Long-Term In-Situ Strain Measurements of a High Density Polyethylene Geomembrane in a Municipal Solid Waste Landfill

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ABSTRACT

This paper presents in-situ strain measurements collected over three years from strain gauges installed on a 1.5 mm (60 mil) high density polyethylene geomembrane (HDPE) used to construct a municipal solid waste landfill in Northern California. Long-term strain measurements were conducted to determine if the HDPE and liner system were performing as expected during and after construction of the facility.

This study provides evidence that the HDPE component of the liner system was behaving in the manner in which it was designed. The first three years of monitoring indicate that strain in the HDPE at the top of the side slopes was greater than the strain at the bottom of the side slope, and that side slope strain was greater than strain at the bottom of the facility. The results from this real-world, full-scale HDPE strain measurement project confirm the validity of current geomembrane liner design procedures.

INTRODUCTION

This project had as its primary objective field verification of maximum strain of a 1.5 mm (60 mil) HDPE in-situ. Data from this site allowed for the determination of the strain distribution over the instrumented area in response to waste placement Operations at the facility. A definitive answer to the question of the long-term in-situ strain response of HDPE can now be given. This full-scale instrumented field site quantified the phenomena and allowed engineers to make rational decisions concerning future landfill liner designs.

The instrumented municipal solid waste cell was located at the Yolo County Central Landfill (YCCL), situated 5 kilometers (3 miles) northeast of Davis, California, USA. The climate was semiarid, the topography was relatively flat, and the site was underlain by 6 meter (20 feet) of moderately over-consolidated clays with interbedded silts, sands and gravels.

The YCCL, like most landfills, has seen a marked technological improvement in the manner in which waste has been disposed of over the past 15 years. The County boasts the following facilities in the management of their waste stream:

- Recycling Drop-off Facility;
- Methane Gas Recovery Facility;
- Metal Recovery Facility;
- Wood and Yard Waste Processing Facility;
- Liquid Waste Management Facility;
- Household Hazardous Waste Collection Program; and,
- 142 hectares (350 acres) of Subtitle D landfill space.

The entire operation as of 1993 was permitted to handle 1,634 tons-metric per day (1,800 tons per day). At present it is operating at 75% of its capacity.

This investigation was conducted on the first 8 hectare (20 acre) HDPE composite lined landfill cell at the YCCL constructed to meet Subtitle D standards, Module A. The composite liner system consisted of 0.6 m (2 feet) Of $1x10^{-7}$ cm/sec compacted clay liner overlain by a 1.5 mm (60 mil) HDPE, HDPE geonet, non-woven geotextile and 0.3 m (one foot) of soil operations layer. In total, 38 foil strain gauges were installed in a half-bridge Wheatstone configuration at 19 locations within Module A. The gauges have been monitored since their installation in the fall of 1991.

INSTRUMENTATION INSTALLATION PROCEDURES

Strain gauges and thermocouples were installed at seven stations along the north and east side slopes of Module A. Figure 1 shows the YCCL site plan and the location of the seven strain gauge stations (A through G) within Module A. One to four pairs of strain gauges were installed at each of the seven stations. Figure 2 shows a typical cross-section of Module A indicating the locations of the strain gauges and thermocouples. The instrument locations at each station were arranged in the following manner:

- S1 (T1) --- top of slope
- S2 (T2) --- middle of slope
- S3 (T3) --- toe of slope
- S4 (T4) --- bottom of cell

The instruments at locations 1, 2, and 3 were installed approximately 4.6 m (15 feet) apart from one another down the slope, and the instruments at location 4 were installed approximately 23 m (75 feet) from location 3.

Selection and Placement of Strain Gauges. In a survey by Herceg (1976), ten different electromechanical transducer elements were characterized with respect to resolution, hysteresis response, dynamic response, temperature compensability, environmental sensitivity, linearity, mechanical overload capability, robustness and life expectancy. Foil strain gauges were rated "good to excellent" for each of these attributes, and were found to outperform by far the other alternatives for this application. Foil strain gauges were the obvious choice for this application.

