Geosynthetics: Applications, Design and Construction, De Groot, Den Hoedt & Termaat (eds)
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The use of geosynthetics to prevent the structural collapse of fills over areas prone to subsidence

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ABSTRACT: The consequence of subsidence beneath fills can range from a mild serviceability loss to total structural collapse. Over the last 15 years geosynthetics have been used increasingly to prevent the collapse, and control the deformation, of earth fills constructed over subsidence-prone areas. Recent design procedures adopt the limit state principle whereby the ultimate limit state is associated with collapse due to tension membrane rupture or band failure. The serviceability limit state is governed by tension membrane stiffness and void geometry. A number of examples of the use of geosynthetics for this application are also presented.

1. INTRODUCTION

Subsidence is the lowering of the ground following underground extraction or removal of an ore body either resulting from mans activity or as a result of natural causes. Two types of subsidence can be identified - continuous and discontinuous.

Continuous subsidence involves the formation of a relatively smooth surface subsidence profile free of step changes. The resulting displacements of the surface may be of only elastic orders of magnitude when compared with the dimensions of the mining depth. This form of subsidence is usually associated with the extraction of thin flat dipping ore bodies overlain by weak non-brittle sedimentary strata. The longwall mining of coal typically produces this form of subsidence, Figure 1.

Discontinuous subsidence is characterised by large surface displacements over limited areas and the formation of steps or discontinuities in the surface profile. This form of subsidence results from a number of mining methods including those used either currently or in the past, Figure 1. The incidents of discontinuous subsidence of these forms are widespread and in areas are growing. Subsidence involves a range of mechanisms which may develop suddenly or progressively and can occur at a range of scales. In the United Kingdom interest is centred on surface subsidence associated with the development of crown holes or solution cavities, and subsidence resulting from active longwall workings, the collapse of old workings and the sudden collapse of abandoned mine shafts. The latter often replicate the effects of chimney caving, Figure 1(b).

Old workings can fail in a number of ways including pillar collapse which results in subsidence in the form of crown holes. The surface damage in the mining region of Northern Pennsylvania in the United States is due to the development of crown holes over abandoned old mine workings. The most catastrophic failure of this type was recorded in 1960 in South Africa when a room and pillar mining area covering 3km^2 collapsed with a loss of 437 lives, Bryan et al (1964). The chimney collapse in the Mufulira mine disaster in 1970 in Zambia caused 89 deaths, Commission of Enquiry (1971). The collapse of old mine shafts in parts of the United Kingdom is recognised as a major hazard, Kempton (1992).

In the past, the social costs of mining were accepted as the norm whilst buildings and structures were sufficiently small and flexible that the effects of mining subsidence could be tolerated or avoided by sterilising the appropriate area for mining purposes. Modern mining methods, which require major capital investment and mechanisation, make this

