# Reinforced soil in areas of mining subsidence
## Le sol armé dans les régions d'affaissement minier

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SYNOPSIS: This paper gives details of a recent survey carried out both in France and the United Kingdom to assess the performance of reinforced soil retaining structures constructed in areas subject to mining subsidence. Although comprehensive monitoring had not been carried out, the survey obtained details of the ground movements at a number of the sites. Visual examination indicated that the structures had performed well and showed no signs of distress. The importance of horizontal ground strain and structural geometry in relation to the effects of mining subsidence are highlighted. To supplement the field data and study trends in behaviour, both finite element analyses and a semi-empirical approach were employed to investigate the influence of different geometries and strain patterns.

## 1 INTRODUCTION

Mining subsidence is ground movement caused by mineral extraction. In most cases movements extend to the surface with three dimensional components of displacement along all axes of a general cartesian coordinate system. These displacements are imposed on any structural facilities in the affected zone and can induce damage or even collapse.

The effects of modern mining methods can result in settlements in excess of 1m in conjunction with relatively large horizontal ground strains. Although case histories generally show such ground strains to be in the range ±1 to ±3mm per metre, strains of up to 2%, i.e. 20mm per metre have been measured (O'Rourke and Turner, 1979).

The most common mining method employed in the recent past as the pillar and stall or room and pillar method. Although largely superceded in the United Kingdom, the method is still used in some parts of the world. Surface movements induced by this method of mining are usually the result of a progressive breakdown with time of the coal pillars and the bridging strata between these pillars. The estimation of the extent and rate of subsidence in these circumstances is unreliable, although an assessment of the total vertical movement may be possible with knowledge of the mining method, geometry of the workings and geology.

Longwall mining involving the complete removal of a given thickness of coal is the technique now most commonly employed. Mechanical cutters excavate continuously across the working face so that no pillars are left in a mined area. The roof immediately adjacent to the working face is supported by mechanical props, these are advanced with the coal face allowing the roof to collapse into the unsupported cavity. The collapsed material generally extends some 10 - 15m above the worked seam. Strata at higher levels and extending to the surface, sag into the trough which is formed. This trough advances with the face and, as indicated in Fig. 1, covers a region larger than the excavated area (NCB,1975), the majority of this movement taking place within 12 months of the excavation.

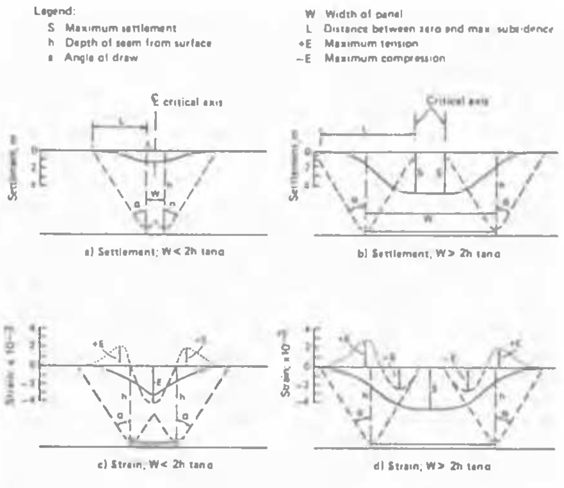


Fig.1 Cross-sectional view of subsidence trough with ground settlement and strain patterns (NCB, 1975)

As the subsidence trough develops, the centre subsides vertically while the remainder moves inwards towards the centre, resulting in both vertical and horizontal movements. These differential horizontal movements cause strain in the ground, producing a zone of compression towards the centre and tension at the edges of the ground surface above the excavated area. Thus at any point on the subsidence profile, the ground surface is subjected to vertical subsidence, horizontal displacement, horizontal strain, ground slope, rotation and ground curvature.

## 2. EFFECT OF MINING SUBSIDENCE ON SURFACE STRUCTURES

Structures subject to mining subsidence may be designed either to resist the strains or to be sufficiently flexible so that the imposed movements do not induce unacceptable stresses. The movements to which a typical 50m long highway structure may be subjected are as follows (I.C.E., 1979):

1. Differential horizontal displacement of 150 - 250mm
2. Differential transverse displacement of 150mm.
3. Differential vertical movement over total length of 0.6 - 0.9m.
4. Differential longitudinal and transverse tilt of 1 in 80 and 1 in 150 respectively and differential rotation in plan of 0° 20'

These values exceed the tolerance limits recommended by Moulton et al (1982) for bridges as well as those proposed by Skempton and Macdonald (1956) on allowable angular distortion for framed buildings and load bearing walls. The figures also exceed the permissible differential settlements for load bearing wall structures (Polshin and Tokar, 1957; Burland and Wroth, 1974) but are similar to those of the CLASP system of construction which was principally used for the design of schools in areas of mining subsidence (Jones, 1963).

