Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Design method for geosynthetic as reinforcement for embankment subjected to localized subsidence

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ABSTRACT: For combating the risk of accidents due to localized sinkholes under road and railway embankments, these structures are reinforced with geosynthetics. The paper give the main results get from a wide-ranging experimental program (full scale tests). Based on these observations, we propose a design method, which gives geosynthetic stiffness and tensile strength for serviceability criteria.

1 INTRODUCTION

The presence of underground cavities in certain development areas creates the risk of subsidence, seriously affecting the use of infrastructure and threatening the safety of users. Because of the difficulty in locating small-diameter cavities at moderate and great depths and the changing and unpredictable nature of subsidence phenomena, recent research has concentrated on finding preventive reinforcement solutions so that when a sinkhole occurs under an embankment, the infrastructure can continue to be used in acceptable conditions until more extensive repairs can be carried out.

With this in view, a solution involving geosynthetic reinforcement was proposed, especially to prevent the risk of accidents connected with the existence of small-diameter cavities (maximum diameter of the order of 4-5 m). In the event of the ground subsiding under an embankment, the aim was to limit surface deformation to acceptable levels, so that traffic could continue to circulate until permanent repairs were carried out.

A research programme entitled RAFAEL (Renforcement des Assises Ferroviaires et Autoroutières contre les Effondrements Localisés – Reinforcement of Railway and Motorway Foundations against Localised Subsidence) was launched by a number of French industries and research organisations. Full-scale tests on motorway and railway structures were performed (Gourc et al, 1999, Giraud, 1997). The aims of this programme were to test the efficiency of the proposed reinforcement solution, to determine the mechanisms occurring around the point of failure of the reinforced structures and to present reference tests for determining a design method. Because of this, the tests do not correspond systematically to the design of a working structure, as the strain values considered here are often greater than the permissible deformations for a structure in service.

2 FULL-SCALE EXPERIMENTS

2.1 *Basic geometry*

The experiments involved cavities 2-4 m in diameter, reinforced by one or two sheets of geotextile and positioned under the roadway or tracks at a depth H of 1.5 m. The cavities were filled with clay beads. Suction pipes were installed in each cavity to remove the clay beads and initiate subsidence in the overlying fill material. The road experiments (Fig. 1) were performed directly without surfacing on the road bed in order to gain a more accurate idea of the phenomena connected with localised subsidence. In the case of the railway experiment (Fig. 2), a conventional railway structure (with ballast, concrete sleepers and rails) was built to enable trains to circulate. When the overlying fill did not subside on emptying the cavity, trafficability tests were performed by driving lorries or trains over the structure.

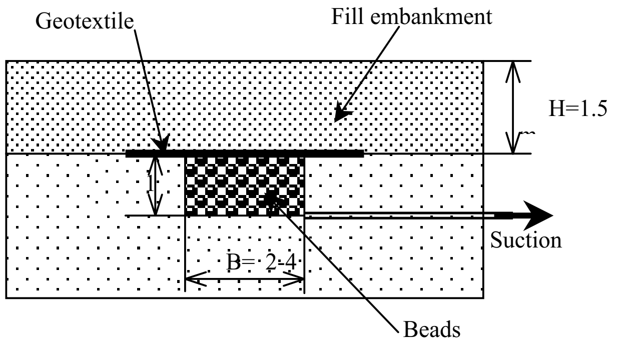


Figure 1. Geometry of the motorway experiment (SCET 1 to SCET 3 tests)

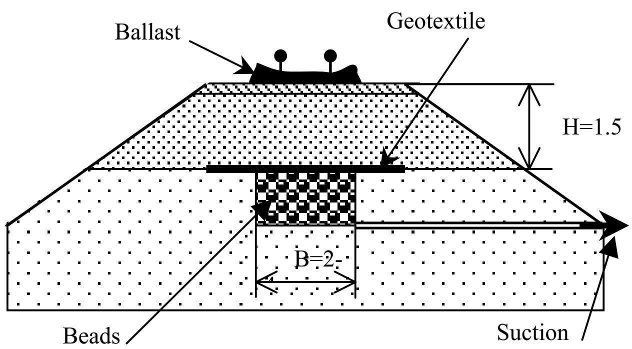


Figure 2. Geometry of the railway experiment (SNCF 1 to SNCF 4 tests)

2.2 *Fill material*

The fill material used in the experiments was alluvial sandy gravel with a grain size distribution of 0/300 mm and density γ of 21.1 kN/m^3. The mechanical characteristics of the fill were obtained by means of tests performed in a large (1 m x 1 m) direct shearbox. The internal friction angle φ and cohesion c of the material in its natural state (i.e. unsaturated, with a water content w = 6%) were estimated respectively at 38° and 40 kPa.