Consideration was given to the anticipated range of strain measurements, and to gauge locations in order to maximize the value of collected data. The potential loss of gauges due to the stresses from the installation of overlying materials was assessed. Wire routing, landfill operations logistics, and moisture proofing were all carefully evaluated before any gauges were installed in the field. Sample gauges were tested using different types of epoxy resin at different curing pressures and temperatures to arrive at an optimum installation technique.

The strain gauges selected for installation were EP-08-20CBW-120 with LE option, manufactured by Micro-Measurements. These gauges are manufactured of fully annealed constantan foil processed for very high ductility (20% strain limit), with leads and polyimide backing for superior elongation capability, and an operating temperature range suitable for expected temperatures in the waste pile.

Attachment of Strain Gauses to HDPE. Strain gauges can be bonded to almost any solid material if the surface of the material is properly prepared, although the degree of difficulty varies. Because HDPE is a non-polar substrate, it is difficult to form a good long-term bond without specific, surface-activating chemical treatment. Cleanliness of the HDPE surface is extremely important for gauge mounting. Five basic steps were performed to prepare the HDPE surface. These were: solvent degreasing, abrading, surface etching, rinsing with deionized water and neutralizer solution, applying gauge layout lines, conditioning, and neutralizing. This preparation protocol produced a chemically clean surface, an appropriate surface roughness, neutral surface alkalinity, and visible gauge layout lines for locating and orienting the strain gauges. Figure 3 shows the strain gauges on the prepared HDPE before resin application.