Because of their flexibility, reinforced soil structures appear very suitable for areas of mining subsidence but there is little published data on the performance of these structures in such conditions. A recent study undertaken for the Department of Transport in the United Kingdom identified a limited number of structures in France and the U.K. which had been subjected to mining subsidence (Table 1). Examples in France related to reinforced soil structures overlying old pillar and stall workings which had collapsed, inducing ground movements at the surface. Although there were no observations of internal strain or reinforcement tension, all indications were that the structures behaved well with no signs of distress. There are no reported cases of reinforced soil in France overlying active longwall mine workings. However, in the U.K. several reinforced soil structures have been subjected to mining subsidence arising from longwall mining. One case related to the construction of a number of polymeric reinforced soil retaining walls in Derbyshire while the other involved the construction of two small sloping bridge abutments also reinforced with polymeric material. Because of encroaching subsidence, a decision was taken to construct these latter structures of reinforced soil. There have been no reported problems with any of these structures although the internal strains and forces were not monitored.

A number of case histories have been published giving details of internal observations and describing the successful use of reinforced soil construction in areas subject to ground movement (Brady, 1987; Barsvary et al, 1982; Rodriguez - Miranda and Villarroe 1979; Smith, 1986; Rowe et al, 1984). However, these have generally related to reinforced soil structures with compressible foundations. Although the differential settlements observed in these studies are often of the same order as for mining subsidence, a feature which is generally lacking is the horizontal strain imposed by the passage of a mining wave associated with the collapse of mine workings.

## 3. GROUND STRAINS

It would be expected that the differential settlements and ground strains associated with mining subsidence would impose some additional forces in reinforced soil structures. As far as differential settlements are concerned the published case histories generally confirm that the flexibility of these structures give them a relatively high tolerance to soil movements. The horizontal ground strains present more of a problem, however, as there is a dearth of information on this topic. Some obervations of horizontal strain towards the base of a reinforced soil structure and the effect on reinforcement tension are reported by Murray and Farrar (1988) in a recent paper. Their data relate to compressive horizontal ground strains which were attributed to the effects of settlement and ground anchors in the association with sheet piling. The compressive strains observed at this site, which were of the order of 0.7% at the base of the structure, induced relatively large compressive forces in the reinforcing elements in this region (Fig 2). Total vertical settlements of the order of 90mm were also observed. As there were no visible signs of distress, it was concluded that the study provided further evidence that the reinforced soil structure coped effectively with the relatively large ground movements which occurred. It should be noted, however, that if the horizontal ground strains had been tensile rather than compressive there would have been a significant increase in reinforcement tension above that produced by the self-weight forces imposed by the structure.

It is apparent on the basis of the results presented in Fig 2 that the superposition of opposing tensile and compressive strains would induce a smaller compressive force than would occur if the strains were additive. Thus tensile strains in both the soil and reinforcement would have resulted in tensile forces of much greater magnitude than the compressive values observed. A limitation to the magnitude of this tensile force would occur when the fully mobilised shear strength at the interface was attained as slippage would then take place. Therefore, to reduce the