2.3 *Geosynthetic sheets*

The choice of geosynthetic was based on its membrane-type operation (i.e. the ability of the sheet to absorb forces perpendicular to its plane by tensile force after being deflected). The reinforcements used were one-directional geosynthetic sheets (non-woven sheets reinforced by additional threads in the direction of traffic), unrolled continuously in the direction of the road/track. The sheet was much wider than the diameter of the cavities (5.3 m for cavities of diameter B = 2 m and 7 m for those of diameter B = 4 m). Depending on the cases studied, one or two geotextile sheets of different tensile stiffnesses were used to be able to compare the results obtained. The main characteristics of the tests performed in the seven experiments (SCET 1 to SCET 3 for the road tests and SNCF 1 to SNCF 4 for the railway tests) are set out in table 1. J is the tensile stiffness of the textile in the direction of geosynthetic production (direction of reinforcement) obtained at 5% strain and T_f is the tensile strength. The tensile stiffnesses obtained in the transverse direction were much lower; they were 25 kN/m for all the geosynthetics tested.

2.4 *Trafficability tests*

After emptying the cavities, trafficability tests were performed whenever possible. A lorry loaded with 13 tonnes on the back axle was used for the road experiments. A French railways locomotive and traffic simulator (stabiliser) were used for the railway experiments. The stabiliser is used to apply a vibrating load to the rails. Each passage of the stabiliser produces fatigue in the ballast layer equivalent to 80,000 – 100,000 tonnes of goods.

2.5 *Instrumentation*

The aim of the instruments used in the tests was to measure strain and deflection in the geotextile sheet, as well as settlement at the surface and in the bulk of the fill material. The measurements were made on a continuous basis during the cavity emptying phase and during the trafficability tests.

Four vertical displacement sensors were anchored at the bottom of each cavity and fixed on the sheets used to determine the vertical sag displacement of the geotextile. Five strain gauges were fitted at different points of the geotextile sheet to measure local strain. Five cable-type displacement sensors were used to measure the elongation of the sheet and estimate strain by taking the difference between two measurement points. Topographical levelling measurements were carried out in the direction of traffic circulation and in the transverse direction in order to measure surface settlement.

2.6 *Experimental results*

The main results obtained during the experiments are set out in table 1 below. It should be noted that the experiments were performed in conditions close to the limit of failure of the reinforced structures and consequently the strain and deflection levels observed are often higher than those that would occur in a structure designed for normal service conditions.

Table 1. Main features and results of the field experiments (Characteristics and results of tests after traffic)

Type of test	B (m)	H/B	γ (kN/m^3)	J (kN/m)	T_f (kN/m)	d_s (m)	d_g (m)	Fill behaviour
SCET1	2	0.75	21.1	1818	200	0.0	0.22	Stable arch
SCET2	4	0.375	21.1	1818	200	0.2:	>0.6	Arch collapse
SCET3	4	0.375	21.1	3600	230	0.2:	0.48	Partial collapse
SNCF1	2	0.75	21.1	455	50	0.0	0.28	Stable arch
SNCF2	4	0.375	21.1	1818	200	0.1	0.51	Partial collapse
SNCF3	4	0.375	21.1	2x181:	2x200	0.1	>0.5	Arch collapse
SNCF4	2	0.75	21.1	1818	200	0.0	0.20	Stable arch

3 THE MECHANISM OF SUBSIDENCE

For a given cavity diameter, the experimental results are fairly homogeneous, irrespective of the type of test performed (road or rail). It was observed that a stable arch formed for cavities 2 m in diameter (H/B = 0.75) and the fill material completely collapsed on to the sheet either after the cavity had been emptied or during the trafficability tests in the case of 4 m cavities (H/B = 0.375).

These mechanisms are due to the same process of subsidence initiated at the beginning of the operation to empty the clay beads. The ground above the cavity is progressively separated from the fill and presses on the geosynthetic sheet. Under the weight of the ground pressing on it, the sheet is deflected and assumes the shape of a membrane. The subsidence mechanism then continues gradually throughout the emptying process and tries to progress towards the surface.

