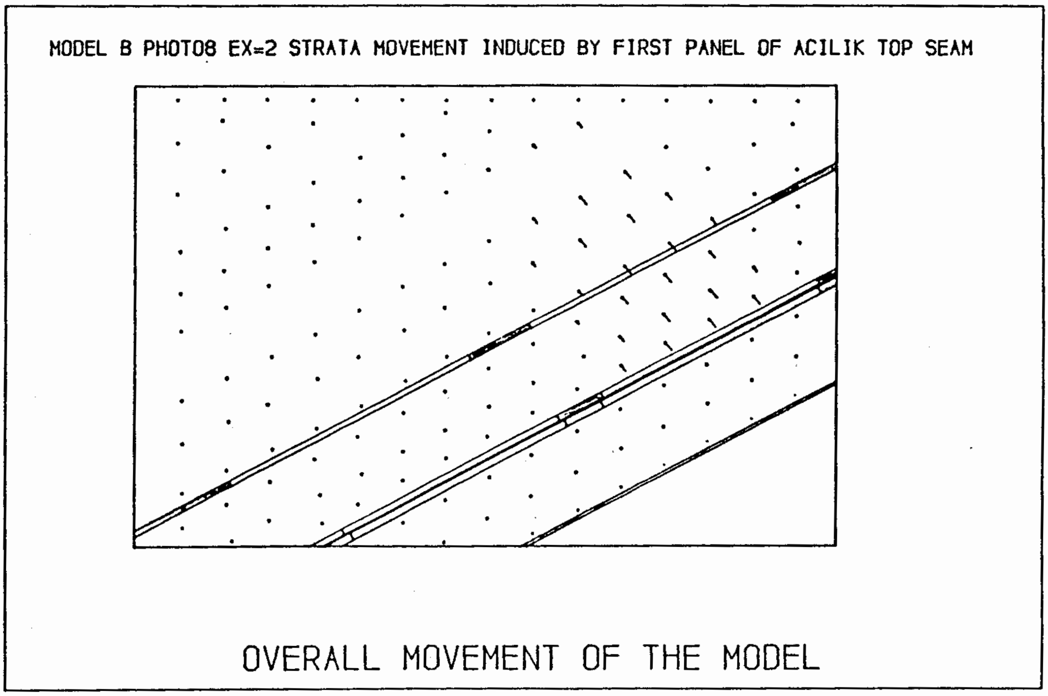


FIGURE 2 : Movement Vectors

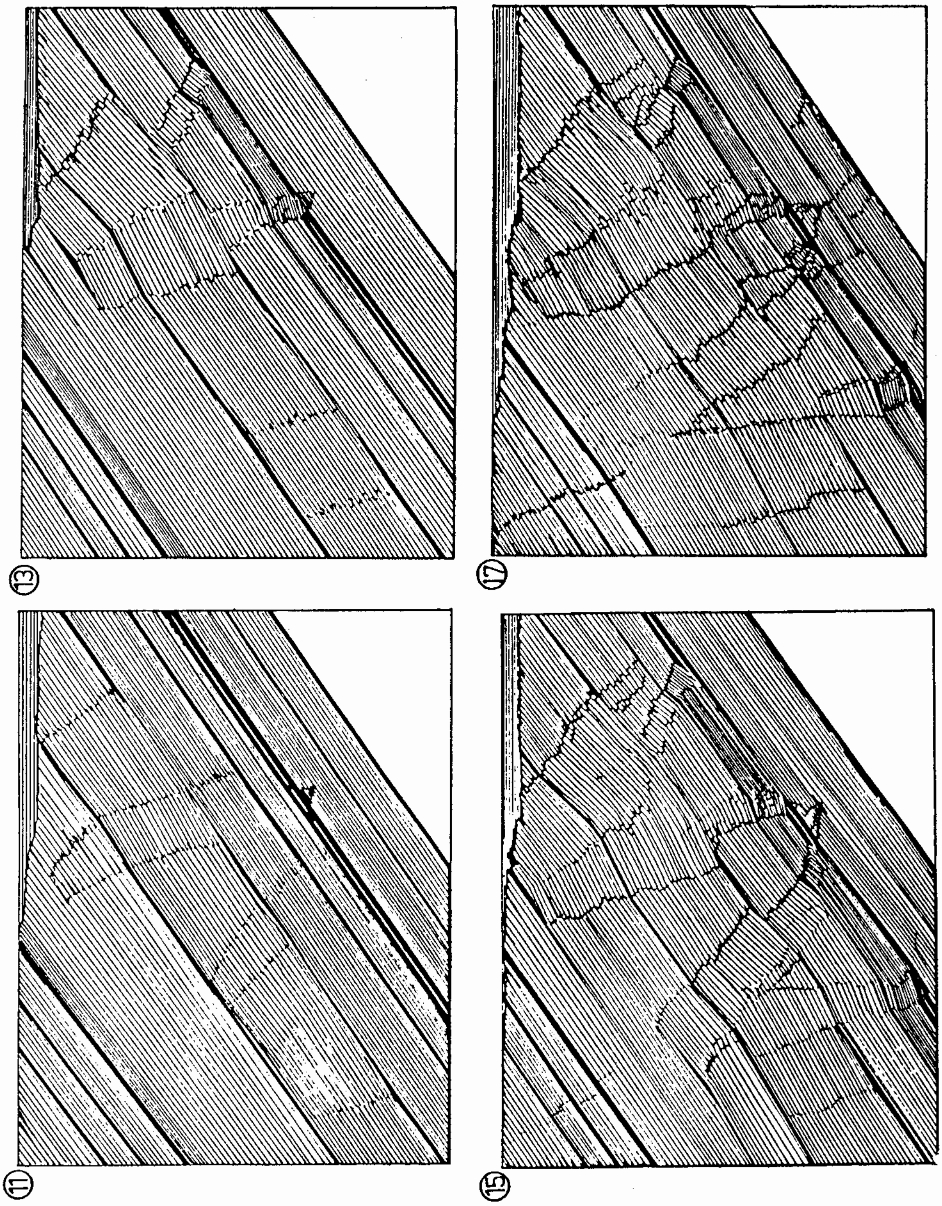