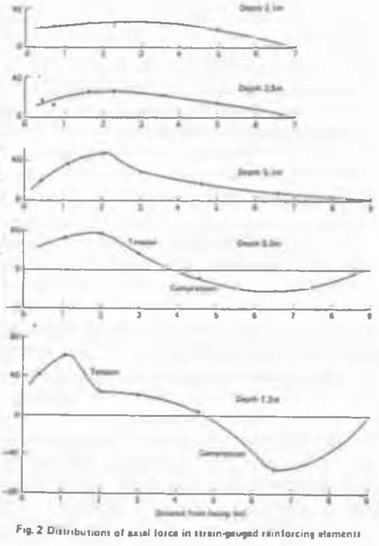


Fig. 2 Distributions of axial force in strain-gauged reinforcing elements

| LOCATION | STRUCTURE DATE BUILT | HEIGHT (m) FACE AREA ($m^2$) | REINFORCEMENT, FACING | MINING ACTIVITY | GROUND MOVEMENTS - MEASURED / (ESTIMATED) | | |
|---|---|---|---|---|---|---|---|
| | | | | | SETTLEMENT (mm ) | GROUND STRAIN TENSILE (mm/m ) | COMPRESSIVE (mm/m ) |
| FREYMING FRANCE | ABUTMENTS carrying deck over railway and road 1975 | 14m<br>4,000$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Collapse of pillar and stall workings of coal mine | >300 | 2 | 2 |
| | WALL retaining interchange Slip road 1975 | 6m<br>300$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Collapse of pillar and stall workings of coal mine | * | 2 | 2 |
| | ABUTMENTS carrying deck over road 1975 | 7m<br>600$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Collapse of pillar and stall workings of coal mine | >450 | 2 | 2 |
| LONGWY FRANCE | ABUTMENTS carrying road over road 1984 | 14m<br>2,000$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Iron ore mines at 60m depth 20% residual settlement to occur | (300 to 500) | Deckjoints to allow for 150mm lateral movement in 35 metre open span. | |
| | ABUTMENTS carrying road over road 1986 | 8.0m<br>500$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Iron ore mines at 60m depth 20% residual settlement to occur | (300 to 500) | | |
| OXCROFT DERBYSHIRE ENGLAND | WALLS coal disposal plant for colliery | 5-7m<br>490$m^2$ | Polymeric strip (Paraweb), T section concrete (Discrete panel) | Longwall coal mine; 3 seams 1980, 1986, 1987 | 75 - 100<br>25 - 50<br>100, Max 250 | 1<br><1<br>1 | 0<br>0<br>0 |
| FAIRBURN YORKSHIRE ENGLAND | ABUTMENTS 45° sloping face | 2.5m | Polymeric Fabric (Terram RF12), Wraparound fabric facing, concrete block on face | Longwall 1 seam | 1360<br>(Ground Slope 1 in 80) | 3 | 5 |
| CRUSNES FRANCE | WALL retaining national road 1981 | 5.0m<br>300$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Collapse of pillar and stall workings | 500 | | |
| CARVIN FRANCE | ABUTMENT motorway 1975 | 6m<br>200$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Coal | | | |
| MORSBACH FRANCE | 3 WALLS retaining 1971 | 10.5m<br>1,000$m^2$ | High adherence galv steel strip, Cruciform Concrete (Discrete panel) | Collapse of pillar and stall workings of coal mine | | 2 | 2 |

* 600mm due to compressible foundation followed by 600mm of subsidence (wall then flooded).

Note: Where no ground movement is given this is due to lack of precise detail and does not imply no movement.

TABLE 1 Summary of results from survey of reinforced soil structures on areas of mining subsidence

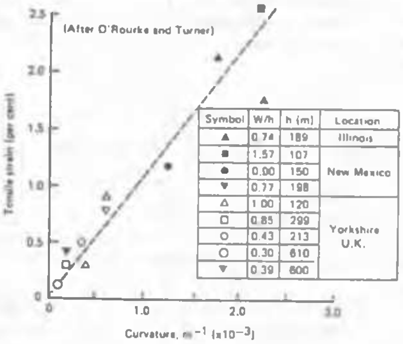


Fig.3 Horizontal tensile strain versus convex curvature for U.S. and U.K. Longwall Panels

possibility of rupture of the elements in these circumstances, ideally, the available tensile strength of the elements should be greater than the limiting pull out force or shear resistance at the interface.

O'Rourke and Turner (1981) have correlated field measurements of horizontal tensile strain with maximum convex curvature based on differential settlement observations (Fig 3). These results confirmed that the position of maximum strain and maximum curvature corresponded. Finite element analyses have been carried out to provide further data on the influence of ground curvature on structural behaviour. As input to the analysis curvature was simulated by ground strain. A summary of the results is presented qualitatively in Table 2 and contrasts the behaviour of reinforced soil and conventional cantilever retaining walls for convex and concave ground curvatures with the axes of the troughs running in a direction both parallel to, and normal to, the wall or facing.

