LONG TERM PERFORMANCE OF GEOGRID STRAIN GAUGES

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ABSTRACT

Electrical wire resistance strain gauges were used to monitor the strain variation along geogrids which were installed to reinforce a fine-grained cohesive soil embankment with 1:1 slopes and a 12 m height. The construction of the embankment started in 1986 and finished in 1988. The measurements by the EWR strain gauges during and shortly after construction and in 2003 are reviewed. The strain gauges gave reliable performance over this long period of time. The attachment procedure of EWR gauges to the geogrids, which was adopted for this project, proved to be successful after 18 years of performance under the field conditions. Almost all the EWR strain gauges show a slight reduction in the magnitude of strains measured along the geogrids during the last 13 years.

RÉSUMÉ

Des jauges de deformation ont été employées pour surveiller la variation de contrainte le long des geogrilles qui ont été installés pour renforcer un remblai cohésif à grain fin de sol avec des pentes de 1:1 et une taille de 12 m. La construction du remblai a commencé en 1986 et a fini en 1988. Les mesures par les jauges de deformation pendant et peu de temps après la construction et dans 2003 sont passées en revue. Les jauges de deformation ont donné l'exécution fiable au-dessus de cette longue période. Le procédé d'attachement des mesures aux geogrilles, qui a été adopté pour ce projet, s'est avéré réussi après 18 ans d'exécution dans les conditions de champ.

1 INTRODUCTION

Use of geosynthetic material to reinforce slopes is relatively new and it was first used about 3 decades ago. Soil reinforcement has gained the interest of geotechnical engineers and is now being used in routine design. The increasing use and acceptance of soil reinforcement has been triggered by a number of factors, including potential cost savings, aesthetics, ease of construction techniques and the ability to tolerate large differential settlement (Abu-Hejleh *et.al*, 2002). The reinforcing function of the geogrids depends upon the tensile resistance of the geogrids which is mobilized through shear between the soil and the members of the reinforcement. In the design of a reinforced soil slope, the tensile resistance from the reinforcement is incorporated into a stability analysis, often using a limit equilibrium method (Jewll, 1991). The magnitude of the tensile resistance is usually determined based on the anticipated tensile strains which develop in the geogrids as the soil mass deforms. Due to the nature of polymeric materials, long-term behavior of the geogrids is a major concern for designers (Fannin and Hermann 1991, Jewell and Greenwood 1988, Koerner 1998, Allen and Bathurst, 2002). Considerable focus has been given in recent years to establishing the long-term performance of geosynthetic reinforcement as a material, addressing such issues as installation damage, creep and durability (Allen and Bathurst, 2002). To achieve a better understanding of the performance of geogrids in a cohesive soil, Alberta Transportation with the Geotechnical Engineering Group at the University of Alberta established a research program on their use in a fine-grained cohesive soil to reinforce the steep slopes of a test embankment. The test fill is located near Devon, approximately 30 km south west of Edmonton, Alberta, Canada. The test fill is 12 m high with 1:1 side slopes and has four sections: three are reinforced with different geogrids and the fourth is unreinforced for the comparison purposes.

The main objective of the test fill was to determine how individual layers of geogrid reinforce a mass of cohesive soil and to measure the stress transfer between the soil and the geogrids during both construction and service. Intensive instrumentation was installed to measure the performance of the soil mass and the individual layers of geogrid. The instrumentation applied to the geogrid layers includes electrical wire resistance strain gauges (EWR), inductance coil strain gauges and thermocouples. The main goal of this instrumentation was to measure the strains of the geogrid layers and the temperature at the strain gauge locations. The temperatures were measured to account for any temperature effect on the measured geogrid strains (Liu *et al.*, 1991).

Another goal of the construction of the test fill was to evaluate how the geogrid layers reinforced the soil mass. Hence measurements of the soil deformation and the pore water pressure response provide information related to understanding this performance. Horizontal and vertical extensometer, horizontal and vertical inclinometers and pneumatic piezometers are installed both in the foundation and embankment soil. Also field level and angular surveys were carried out from fixed benchmarks during and after the fill construction as part of the field instrumentation to assist in understanding the readings obtained from the extensometer and inclinometer instrumentation.

This paper is limited to presenting the long-term performance of the EWR strain gauges attached to the Tensar SR2 geogrids and the long-term strains in these geogrids.