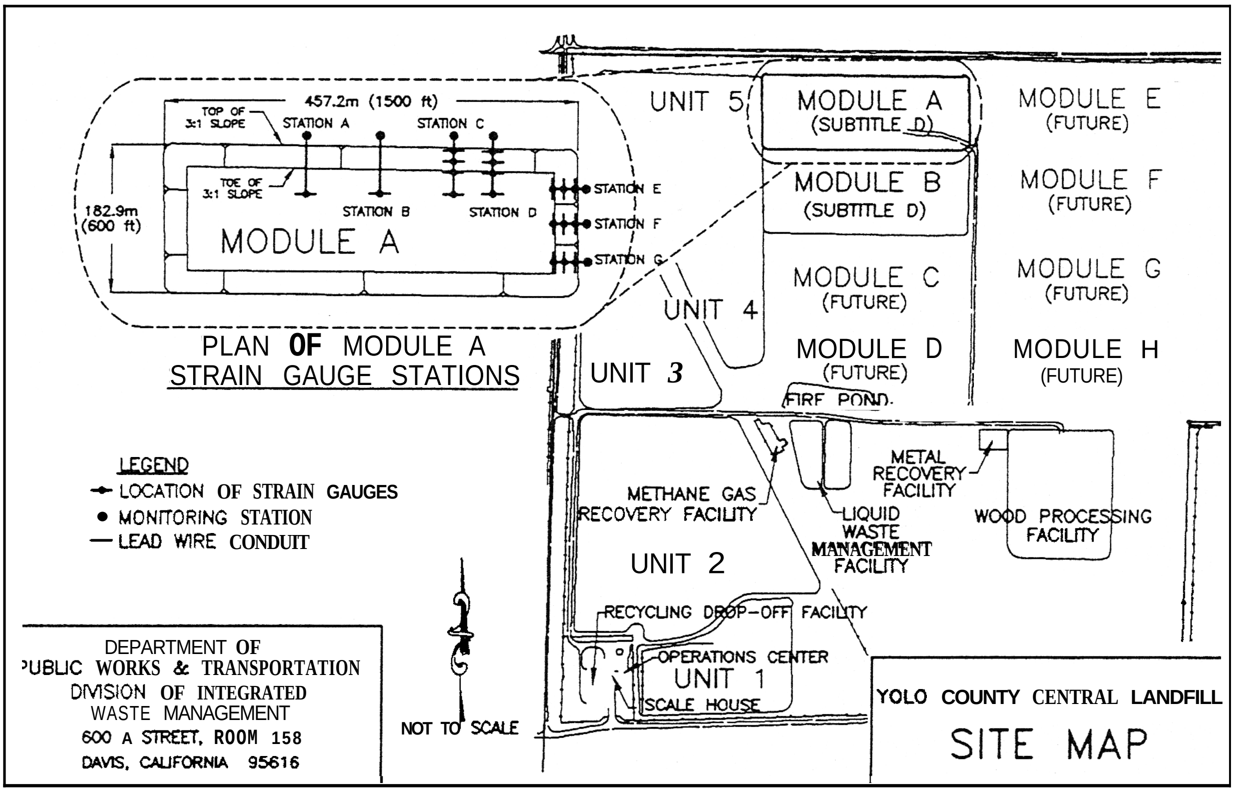

Figure 1. Site Plan and Location of the Seven Strain Gauge Stations in Module A.

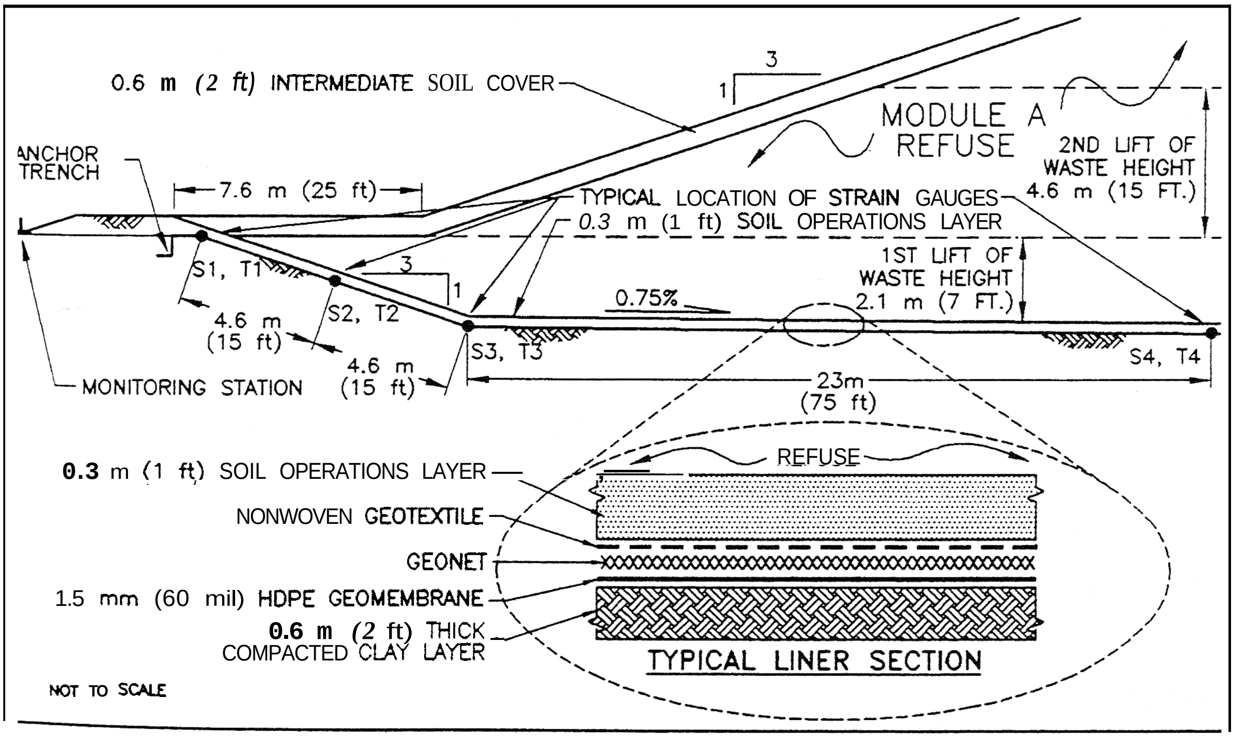

Figure 2. Typical Cross-Section of the Instrumented Landfill Liner System.