It is emphasised that the comparison in Table 2 was based on rather extreme assumptions concerning curvature to allow the trends of behaviour to be more clearly defined. It is unlikely that these values would occur in practice, particularly in the case of the axis of the subsidence trough running parallel to the facing, as the relatively narrow width of a reinforced soil wall will greatly limit the differential movements which can take place over this width. However, even on this basis it is apparent from the table that a reinforced soil structure generally offers the best solution. The only case where this system may encounter serious problems occurs when the axis of the subsidence trough is parallel to the facing and produces a 'hogging' mode of curvature in the reinforced backfill. For this case the finite element analysis indicated that a tensile strain of 1% would increase the tension in the lower part of a structure by a factor of between 2 - 3, depending particularly on the conditions at the reinforcement interface. The effect of the tensile strain gradually reduced at higher levels and the increase in tension at the top of a typical height of structure would be quite small. Note that to ensure that the results from a finite element analysis are realistic, a limit must be imposed on the shear strength at the interface between the reinforcement and soil. Once this strength is exceeded, slippage occurs preventing further increases in tension at a particular location.

The recent survey of reinforced soil structures (Table 1) indicated ground strains of the order of 0.3%, i.e. 3mm per metre. These are much smaller than the value of 1 per cent employed in the above analysis. Preliminary finite element analyses using a value of 0.3% strain suggest that the increases in tension induced would be about 50% above the normal working condition. Further studies on this topic are currently in progress at TRRL.

A point of particular importance which must be considered for all types of structure is the influence of large tensile strains on the backfill and foundations soils. These strains could seriously impair their strength if they are sufficient to produce a reduction in density which induces the post-peak phase of the strength versus strain relation. To avoid difficulties in such circumstances it would be prudent to employ a friction angle for the soil

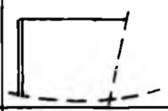
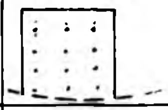
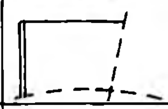
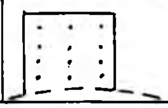
| Curvature of ground | Direction of axis of subsidence trough | Cross-section and front elevation of structure | Effect on conventional wall | Effect on reinforced soil wall |
|---|---|---|---|---|
| Convex ground surface | Parallel to wall or facing |  Cross-section | Increase of pressure could seriously damage the wall unless special precautions are taken. | Increase in pressure should not pose any problems as slippage of reinforcement will alleviate forces. |
|  | Normal to wall or facing |  Elevation | Damage to wall unless sliding joints are included.<br>Problems of serviceability likely. | No particular problems with moderate ground strains. Sliding horizontal and vertical joints with large strains. |
| Convex ground surface | Parallel to wall or facing |  Cross-section | No particular pressure problems as active condition induced. Cracking of backfill may occur. | Increase in tensions particularly near the base. Cracking of fill should be less of a problem. |
|  | Normal to wall facing or |  Elevation | Damage to wall unless special precautions taken. Problems of serviceability likely. | No particular problems with moderate strains. Special joints needed for large strains. |

TABLE 2 Influence of ground curvature on behaviour of conventional and reinforced soil structures

corresponding to the critical state strength (Atkinson and Bransby, 1978).

Although the results of the finite element analysis in Table 2 suggest that tensile strains behind a conventional wall will have little effect, in practice there may be cracking of the backfill allowing the ingress of water, particularly if the material is partially cohesive. With unreinforced backfills such cracks are likely to be localised and would therefore be large. In contrast, reinforced backfill will tend to induce greater uniformity of strains so that any cracking may be limited to a number of small cracks or may even be prevented.

## 4. GROUND MOVEMENT EFFECTS IN RELATION TO GEOMETRIC CONSIDERATION

Finite element analyses based on linear elasticity considerations have been also employed to investigate the relation between tensile strain and the geometry of a reinforced soil retaining wall and its foundations. The study, which was carried out in France for the Reinforced Earth Company, involved an examination of the damping effect on the tensile strains produced by different thicknesses of foundation soils separating a reinforced soil wall from rock strata. The elastic properties of the subsoil were assumed to be 30MPa and 0.33 for Young's modulus (E) and Poisson' ratio ( $\nu$ ) respectively. The results of the analyses indicated that very significant attenuation of the strain occurred even with a relatively thin foundation layer. It was also apparent from the results that the behaviour was insensitive to increases in the ratio of depth of soil strata to width of wall above 1/3 as thereafter the strain at the base of the wall remained at about 15 per cent of the value in the rock strata.

It should be noted that the assessment was carried out employing a rather unrealistic soil model which permitted tensile stresses to be developed. It may be that the use of a better soil model which prevented such stresses would show even more rapid attenuation as a consequence of density reduction and particle separation. In essence the analysis provides an indication of the dampening effect on strains induced as a consequence of widely dissimilar elastic properties between two layers of material and the results could be considered equally applicable to structures other than those of reinforced soil.