2 MATERIAL CHARACTERIZATION

2.1 Fill Soil Properties

Most geogrid reinforced soil structures use a well-graded cohesionless fill because granular materials are usually stable, free draining and are not frost susceptible (Sego *et al.*, 1991). To meet the design requirement that the fill soil deforms sufficiently to induce strain in the geogrids, the upper most foundation soil, silty clay, which is relatively soft, was selected as the material to construct this embankment. The soil is classified as inorganic clay or silty clay of low to medium plasticity, using the Unified Soil Classification System. It is composed of 25% sand sizes, 50% silt sizes and 25% clay sizes. Although this material would be described as clayey silt on the basis of its grain size distribution, the Atterberg limits are indicative of inorganic clay of low to medium plasticity. The liquid limit of the fill soil is 42% and the plastic limit is 18%. The activity of the soil is therefore approximately equal to one. X-ray diffraction tests show that the clay fraction is largely montmorillonite (Scott *et al.*, 1987). According to standard compaction tests the optimum water content is 20.5% and the maximum dry density is 1.68 Mg/m^3. To satisfy the design requirement that the fill deforms extensively without undergoing shear failure, the fill soil was compacted wet of its optimum water content of 20.5%. The results of consolidated undrained triaxial tests interpreted from total and effective stress p-q plots gave total and effective stress friction angles of 17.6° and 28° respectively. The cohesion ranges from 23 to 24 kPa in terms of total stress and from 8 to 14 kPa in terms of effective stress. Hofmann (1989) outlined in detail the strength and deformation properties of both the foundation soil and the soil used to construct the embankment.

Table 1.Geogrid properties

Geogrid		Tensar SR2
Type of Polymer		High Density Polyethylene
Structure		Uniaxial Grid
Junction Type		Planar
Weight (g/m)		930
Open Area (%)		55
Aperture Size (mm)	MD[1]	99.1
	CMD[2]	15.2
Thickness (mm)		T 1.27
		A 4.57
Color		Black

[1] Machine Direction, [2] Cross Machine Direction
T: Tension Member, A: Anchor Member

2.2 Geogrid Properties

The northwest section in the test fill is reinforced with Tensar SR2, which is a uniaxially oriented geosynthetic grid manufactured by Tensar Corp. It is one of the most widely used geosynthetics for reinforcement purposes. This type of uniaxial geogrid is best used if the major principal stress direction is known, so the longitudinal members of the geogrid can be oriented in the same direction as the major principle stress direction. Properties of the geogrid are listed in Table1.

3 GEOGRID LAYOUT

To ensure that lateral movements and strains in the soil mass would occur and that each geogrid layer would act independently, only three primary geogrid layers were installed with a 2 m vertical spacing starting at 1 m from the base of the fill. The primary layer at 1 m elevation is 9 m in length and the other two layers are 11 m. These primary geogrids are installed to reinforce the slope against a toe failure within the embankment. Secondary geogrids were installed to reinforce the slope against shallow slope failure and to provide additional reinforcement against failure of the steep soil slope during construction. Each primary geogrid is instrumented to examine the load transfer from the embankment soil to the geogrid as well as the load distribution along the grid. Details of the geogrid instrumentation are presented later. The secondary grids vary in length between 3 and 5 m and are placed at 1 m vertical spacing from each other and with the primary grids. No instrumentation was installed on the secondary geogrids. The secondary geogrids in this section are Tensar SR1 and SS1. Figure 1 is a cross section of the embankment showing the different primary geogrid layers and the locations of the strain gauges along with the locations and lengths of the secondary geogrids.

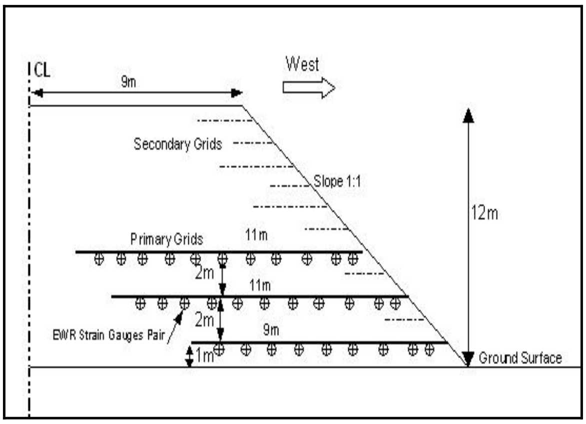

Figure 1.Cross section of fill with primary geogrids and EWR strain gauges

4 GEOGRID INSTRUMENTATION

The primary geogrids have been instrumented with electrical wire resistance strain gauges (EWR), Bison inductance coil strain gauges and thermocouples to monitor the strains induced in the geogrids as the test fill strains. The Bison gauge data will not be covered in this paper. The top of the test fill is 36 m long and the geogrid was installed for half this length or 18 m. A 1 m wide geogrid at the center of this section was instrumented. This geometry ensured that the soil strains at the instrumented section would not be affected by the ends of the test fill. The EWR gauges were installed at 0.5 m and 1 m from the face of the slope and then at 1 m intervals along the geogrid. The 1 m spacing was chosen to ensure that the region of larger deformations within the test fill was monitored. Figure 1 shows the location of the EWR strain gauges in the reinforced section. EWR strain gauges were bonded directly to the longitudinal members. EWR gauges were installed on the top and on the bottom of the longitudinal member at each location to account for any bending in the geogrid. A total of 62 EWR strain gauges were attached to the primary geogrid layers.