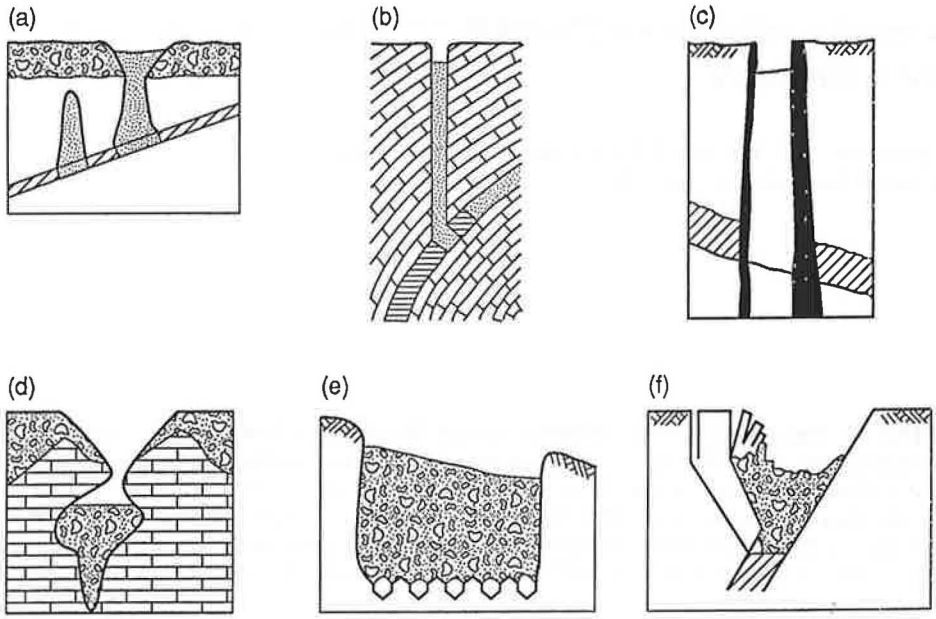


Figure 1 Discontinuous subsidence;
(a) crown hole; (b) chimney caving; (c) plug subsidence;
(d) solution cavities; (e) block caving; (f) progressive hanging wall caving

approach prohibitively expensive. At the same time, the increase in population and the development of the infrastructure has produced conditions where the collapse of old workings or the migration of subsurface voids to the surface can have significant detrimental effects on human safety and result in extensive and costly remedial works.

In some countries the development of sinkholes has resulted in damage on a national scale and the areas prone to the development of sinkholes pose particular problems, particular to highways and railways. Sinkhole development can be on a large scale, at Fenjuxu in Yulin County, China, over 400 sinkholes developed between 1980-1988 due to drought and lowering of the water table, Ministry of Geology and Mineral Resources (1983). In other cases sinkhole development can result in complete destruction of transportation facilities, Bonaparte and Berg (1987). Similar void formations at the surface can be caused by soil liquefaction resulting from earthquake.

2. IDENTIFICATION OF DESIGN PROBLEM

The presence of old workings or subsurface voids has a significant influence on the design of new highways. Investigations to establish the possibility/probability of their existence forms an essential part of the geotechnical investigations of any project.

Highways placed in cut can be particularly vulnerable as the development of the cutting has the effect of reducing the overburden over any old workings or void. Previously stable conditions can become unstable. The construction of embankments or fills can also increase the chance of subsidence. The influence of the effects of the migration of a void to the surface is difficult to predict and depends upon the height of the embankment, the material forming the embankment as well as the size of the void and where it develops below the embankment.

When undertaking the initial feasibility studies for any highway or building project the possibility of the occurrence of discontinuous subsidence should be identified. Once it has been established that subsidence of this nature is a possibility then an evaluation of the potential risk represented by the subsidence is required and possible countermeasures identified. In the case of a highway scheme the main consideration is the safety of the public followed by the development of the most cost effective solution. Decisions regarding safety need to consider the degree of risk presented by the potential hazard and the level of risk that is deemed acceptable. This has to be balanced against the cost of reducing the level of risk and the legal responsibility of the designer or owner in terms of their duty of care.

The assessment of hazards represented by subsurface voids is primarily concerned with the risk to life. In many cases the unexpected occurrence of a void at the surface is potentially very dangerous and precautions to prevent disasters are necessary. The risk of financial loss can be of secondary concern, although the loss of serviceability such as disruption of the riding quality of a highway is serious in that a consequence of this could be an accident. An often quoted acceptable level of risk in respect of loss of life is an annual probability of 1 in 1,000,000. If the probability of an event occurring is greater than this, preventative or remedial action is usually required.

Preventive or Remedial Works

The strategy available to prevent or ameliorate the effects of subsurface voids falls into three general areas:

i. Ground Support Techniques
ii. Ground Modification Techniques
iii. Construction Techniques, Figure 2

The method chosen depends upon the extent of treatment required and the nature of the hazard. The use of ground modification techniques might be possible to justify in localised areas but are unlikely to be used in association with a highway scheme. The most common techniques are probably associated with ground support, with the most usual being the use of stowing and grouting. The use of special foundations can be classified as a construction technique. With the introduction of high strength polymeric materials, these techniques can be shown to be economic.