It is evident that the size of a structure will play an important role in regard to the effect of ground movements since small structures will be generally subjected to less differential movements over their length than large structures. Thus, as is apparent from Table 2, the range of ground strains and curvatures which a reinforced soil structure has to resist is much greater when the axis of the subsidence trough is normal to the facing because of the greater length of the wall in this direction compared to its width. It is reasonable to assume as a rough guide that the magnitude of imposed forces resulting from mining subsidence will be proportional to the geometry of the mine workings and over-lying strata. Small structures are therefore likely to be affected mainly by shallower workings.

Although the inherent flexibility of reinforced soil structures avoids many of the problems encountered by more rigid conventional structures in areas of mining subsidence, difficulties can occur where long lengths of wall are constructed using concrete facing panels. Such panels permit considerable articulation without damage because of the compressible jointing employed between adjacent units but excessive movements could introduce problems unless special precautions are taken.

In assessing the influence of structural length on possible distortions induced by ground movements consideration must be given to both ground strain and ground curvature. Fig 4 shows the separate effects of these two components of distortion for both concave and convex modes of ground curvature. The total distortion of the structure shown in the figure, which may be regarded as the front elevation of a length of reinforced soil retaining wall, is obtained from the sum of the distortions in the upper and lower diagrams for the appropriate form of curvature.

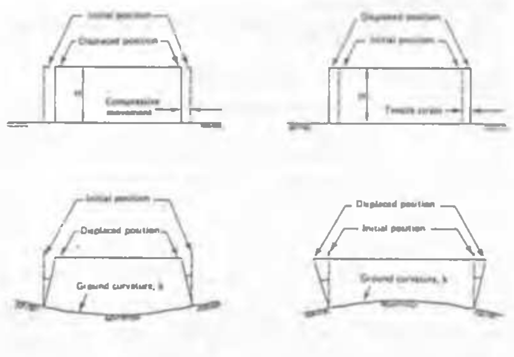


Fig.4 Structural response to horizontal strain and curvature at ground surface

A method of determining the magnitude of the strain at the top of a wall ($\epsilon_t$) can be obtained from considerations fo the geometrical relations between curvature and wall height for a particular strain at the base ($\epsilon_h$). It has been previously pointed out that ground curvature ($\kappa$) and ground strains are related and an empirical expression has been proposed by Ewy and Hood (1984) linking these two quantities:

$$\text{i.e. } \kappa = k\epsilon_h^n \text{ .............(1)}$$

The values k and n are constants determined from field data and studies have indicated that k may range between 0.049 and 0.482 for both concave and convex curvature (Ewy and Hood, loc. cit.) the data given by O'Rourke and Turner (1979) in Figure 3 produces a good correlation and a value of k equal to 0.11. Studies have also indicated that the exponent term(n) is frequently unity.

On the basis of Equation (1) and assuming uniform curvature, it can be shown from simple geometry considerations that the increase in strain at the top of a structure which includes the effects of both ground strain and curvature is given by :

$$\epsilon_t = \epsilon_h + 2H\tan\alpha/L \text{ .......(2)}$$

Where $\alpha = {}^1/_2$ the angle subtending the curvature of the ground. The values of $\alpha$ and $\kappa$ are related by the expression:

$$\sin\alpha = \kappa L/2 \text{ .............(3a)}$$

**and for small angles :**

$$\tan\alpha \simeq \sin\alpha \simeq \alpha = \kappa L/2 \text{......(3b)}$$

Substituting the expressions for $\tan\alpha$ and $\kappa$ given by Equations (3b) and (1) respectively in Equation (2) produces the following relation after assuming a value of unity for the exponent term :

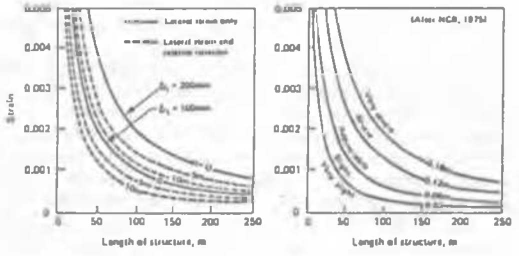
$$\epsilon_t = \epsilon_h(1 + kH) \text{............(4)}$$