The EWR strain gauges installed on the geogrids are universal general-purpose electrical wire resistance gauges with a wide range of operating temperature (-75°C to +205°C). They consist of a constantan grid completely encapsulated in polyimide, with a large, rugged copper-coated tab. The measurable strain range for this type of gauge is ±5%.

The readout system is based on the principle of the Wheatstone Bridge and a quarter bridge system was used for the readings. The strains were measured using a P-3500 strain readout box in units of 10 micro strains. The gauge factor was 2.092 to 2.12 and the balance setting was 0.979.

Since the mechanical properties of the geogrid vary with temperature, a thermocouple was installed with each set of strain gauges. A dummy EWR strain gauge on a small piece of geogrid was also placed in the test fill at 0.5, 1 and 5 m distances from the slope face at each level of primary reinforcement to evaluate temperature and other environmental influences on the EWR strain gauges.

5 ATTACHMENT OF EWR STRAIN GAUGES TO GEOGRIDS

The attachment of EWR strain gauges on to the geogrids were performed by following the procedure presented by Soderberg (1990):

(1) Sand the location where the gauge is to be installed, (2) Clean the sanded surface with Freon degreaser and wiping it with MM gauge sponges, (3) Clean degreaser from surface with “M-Prep Conditioner A#MCA-1” and wipe it off with MM gauge sponges, (4) Neutralize the conditioner in step 3 with M-Prep neutralizer 5 No.MNS-1 and wipe it off with MM gauge sponges, (5) Clean the back cover of the strain gauge package with Freon degreaser, conditioner A and neutralizer S as described in steps 2 through 4, (6) Place strain gauge down on the cleaned surface of the back cover described in step 5, (7) Place 2 inch piece of scotch brand magic transparent tape over the gauge, (8) Mix M-Bond AE-10 (resin/curing agent) epoxy, (9) Peel back scotch tape so as to expose the bonding side of gauge and using a clean glass rod apply a small amount of epoxy to both the gauge and the geogrid surfaces, (10) Replace gauge/tape onto geogrid, (11) Roll finger over gauge to spread glue out beneath gauge, (12) Clamp the gauge and allow 24 hours for adhesive to set, (13) Remove clamp and carefully peel off scotch tape, (14) Trim any excess dry epoxy from sides of geogrid ribs, (15) Apply M-Flux AR activated resin soldering flux to the gauges, (16) Solder two leads of 7×#40 PVC insulated audio connecting cable, (17) Remove excess soldering flux with M-lin resin solvent and soak up excess solvent with Q-tips, (18) Apply a liberal amounts of M-coat BT air drying nitrite rubber coating to surface of the strain gauge, (19) Attach 4 conductor; 7×#30 tin copper “Unreal” cable to the strain gauge pair, (20) Heat shrink all connections between leads on gauge and the Unreal leads making sure to protect the geogrid from any heat from the heat gun, (21) Apply 2.5cm×2.5cm M-coat FB-2 Butyl rubber general purpose strain gauge protective coating; sealing all cracks with silicon adhesive sealant; the Unreal cable is attached to the geogrid by means of 5 cm plastic ties to reduce any strain on the soldered connection.

Pairs of aluminum splints were installed to protect the gauges from damage during transportation and installation of geogrids in the test fill. These splints were removed following the geogrid installation in the field and the gauges were covered with a piece of Styrofoam to protect them from damage during fill placement and soil compaction.

6 FILL CONSTRUCTION AND GEOGRID INSTALLATION

The construction of the test fill started in the summer of 1986 and required three construction seasons to complete. The fill was constructed in three stages. The site and foundation preparation was started on June 8, 1986 with grading of the site. On September 4, 1986 fill placement started. The soil was hauled from the borrow area by dozer pulled scrapers and compacted using a four wheel compactor. A small dozer and compactor were used along the edge of the slopes and near the instrumentation. The fill was placed and compacted in lifts between 0.15 and 0.4 m. When the fill reached 1 m it was leveled and the bottom primary geogrid layer was laid out on the soil. White Styrofoam protectors were placed over the EWR strain gauges and the Styrofoam was attached to the grid using electrical tape.