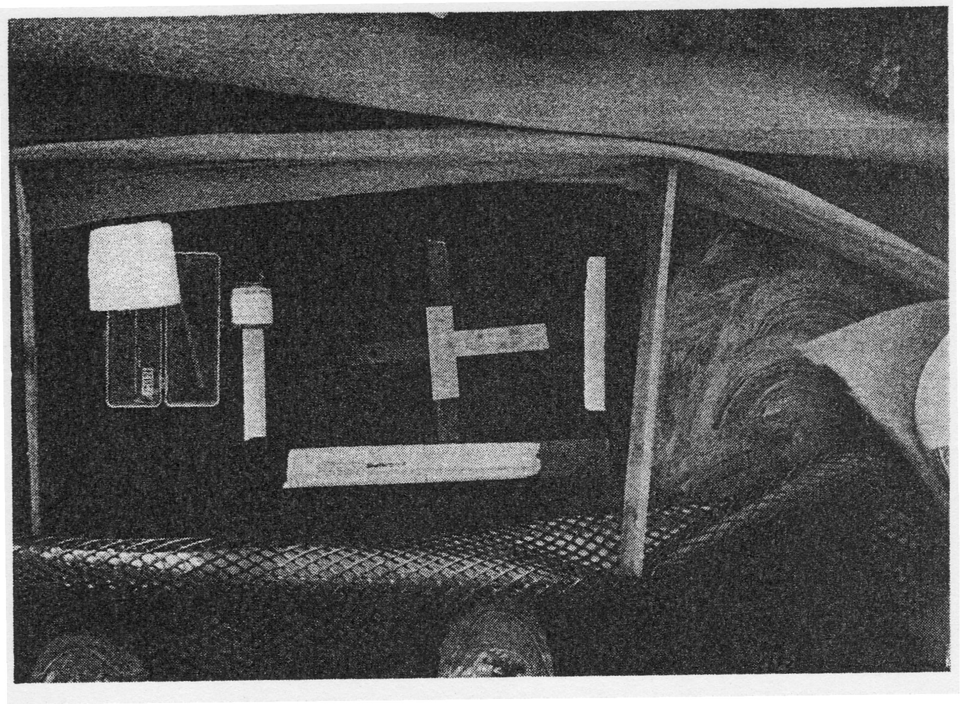

Figure 3. Strain Gauges on Prepared HDPE Prior to Resin Application

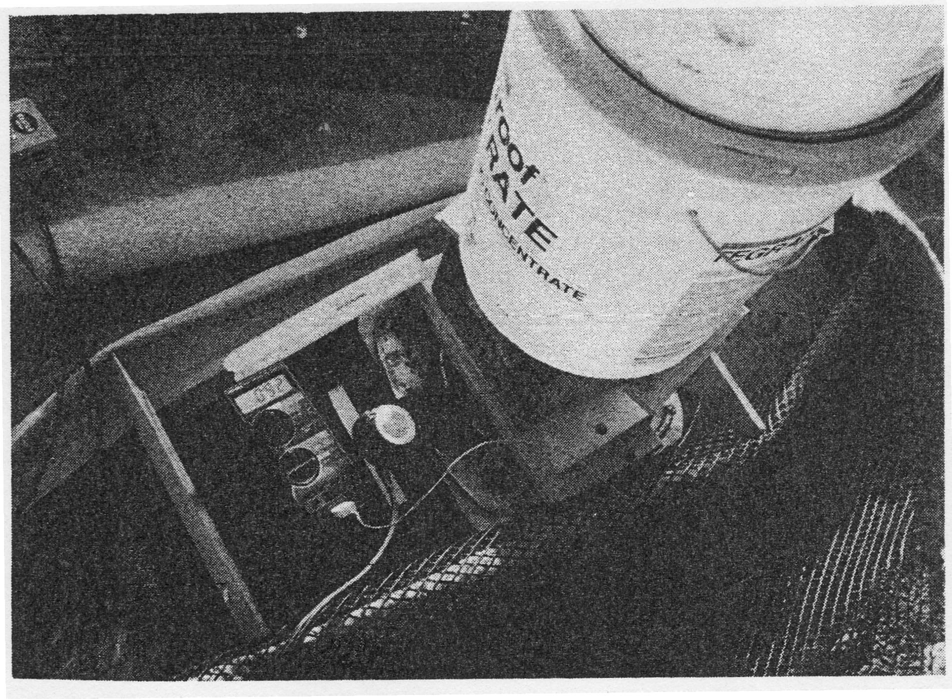

Figure 4. Application of Elevated-Temperature and Pressure