Clearly the sign of $\epsilon_t$ is determined by that of $\epsilon_h$. Equation (4) can be solved if a value of K is selected. The equation indicates that, for a given condition, the strains induced are dependent on the height of the structure and the ground strains as might be expected. As the ground strains are themselves controlled by curvature and affected length of structure, the above equation may be recast to consider the influence on ground strain of specific displacements ($\delta_t$) at the top of a structure, for different heights and length:

$$\text{i.e. } \epsilon_t = \frac{\delta_t}{L(1 + kH)} \text{ .........(5)}$$

The results of the analysis (Jones and O'Rourke, 1988) are presented in Fig 5 together with empirical relations published by the National Coal Board (1975) in relation to damage to masonry structures. It can be seen from figure 5b that for moderate strains, i.e., as occurs with the upper criteria for the CLASP system of school buildings and also those found in the vicinity of the reinforced soil structures in Table 1, the effect on even a rigid structure of small dimension (less than 10m) is "very slight" and could be expected to be even less with reinforced soil structures.

It is apparent from the figure that the analytical trends based on Equation 5 conform reasonably well with the empirical data. The results also confirm that the length of a structure is an important criterion as shown by the fact that relatively small ground strains can inflict severe damage to longer length structures. To accommodate large strains which would damage facing panels, therefore, joints capable of vertical and lateral movement should be incorporated in the facing at 10m-15m intervals along the length of the wall. It should be noted that the distortion of a relatively rigid structure as described above does not apply to the crossection through a reinforced soil structure as the particulate nature of the soil imposes a different mode of deformation. Any tendency to expand or compress the soil as indicated in the lower diagrams of Fig 4 would result in the development of active and passive states with shear planes and associated shear strains (Fig 6).This to a large extent explains why ground strains at the base of a reinforced soil structure has a diminishing effect towards the top.



a) Analytical trends

b) Empirical relationships

Fig.5 Relationship between strain and length of structure for various levels of deformation

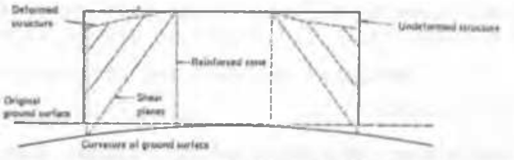


Fig.6 Influence of ground curvature on deformation of reinforced soil structure

## 5. CONCLUSIONS

1. Because of their flexibility, reinforced soil structures appear very suitable for areas of mining subsidence but there is little in the way of published data on the performance of these structures in such conditions. Several published papers are available relating to the behaviour of reinforced soil structures constructed on compressible foundations and although the differential settlements obtained are of similar order to those which would occur with mining subsidence, the lack of horizontal strain data which would be induced by the passage of a mining wave, renders these studies less appropriate. A recent survey of reinforced structures in the United Kingdom and France carried out on behalf of the Department of Transport has identified a limited number of reinforced soil structures which have been subject to mining subsidence and although comprehensive details of their behaviour were lacking, all indications were that they behaved well with no signs of distress. There is clearly a need for comprehensive studies of the behaviour of reinforced soil structures in areas of mining subsidence.

2. Ground strains are an important consideration in the design of reinforced soil structures and it could theoretically be expected that such strains may increase the reinforcement tensions. However it is not clear as to the magnitude of the strains induced in a structure as a result of the ground strains in the vicinity. Although tensile ground strains up to 2% have been induced by modern mining techniques in some types of structure other than reinforced soil, the recent survey indicated generally much smaller values of the order of 0.3% in the vicinity of reinforced soils structures which showed no signs of distress. An assessment of the influence of horizontal strains by the finite element method suggested that the worst condition would arise as a result of hogging curvature when the mining subsidence trough runs parallel to the facing. However, rather extreme values of curvature were assumed which would occur very rarely, if at all.

3. Geometrical considerations play an important role in relation to the influence of ground strains on the performance of a structure. A parametric study using the finite element method demonstrated that the thickness of soil separating the structure from underlying rock strata had a strong influence on the magnitude of the horizontal strains transmitted into the structure. It is the size of the structure which can be shown to be of primary importance with respect to damage although most reinforced soil structures are long rather than wide. In the longitudinal direction there is no structural continuity except for the facing which usually exhibits a degree of strain compatibility. This can be further enhanced using constructional techniques, typically employing vertical movement joints. In the lateral direction the relatively small length of the reinforcements tends to reduce the influence of ground strain.

## 6. ACKNOWLEDGMENTS

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