The first set of field measurements for the bottom geogrid layer was taken on September 23, 1986 one day after installation and following placement of one 15 cm lift of soil above the instrumented grid. This set of readings is considered the initial readings and these strain gauge values are subtracted from all subsequent readings. Additional soil was placed and compacted on top of this reinforcing layer until the embankment reached the 3 m height when the construction was stopped on October 23 due to the onset of freezing temperatures. Horizontal instrumentation in the soil and one layer of secondary geogrid reinforcement had been placed at the 2 m level. The construction was resumed on August 30, 1987 and an additional 3 m of fill was placed and the middle and the top primary reinforcement geogrids were placed at the 3 and 5 m level following the previously outlined procedures. Construction was shut down on November 3, 1987 due to freezing temperatures. In addition, soil instrumentation and secondary reinforcement were placed at the 4 m level. The construction of the test embankment continued the following summer. An additional 6 m of soil was added to complete the 12 m high fill by October 29, 1988.

Figure 2 shows the fill height versus time during construction. Six layers of secondary reinforcement geogrids were placed during the 1988 summer construction. Due to the rainy weather and construction delays, the top 6 m of fill was placed at higher moisture contents than recommended in the original design. Also the lifts were thicker than used in the lower 6 m of the fill. The top 6 m of the embankment had a water content about 3 to 5% higher than the soil placed in lower half of the fill (Liu, 1992).

7 DUMMY EWR STRAIN GAUGE READINGS

EWR strain gauges were attached to short pieces of geogrid following the same procedures as used on the primary reinforcement and installed in the fill in the same manner. The purpose of these gauges was to evaluate the influence of the wet soil environment, the soil confining pressure, the temperature and the readout instrument on the performance of the gauges and to provide correction factors for the geogrid gauges associated with environmental influences. These dummy gauges were placed at each primary geogrid layer at 0.5, 1.0 and 5.0 m respectively from the slope surface. As for the geogrid gauges, the first reading following placement of a 15 cm soil layer on the geogrid was taken as an initial reading and is subtracted from all subsequent readings. The dummy gauges were placed adjacent to thermocouples so temperature influences could be evaluated. Figure 3(a) shows the variation of strain over time in a dummy gauge located 1 m from the slope face in the bottom geogrid layer without any correction for temperature-induced strains. Figure 3(b) illustrates the temperature variation with time at the same location.

In order to estimate apparent strains developed in geogrids due to variation in temperature, thermal expansion tests were conducted in the laboratory. EWR strain gauges were bonded to pieces of geogrid material in the same manner as they were bonded for use in the test fill. Strains were measured at different temperatures under stress free condition (without any soil confinement and tension of the geogrid). The thermal expansion coefficient of the geogrid was calculated to be 0.017 percent strain per degree Celsius. This coefficient was confirmed by the manufacturer (Liu, 1992).

To calculate the strain at each gauge location, the temperature-induced strain was calculated by multiplying the thermal expansion coefficient of the grid by the temperature difference at the reading time and at the initial reading. Then this apparent temperature induced strain is subtracted from the strain calculated by subtracting the initial reading from the present reading. After applying the correction for temperature-induced strains, the variation of strain for the same dummy gauge is presented in figure 3(c). All nine dummy gauges showed similar results. The uncorrected strains were quite consistent while the corrected strains were mirror images of the temperature.

All nine dummy gauges worked well during construction and are still giving consistent readings. These dummy gauges show that the gauges, leads, connection boxes and readout box all are performing satisfactorily during this 17-year period. Figure 4(a) shows all the readings to date without any temperature correction. Variation in readings after 17 years is only ±0.10% strain. Figure 4(b) shows all the readings with the temperature correction applied. The variation in readings is ±0.30% strain. Therefore, when the dummy gauge readings are corrected for geogrid thermal expansion and contraction the variation in strain readings is considerably larger. It appears that a geogrid temperature correction is not applicable. The confining stress of the soil must prevent the geogrid from undergoing thermal expansion or contraction and as a result the strain of the geogrid is over or under estimated when a temperature correction is applied.