If the depth of the fill material H is small in comparison with the width of the cavity B, the subsidence will rise rapidly to the surface and lead to total collapse of the soil cylinder above the cavity (Fig. 3). The surface deflection d_s is then a function of the stiffness of the geosynthetic J (deflection d_g varying at the base of the collapsed soil cylinder) and soil decompaction capacity (variable increase in the initial volume of the soil due to dilatation when soil particles packing changes). The ratio between the dilated soil volume V_{sf} and the initial soil volume prior to decompaction V_s is called the expansion coefficient: $C_e = V_{sf}/V_s$. There are few experimental results available concerning the expansion coefficient C_e, but it is possible to obtain a coefficient C_e = 1.15 for fill materials.

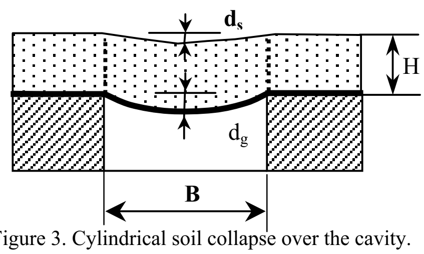
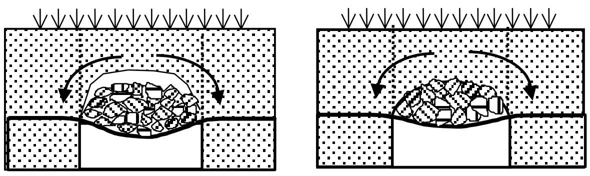


Figure 3. Cylindrical soil collapse over the cavity.

If the depth of fill H is large in comparison with the width of the cavity B, there is a progressive redistribution of forces in the fill that has not subsided and a soil arch forms, enabling the forces to be transferred to the edge of the cavity. The geosynthetic is deformed under the weight of the collapsed soil. Its membrane sag displacement frees a space ΔV_g that may be partly or totally filled by the increase ΔV_s in volume of the expanded soil: $\Delta V_s = V_{sf} - V_s = (C_e - 1)V_s$. If a gap remains between the arched surface soil and the expanded collapsed soil

(Fig. 4a), the subsidence mechanism may continue, for example following dynamic loading due to the passage of trains or lorries, and lead to a surface deflection as in the case of Figure 3. If the soil expands sufficiently, there is no loss of contact between the arch and the expanded collapsed soil (Fig. 4b); the arch may be considered stable and the subsidence mechanism stopped.



-a. A changeable stability arch -b. A stabilised arch
Figure 4. The various types of arch behaviours.

4 DESIGN METHOD

4.1 *Principle of the method*

The design criteria include first and foremost surface geometry criteria. Even after the embankment has subsided, a suitable level of traffic use must be guaranteed until the subsidence can be filled in.

To comply with professional requirements, a simplified calculation method has been developed (Blivet et al., 2001) from a combination of experimental and numerical studies. For the sake of safety, it is assumed that the fill above the cavity collapses completely, as in Figure 3. The design method involves successively evaluating:

- the loads acting on the geosynthetic sheet,
- the displacement of the geosynthetic sheet,
- surface displacements.
- Diameter B and surface deflection d_s are prescribed values.

4.2 *Evaluation of loads acting on the geosynthetic*

The maximum loads acting on the geosynthetic are produced by the collapse of the soil cylinder above the cavity and by possible surcharge p acting on the surface. This assumption, based on experimental considerations, differs from the calculation hypotheses recommended by British Standard Institution (BS 8006, 1995) which assumes that the area of ground affected by subsidence is funnel-shaped. Further studies were performed in addition to the first experiments of the RAFAEL programme (Blivet et al., 2000) using fill materials of very different types (sand, silt and ballast). The results obtained with this second series of tests confirmed the first results, namely that the area affected by subsidence is limited to the soil cylinder above the cavity, due to the presence of the geosynthetic. A comparison between the two calculation methods (RAFAEL and BS 8006) on a specific case from the RAFAEL experiment (Blivet et al., 2000) showed that this assumption strongly affected the design.