The method selected to reduce the risk of subsurface void influencing any construction depends largely on environmental considerations and cost. Some stabilisation techniques can be very expensive, being a reflection of the fact that they are specifically associated with large areas or large volumes of material. The use of grouting techniques, which has been the favoured method, can be expensive with equivalent costs ranging from £17 - 58 per cubic metre of working. The main advantage of grouting is its simplicity and the fact that treatment can be restricted to relatively small areas. However, grouting is not an option in some conditions, particularly in the case of sinkhole development or when detailed records of past mining activities are unavailable. In addition where the problem is widespread grouting is often expensive when compared to the use of tension membranes based upon the use of high strength geosynthetic materials.

Once it has been decided that the use of reinforcement acting as a tension membrane presents

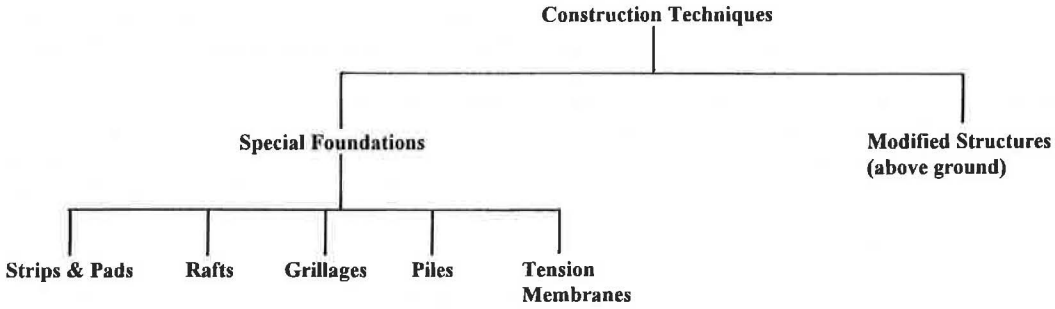


Figure 2

a suitable solution the problem of the design of an earth structure over a void can be subdivided into two categories:

i) design to resist complete collapse into the void while accepting loss of serviceability.

ii) design to limit deformations so as to maintain serviceability of the structure over the void.

The two categories are dependent upon the size of the potential void. In the case of large voids (≥ 10m) the reinforcement can be considered to be providing a safety role and the reinforcement function is to prevent a catastrophic situation, the *ultimate limit state* for collapse, occurring with a potential risk to life. In this case the support of the road would be required for a matter of hours until the void had been backfilled or the structure repaired.

The second category of design occurs when the void is relatively small (typically 2-5m), in this condition the reinforcement material has to have sufficient strength and stiffness to support the structure within the required *serviceability limits* for the life of the facility. In the case of a highway embankment the life of the facility is typically assumed to be 60 years.

The ability of any reinforcing material to fulfil the reinforcement function depends upon the size of the void to be bridged, the nature and height of the earthfill supported by the reinforcement together with any surcharge loading and the serviceability limits specified. Current practice in the United Kingdom is to limit differential surface deformations to 1 per cent for motorways and trunk roads and to 2 per cent for lower class roads, BS8006 (1995).

3. ANALYTICAL METHODS

Current methods of design of tension membranes adopt a conservative approach, due to the uncertainties involved and the simplicity of the analytical techniques employed. The soil and reinforcement are assumed to be resting initially on a firm foundation. With the development of a void under the reinforcement the overlying soil deflects into the void. The deflection of the soil layer generates arching within the soil above the reinforcement and the load in the reinforcement over the void is less than the theoretical weight of the soil above the void. Deflection of the reinforcement into the void mobilises part of the reinforcement strength and the material will act as a tension membrane supporting loads normal to the plane. As a result of the reinforcement straining two limit states cases can be considered:

i) ultimate limit state where the soil-reinforcement system fails either by rupture of the reinforcement or lack of soil/reinforcement bond

ii) serviceability limit state where the soil-reinforcement system deflects an amount governed by the geosynthetic stiffness and fill/void geometry.