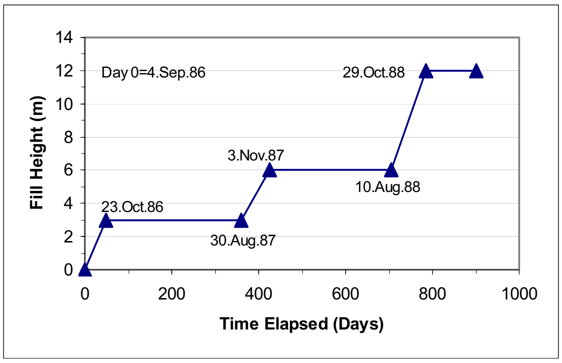

Figure 2. Construction schedule of Devon test fill

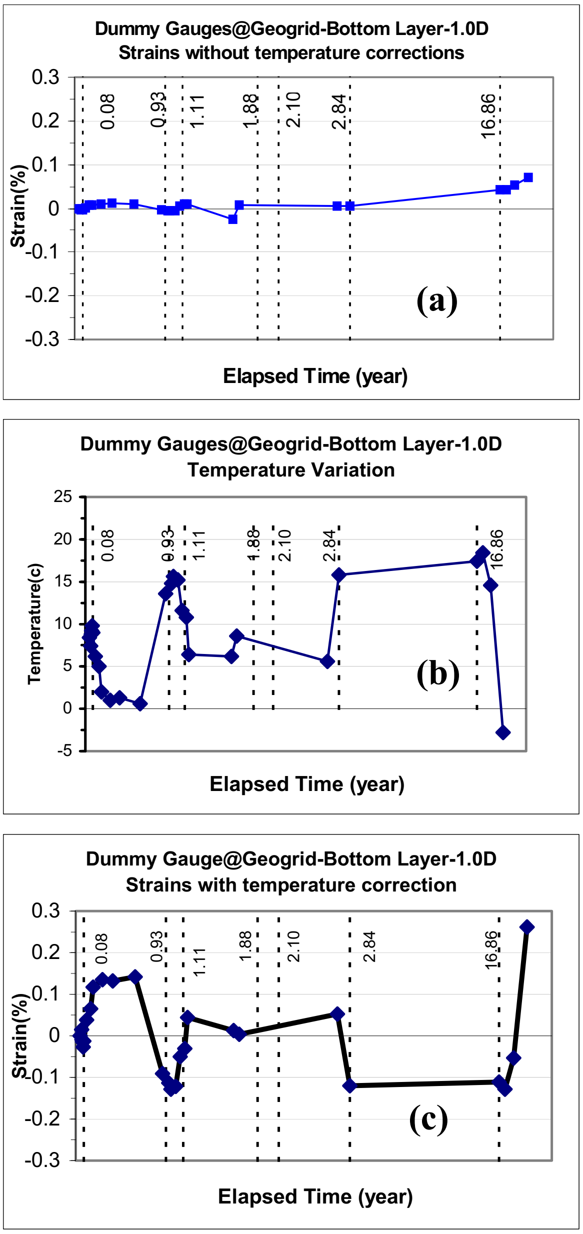

Figure 3.Dummy gauge at the geogrid bottom layer-1.0m into the slope, (a) strains without temperature correction, (b) temperature variation, (c) strains with temperature correction

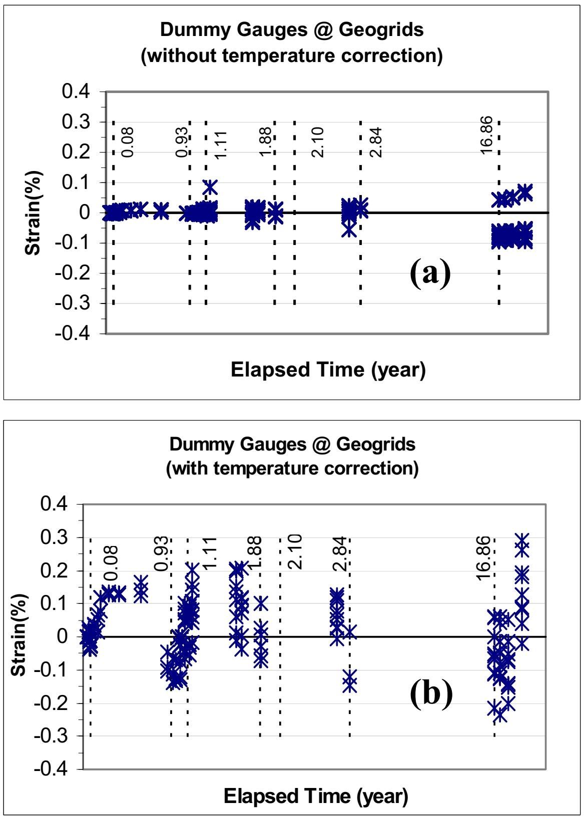

Figure 4.Dummy gauges strain variation-(a) without temperature correction, (b) with temperature correction

8 READINGS OF EWR STRAIN GAUGES ON THE GEOGRID

During construction and following completion of the test fill to 1990 a total of 38, 23 and 20 sets of field readings were taken on the bottom, middle and top layer of the geogrid respectively. Four new sets of readings on each layer were carried out in 2003. The strain was calculated by subtracting the initial reading from the present reading, after applying the temperature correction mentioned before. In order to overcome systematic errors, the same readout device was used for the field measurements from 1986 to 2003. The calibration of the readout box was checked in 2004 and it was observed that the maximum difference between the actual and measured strain is about 0.08% strain at a 4% measured strain. This confirmed that the calibration of the readout box had not changed through this 17-year period.