The calculation principle used to evaluate the load q acting on the geosynthetic sheet (Giraud, 1997, Villard et al., 2000) is derived from the limit equilibrium method originally developed by Terzaghi. This assumes that the soil immediately above the cavity collapses in the form of a vertical column between the adjacent soil masses, which remain stable. The frictional shear resistance created along the areas of slip opposes the displacement of the active soil mass, thus reducing the loads on the geosynthetic sheet. The equilibrium of the collapsed soil cylinder allows a relation (Equation 1) to be defined between the load q acting on the geosynthetic sheet and the applied loads (intrinsic weight and surcharge p). K is the coefficient of active pressure.

$$q = \frac{B\gamma}{4K\tan\varphi}\left(1 - e^{-K\frac{4H}{B}\tan\varphi}\right) + p\,e^{-K\frac{4H}{B}\tan\varphi} \qquad (1)$$

4.3 *Evaluation of geosynthetic sheet displacement*

The displacement of the geosynthetic sheet can be evaluated by studying its membrane-type behaviour. Simple analytical formulae have been developed for the membrane effect in the case of homogeneous and isotropic sheets and simple loading geometries: loads distributed vertically or perpendicular to the plane of the deformed sheet (plane or axisymmetrical case). These formulae can be used to evaluate the tensile forces and strains in geosynthetic sheets as a function of the applied load.

A numerical study based on the finite-element method (Villard et al., 1998) was performed to take into consideration the fibrous structure of geosynthetics: the sheet consists of non-woven fabric (uniform distribution of the fibres in the horizontal plane) and reinforcement in a given direction. The calculations consider large strains and enable any sheet geometry and load to be studied. A 3D parametric study of the membrane effect was carried out (Gourc and Villard, 2000), focusing on the influence of the geotextile structure. This enabled one economically important aspect of the project to be justified, namely that one-directional sheets (e.g. non-woven geosynthetic reinforced in a single direction) unrolled continuously in the direction in which traffic passes along the road or track are technically and economically the most efficient for this type of application as they are easy to manufacture and install, anchorage is guaranteed in the direction of the road or track and reinforcement is optimum compared for example with sheets (with the equivalent number of fibres) reinforced in two directions (direction of traffic and crosswise).

The analytical formulae proposed for the RAFAEL design method assume that the geosynthetic sheet is one-directional (i.e. strengthened in one particular direction) and that the load q acting on the sheet is uniformly distributed. Equation 2, obtained by writing the static equilibrium for a portion of sheet, establishes a relation between the maximum tensile force in the sheet T_{max} (T_{max} defined per metre of width), the load q, the maximum strain in the sheet ε_{max}, the stiffness of the geosynthetic J and the cavity diameter B. Equation 3, which is also derived from the static equilibrium of the sheet, enables the strain ε_{max} to be determined in the centre of the geosynthetic sheet for a known deflection d_g. Solving equation 2 for known values of B, q and ε_{max} enables T_{max} and J to be determined.

$$T_{max} = \frac{qB}{2}\sqrt{1 + \frac{1}{6\,\varepsilon_{max}}} = J\,\varepsilon_{max} \qquad (2)$$

$$\varepsilon_{max} = \frac{8}{3}\left(\frac{d_g}{B}\right)^2 \qquad (3)$$

4.4 *Evaluation of surface displacements*

When the soil is decompacted during subsidence, surface displacements are less than those observed at the level of the geosynthetic sheet (the space freed during deformation of the geosynthetic sheet ΔV_g being partly filled as a result of the increase in soil volume ΔV_s during decompaction). By assuming that the volume of surface subsidence and the volume freed by the membrane effect of the geosynthetic sheet are paraboloids of revolution, it is possible to establish a relation (Equation 4) between the surface settlement d_s, the maximum deflection of the geosynthetic d_g, the soil expansion coefficient C_e and the depth of the fill H.

$$d_s = d_g - 2H(C_e - 1)$$

4.5 *Design charts*

Two design charts relating to the RAFAEL experiments (B = 2 m and B = 4 m) are presented respectively in Figures 5 and 6. They were obtained from equations 1 – 4. The design parameters are: H = 1.5 m, $\varphi = 38°$, $\gamma = 21.1$ kN/m^3, p = 0 (no surcharge on the fill: case corresponding to the cavity emptying phase) and $C_e = 1.1$. The expansion coefficient C_e was estimated from laboratory tests performed on materials taken from the site. This phenomenon of expansion under very low confinement is not well understood but it has an important effect on the design. A sensitivity study was therefore performed for $C_e = 1.1 \pm 0.025$. The results obtained are presented in figures 5 and 6. The lower and upper limiting curves of the bundles correspond respectively to $C_e = 1.125$ and $C_e = 1.075$.