Analytical techniques used for design have until recently been based upon limit equilibrium methods involving conservative factors of safety using arching theory, tension membrane theory or combined arching and tension membrane theory or continuum models, Giroud et al (1988), Lawson et al (1994). The recent BS8006 (1995) is a limit state code based upon the identification of risk. In this it is compatible with the overall design concept involving geosynthetic reinforcement of fills over voids. BS8006 1995 uses a tension membrane approach but continuum methods of analysis can also be used in the limit state model.

The ability of continuum methods to model the behaviour of a reinforced fill to bridge a void is demonstrated in the numerical analysis of the Ripon Bypass. FLAC (Fast Lagrangian Analysis of Continua), a finite difference based software, uses a dynamic relaxation algorithm that is best suited to ill-behaved systems associated with material and geometric non-linearity, large strains or where physical instability is anticipated. Although FLAC is aimed at providing a static solution to a problem, dynamic equations are included in the mathematical formulations. This procedure first invokes the equation of motion to derive new velocities and displacements for stresses and forces. The strain rates are then obtained from velocities and new stresses from strain rates.

The geosynthetic reinforcement was modelled as a series of bar elements that possess a tensile stiffness only. The fill on the other hand was represented by a Mohr-Coulomb formulation that uses a shear yield function and a non-associated flow rule. The solution procedure consisted of setting the initial geostatic stresses prior to the formation of the void by allowing the fill to equilibrate under its own gravitational force. The void was then formed and the problem stepped to equilibrium.

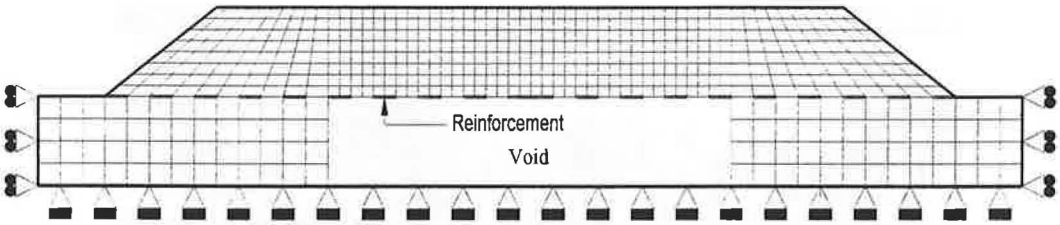


Figure 3

A typical finite difference grid used in the numerical analysis of the Ripon Bypass is shown in Figure 3 which depicts the case where a well defined rock stratum lies beneath the geosynthetic reinforcement. In this instance the arching in the fill above the reinforcement will be a maximum. The rotation of the major principle stress due to the arching in the fill is shown in Figure 4.

4. CASE STUDIES

A61 Ripon Bypass

The area around Ripon in North Yorkshire has for many years been subjected to major subsidence events caused by the underground erosion of layers of gypsiferous marls by groundwater flow. Large interconnected cave systems exist which, from time to time, suffer collapse as roof spans become too large. In time these subterranean movements progressively migrate towards the ground surface, eventually causing subsidence which can, in some cases, be extensive both in size and in terms of the effect on people and facilities. The A61 Ripon Bypass passes through such an area.

A number of possible solutions to the problem of supporting the bypass over the area prone to subsidence was considered. More commonly used grouting techniques were rejected,