Table 2 shows the number of EWR gauges that failed at different stages of construction. In the middle layer all the gauges worked properly up to 2003, in top layer one gauge was recovered during the 2003 measurements but one gauge in the bottom layer was lost. Hence the rate of EWR strain gauge failure over 18 years after installation is 19%, with the majority occurring during construction. This indicates that the EWR strain gauge attachment procedure described above was very successful.

The variation of temperature corrected strain in the bottom, middle and top geogrid layers are presented in Figures 5, 6 and 7 respectively. Each figure shows the strain change along the grid layer at various times. There is no data available between 1990 and 2003.The vertical dashed lines on the plots correspond to the construction stages and the period during which there were no measurements.

9 DISCUSSION OF THE EWR GAUGE READINGS

Typically the tensile strain in the reinforcements increases from zero at the slope surface to a maximum at a certain depth and then decreases as the distance from the slope surface increases (Liu *et al*., 1994). In the geogrid bottom layer, figure 5, when the fill height was 2 m (1st construction stage) and there was only 1 m of soil above the bottom geogrid layer the maximum strain of 0.45% occurred at 1 m from the slope face. In the summer of 1987, just before starting the second stage of construction, the strains along the geogrid dropped slightly and the peak strain at this 1 m location decreased to about 0.33%. During the second stage of construction the strain variation along the grid did not show any specific change but during the third construction stage the whole pattern changed. As the next 6 m of fill was placed, the peak strain along the bottom geogrid moved from the 1 m location to 3 m location from the slope face and the maximum strain increased to 0.9%. After completion of the fill during 1989 and 1990 the peak strain increased slightly and reached about 1% strain at this 3 m location. The new set of readings (2003) on this layer shows that the trend for strain distribution along the geogrid layer has remained unchanged but a drop in strain values has occurred as the peak value at the 3 m location decreased to about 0.7% strain. At the locations where the EWR gauges failed the data has been adjusted according to their values and their changes before failure and also the values at the adjacent strain gauge locations.

In the geogrid middle layer (Figure 6) a peak strain formed during the second construction stage after placing fill on the middle layer. When the fill height was 6 m this peak strain of 0.75% was at 5 m from the slope face. But as the fill was completed it increased to 1.7% at the same location. Until 1990 there was a very slight change in the strain variation along the geogrid and at most locations the change was less than 0.1%. The new measurements on this layer show a small decrease in strain along the geogrid with similar trends as in the geogrid bottom layer. The decrease is about 0.15% strain from the peak and less into the slope. A larger strain reduction was observed close to the slope face except at 0.5 m, which shows an increase.

Figure 7 shows the strain variations with time and location in the geogrid top layer. Before the third construction stage the amount of strain along the geogrid was below 0.5% at all locations but when the fill height reached

Table 2. Number of total failed EWR gauges at different stages

Reading Stage	Geogrid Layer		
	Bottom	Middle	Top
1st construction	0	---	---
2nd Construction	3	0	0
3rd Construction	5	0	7
Year 2003	6	0	6