During Attachment of the Strain Gauges to HDPE.

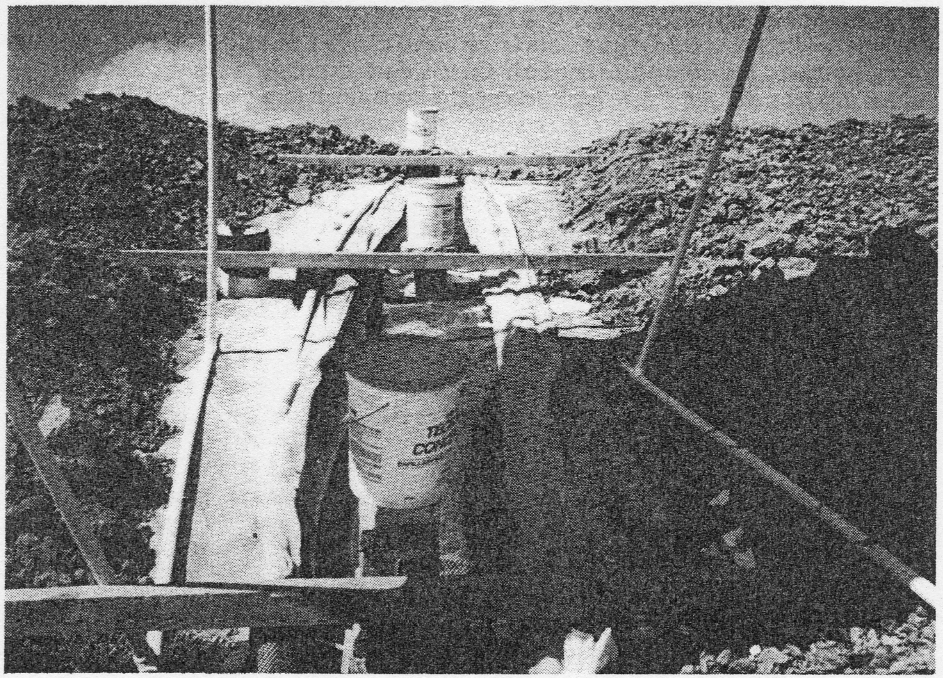

Figure 5. Application of Elevated Temperature and Pressure on Side Slope During Attachment of the Strain Gauges to HDPE.