FIGURE 3 : Fracture and Bed Separation Model B

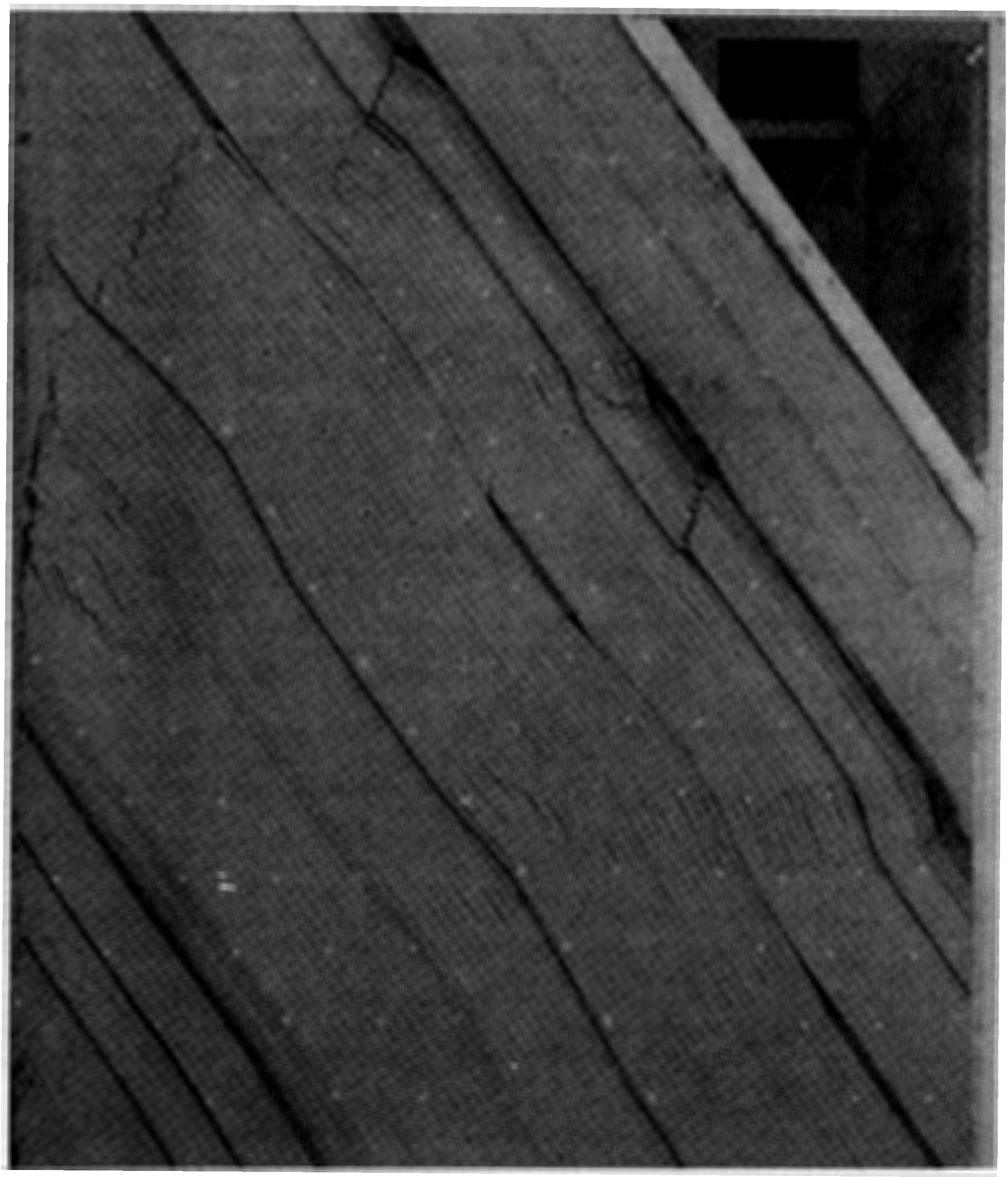


FIGURE 4: After extraction of Piric seam