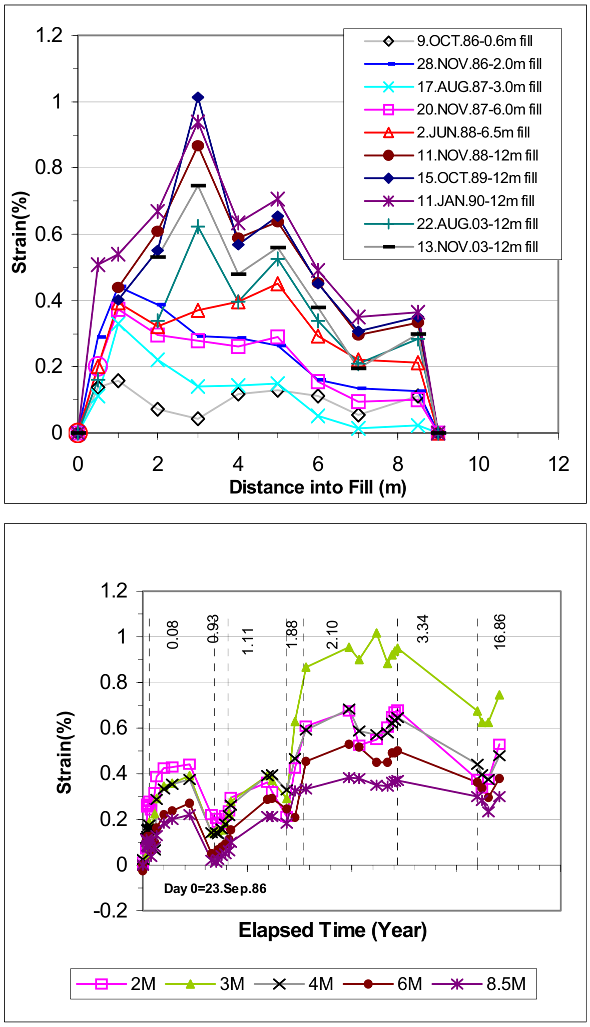

Figure 5. Strain variation-Geogrid bottom layer

10.5 m during the third construction stage the strains increased and the peak strain of 1.85% formed at 3 m from the slope face. In November 1988 following completion of the fill the strains increased at all locations and the peak reached 2.6%. During 1989 and 1990 the strain at the locations beyond the peak and into the slope showed a slight increase at locations within 4m of the slope. The highest increase was about 0.25% at the 3 and 4 m depth locations. The measurements in 2003 revealed similar trends for the strain variations along the grid but there is a small decrease in values. The locations shown by a hollow circle on the plots indicated that the gauges at these points failed and the data was adjusted as described previously.

Comparison of these plots shows that the top layer of geogrid had the largest strain and the bottom layer had the smallest. The tensile strains in the geogrid increased