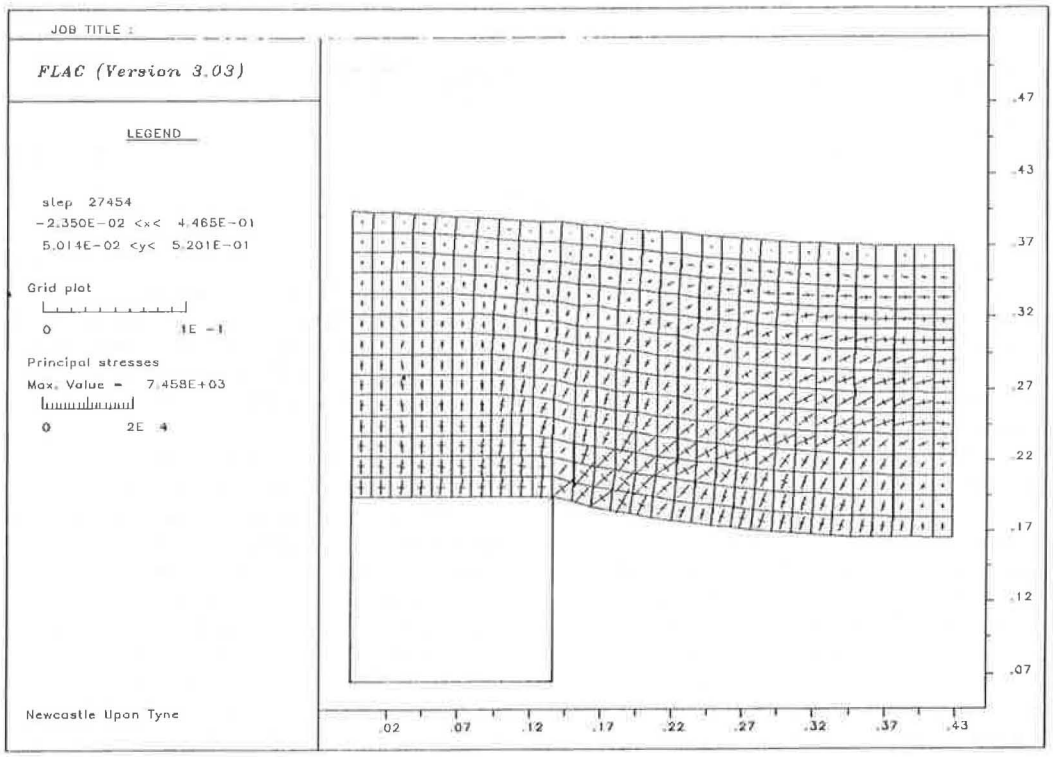
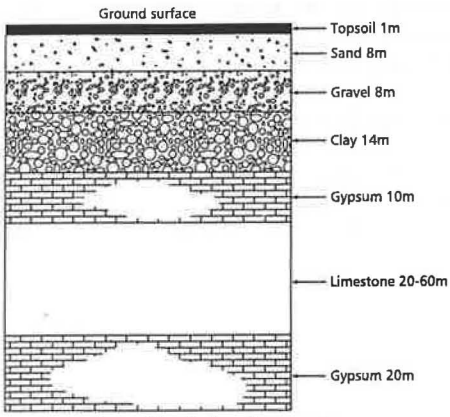
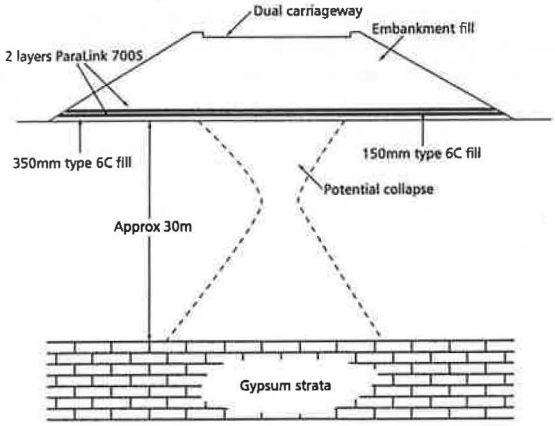


Figure 4



Geological profile of the Ripon area



Design cross section through reinforced embankments

Figure 5

not just because of the prohibitive cost, but also because the continued presence of the eroding groundwater after grouting would ensure that the problem would not be eliminated but merely transferred to another location. A solution using tension membranes was finally adopted as being cost effective and secure against catastrophic collapse.

The possible size of future subsidence events made the long term support of the bypass after a collapse a prohibitively costly option. For this reason the design brief was limited to the need to ensure that the road would be supported for a sufficient length of time to enable remedial measures to be put in hand. The tension membrane was called upon to provide support to the road embankment for at least a 24 hour period during which the danger area could be identified and isolated and maintenance measures devised.