From these charts, it is possible to determine the tensile stiffness of the geosynthetic J and the tensile force T_{max} that it must withstand, once the surface criterion has been defined. For example, the characteristics required for the geosynthetic reinforcement, for a d_s/B ratio of 2.5% (the permissible value for road structures) and for $C_e = 1.1$, are: J = 518 kN/m and T_{max} = 42.3 kN/m for cavities 2 m in diameter, and J = 5578 kN/m and T_{max} = 148.7 kN/m for cavities 4 m in diameter.

Figure 5 shows that for 2 m diameter cavities and $C_e = 1.1 \pm 0.025$, values of J greater than 1800 kN/m produce zero surface settlement. This result is in conformity with the results of the experiments, which showed that no surface settlement could be detected when emptying 2 m cavities.

In comparison with the experiments performed, figure 6 shows that values of J of 1818 kN/m and 3600 kN/m produce unacceptably high surface deflection values for 4 m diameter cavities (respectively d_s/B = 7.4% and d_s/B = 4.2% for $C_e = 1.1$, i.e. d_s = 0.296 m and d_s = 0.166 m). These results should be compared with the experimental results obtained after the collapse of 4 m cavities.

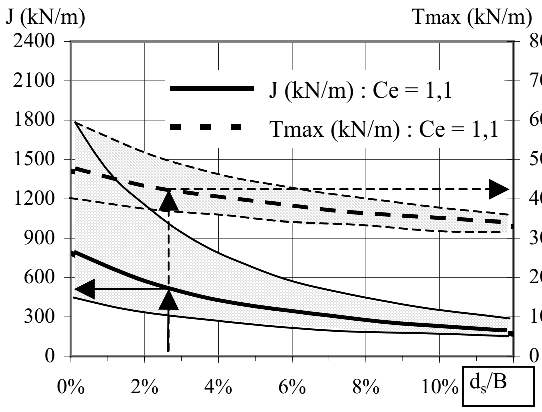


Figure 5. Design chart for B = 2 m and H = 1.5 m.

5 CONCLUSIONS

The full-size tests described here showed that a geosynthetic reinforcement solution could very effectively limit the risks of serious accidents that may occur as a result of localised subsidence under embankments. The technical solution proposed (for depth of fill H = 1.5 m) appears to be particularly

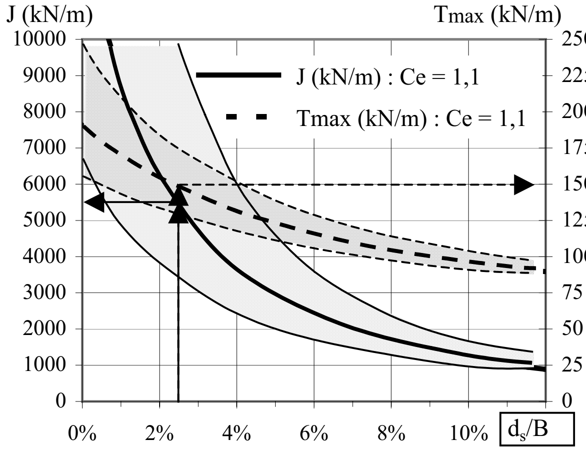


Figure 6. Design chart for B = 4 m and H = 1.5 m.

suited to small diameter cavities (B = 2 m, H/B = 0.75), where no significant surface displacement could be recorded. In the case of larger cavities (B = 4 m, H/B = 0.375), the proposed solution proved to be interesting in so far as it helps to avoid sudden large-scale subsidence and, after rapid backfilling, allows acceptable traffic use until permanent repairs can be carried out. It should be stressed that no failure of the geosynthetic was observed, regardless of the experiments performed. This confirms the effectiveness of this type of design based on the use of the geosynthetic's membrane-like properties.

6 ACKNOWLEDGEMENTS

The authors wish to thank the SNCF, SCETAUROUTE and BIDIM-GEOSYNTHETICS for their contributions to the experiments performed in the framework of the RAFAEL research programme.

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