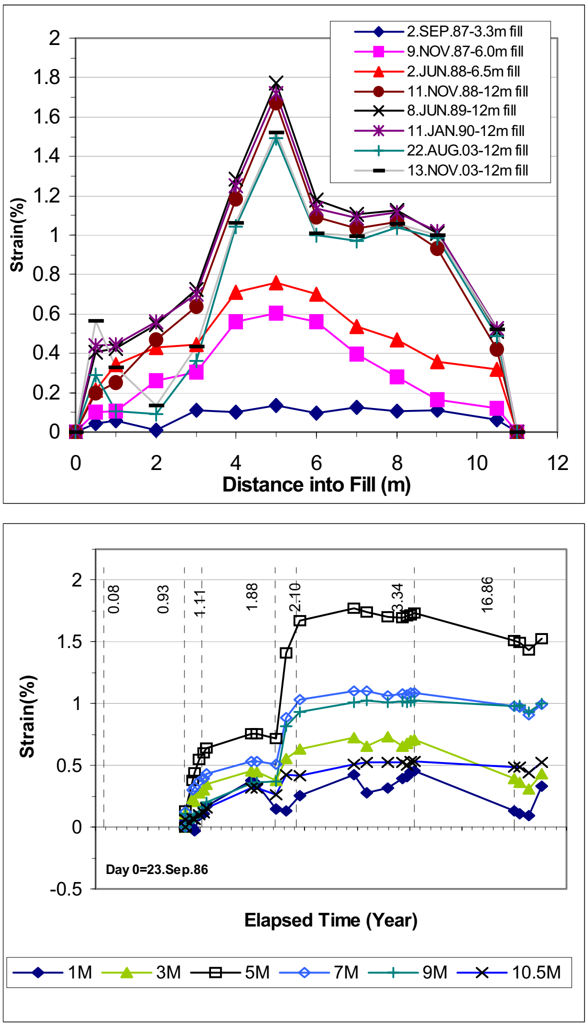

Figure 6. Strain variation-Geogrid middle layer

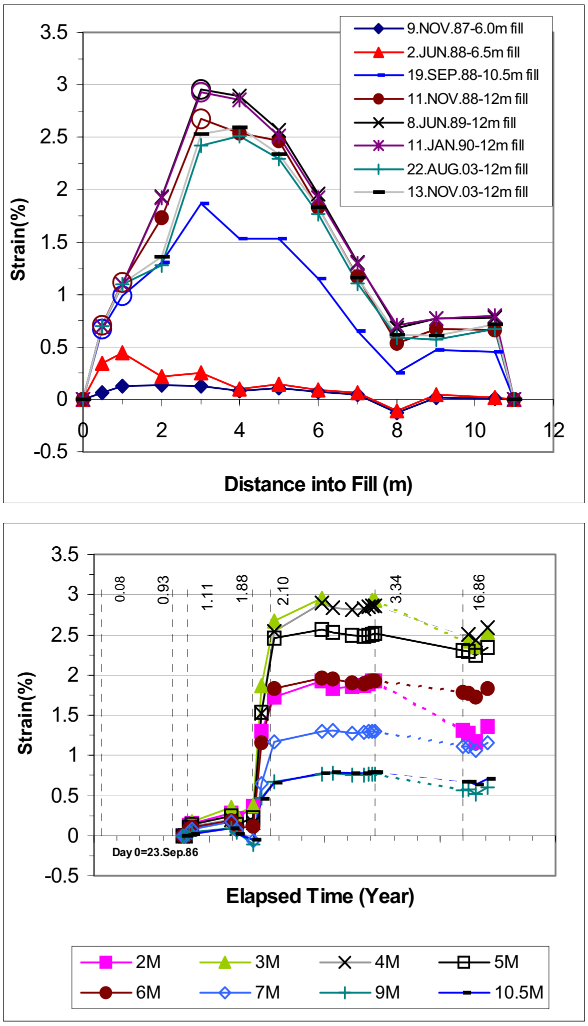

Figure 7. Strain variation-Geogrid top layer

during the construction seasons and there were significant increases during the 1988 construction season when the additional 6 m of soil was rapidly placed. After the completion of the fill the strains showed some seasonal fluctuations until 1990. The measurements in 2003 show that there was a decrease in most strain measurements. Figure 8 summarizes the strain reductions between the 2003 measurements and the last previous reading in 1990. It can be seen that the strains fluctuated less deep within the fill than near the slope surface. These fluctuations were most likely caused by problems related to the corrections applied to account for the thermal strains. By only analyzing the field results it is not possible to investigate the cause for these strain reductions along the geogrid. Possible causes could be creep within the bonding agent between the gauge and geogrid or soil strengthening over the time due to pore pressure dissipation allowing the soil to better resist the gravity stresses.

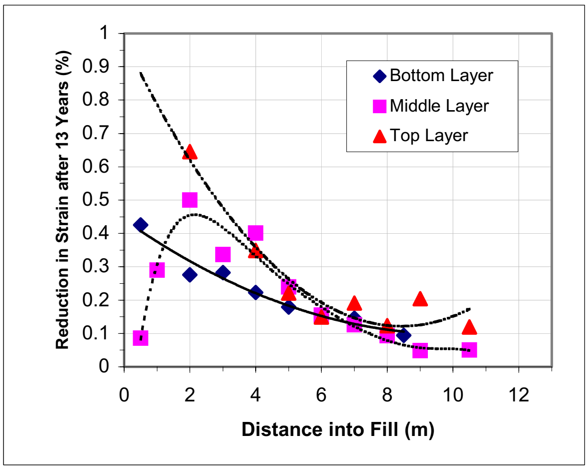

Figure 8. Reduction in strain measurements of the geogrids after 13 years

10 CONCLUSIONS

Electrical wire resistance strain gauges were used to monitor the strain variation along the Tensar SR2 geogrids used to reinforce a fine-grained cohesive soil embankment with 1:1 slopes and a 12 m height. These gauges were attached to the ribs of the geogrids. Strain measurements made during construction and about 16 years after completion of the test fill are reported. Four new sets of readings were made in 2003. Analysis of the field data shows:

1) During the past 16 years after the completion of the test fill few failures are observed in the EWR strain gauges and almost all the gauges gave acceptable performance. The rate of EWR strain gauge failure over 18 years after installation is 19%, which generally happened during the construction phase.
2) The attachment procedure of EWR gauges to the geogrid proved to be successful under the project conditions.
3) The readings in 2003 show the same strain variation along the geogrid as the readings showed before 1990 but small reductions in strains occurred at all locations along the geogrid. The reduction becomes less with distance from the slope face.
4) Typically the tensile strain in the reinforcement increases from zero at the slope surface to a maximum at a certain depth and then decreases with additional distance from the slope surface. The bottom layer peak strain reached about 1% strain at the 3 m location at the end of construction, and then decreased to about 0.7% strain in 2003. In the middle layer the peak value was 1.7% at the 5 m location and the 2003 measurements show a decrease of about 0.15%. In the top layer the peak strain reached about 2.6% at the 3 m location at the end of construction and about 3% two years after fill completion. This value dropped to about 2.5% in 2003.
5) All nine dummy gauges worked well during construction and are still giving appropriate readings. These dummy gauges show that the gauges, leads, connection boxes and readout box all performed satisfactorily during this 17-year period. Variation in readings after 17 years are only ±0.10% strain without temperature correction and ±0.30% strain with temperature correction. When the dummy gauge readings are corrected for geogrid thermal expansion and contraction the variation in strain readings is considerably larger. It appears that a geogrid temperature correction is not applicable.
6) More detailed investigation is required to determine the cause of the strain reduction along the geogrids during the last 13 years. Possible causes can be the creep of the bonding agent between the gauge and geogrid or soil strengthening over time because of consolidation effects.

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