The ParaLink 700S and 325S tension membrane material were designed using a FLAC model of the embankment and the anticipated void geometry. The design solution is illustrated in Figure 5 and the laid ParaLink is illustrated. The work was carried out in 1994 and 1995.

Prestons Road flyover, East London

The construction of embankments on very weak soils where settlement of the embankment is not acceptable can be achieved using construction techniques, Figure 2, such as embankments over piles supported on tension membranes. Construction of new roads in the Docklands area of East London is characterised by the need to deal with the relatively poor ground conditions which exist and the necessary sensitivity which has to be exercised in dealing with earlier construction, much of it historic in nature.

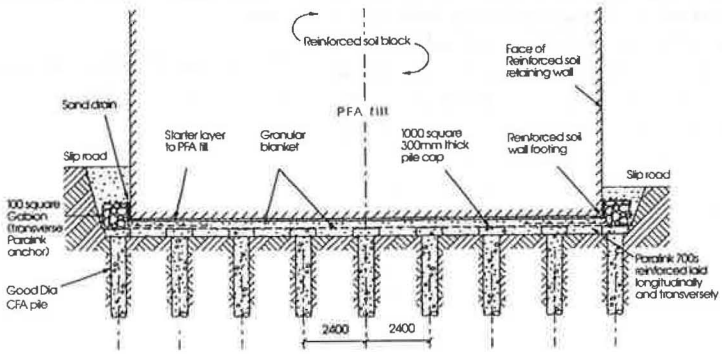


Figure 6

The stratigraphy of the area is typically a layer of made ground about 3-4 metres thick overlying recent alluvium, usually between 2-4 metres thick. Beneath the alluvium is commonly a 3-5 metre layer of river terrace deposits overlying some 10 metres of London Clay down to the dense silty sands of the Woolwich and Reading Beds.

The Prestons Road flyover carries part of an important dual-carriageway road running from the City of London out into the developed Docklands area including to the City Airport. At the flyover the road is carried over a roundabout under which lies the historic Blackwall Tunnel, built in 1868 to carry horsedrawn traffic under the River Thames. Now, of course, the tunnel is an important route across the river for all classes of heavy traffic. A major requirement of the eastern approach ramp to the flyover, and indeed the flyover itself, was that it should not add any additional loads to the historic tunnel. Land was also limited on either side of the flyover and retaining walls were necessary for this reason.

The solution adopted to meet these requirements was to contain the road embankment within reinforced soil walls supported on high strength geosynthetic materials laid over bored piles. The pile spacing varied relative to the embankment height. To keep the embankment loads down the fill chosen for the approach ramps was power station fly ash. Although light in weight such fills can be chemically aggressive and this had an influence on the selection of the geosynthetic material to carry the embankment loads into the piles.

A typical section and illustration through the approach ramps is shown in Figure 6. The ParaLink 700S tension membrane material is shown laid in both longitudinal and transverse directions. In the latter case the ParaLink is anchored by wrapping it round a stone filled gabion basket at each side to prevent the horizontal earth pressures from the embankment imposing horizontal outward forces on the outermost rows of piles. Also shown is the ParaLink being laid over the pile caps under what

would subsequently become the approach ramp. The construction was carried out in 1991/92.

A13 Rainham Marshes

Further to the east of London from the Blackwall Tunnel, the A13 Trunk Road, which passes the entrance to the Tunnel on the north side of the River Thames, is being reconstructed along a new alignment over marshland at Rainham in Essex. Here the road is being constructed over large depths of soft alluvial material and some contaminated land. In order to avoid long term settlement of the road embankment, in particular in locations where the road rises up to pass over flyovers, the embankments are constructed on driven piles overlaid with ParaLink tension membrane materials in both transverse and longitudinal directions. A variety of grades of ParaLink are being used from 500S up to and including 1250S for the highest embankments.

The design of the tension membrane materials was carried out using the simple principles of behaviour of high embankments over positively projecting conduits (Spangler and Handy). Subsequently the adequacy of the designed tension membranes was checked using continuum methods as described earlier in this paper.

Installation of the tension membranes started in 1994 and is expected to continue until late 1996.

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