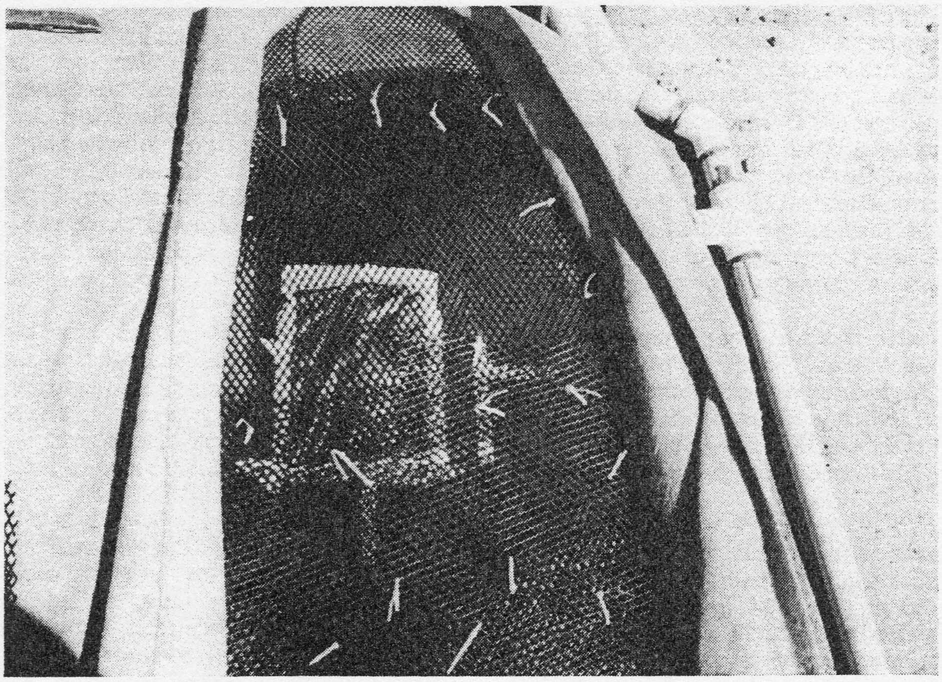

Figure 6. Installed Strain Gauges (Below Geonet) with PVC Conduit for Leadwires Above the Composite Liner.

At each strain gauge location, two strain gauges were mounted perpendicular to each other on the prepared HDPE using M-Bond AE-15 resin system manufactured by Micro-Measurements. An elevated-temperature curing process was utilized to maximize resin stability. A cure temperature of 95 °C (203 °F) for a period of one hour at a clamping pressure of 100 KN/m (14 psi) was maintained. Figures 4 and 5 demonstrate the elevated-temperature curing process which was used during the attachment of the strain gauges. One gauge was set in the principal stress direction oriented down the side slope, and the other perpendicular in order to sense the Poisson strain.

Following bonding, four layers of protective materials were installed to protect the strain gauge and its wiring leads from the landfill environment. The first protective layer was a thin layer of wax, followed by a butyl rubber sealant, then a protective rubber membrane, and finally another thin layer of wax.

Installation of Strain Gauae Leadwires. Leadwires to the strain gauges consisted of 3-wire, 26 gauge, stranded tinned-copper, threaded through protective polyvinyl chloride (PVC) conduits. Figure 6 shows the completed strain gauge installation and the PVC conduits above the HDPE composite landfill liner. Wires were extended from each strain gauge location to a monitoring station where strain readings were recorded using a P-3500 digital strain indicator manufactured by Micro-Measurements.

Installation of Thermocouples. At some of the strain gauge stations, HDPE temperature was monitored using Type K (Chromel-Alumel) thermocouples. Figure 7 shows the HDPE and the ambient air temperature history for various locations at stations C and D.

LABORATORY TESTING AND ERROR CORRECTIONS

Correction to Strain Measurements from Half-Bridge Confiaurations. In the half-bridge strain gauge setup, two gauges are mounted adjacent to each other, one in the principal stress direction and the other perpendicular. This provides an augmented bridge output due to the strain measurement in the perpendicular (Poisson) direction. In order to adjust the measured strains to reflect the strain in the primary (down slope) direction, the strain data was reduced by $1/(1+v)$, where v is Poisson's ratio. Poisson's ratio for HDPE was assumed to be 0.5, as discussed by J.P. Giroud et. al. (1993).

Error Due to Strain Gauae Attachment. By bonding dissimilar materials to the HDPE, the strength characteristics of the HDPE are altered. To quantify these changes, HDPE specimens were laboratory tested as per ASTM D4885, "Test Method for Determining Performance Tensile Strength of Geomembranes Using Wide Strip Testing." Four tests were performed on HDPE specimens complete with strain gauges bonded in the center of each specimen, and the protective layers of wax, butyl rubber sealant, and protective rubber membrane, as per the field-installed assemblies. After the bonding process, these specimens were allowed to cure for a week prior to testing. Tests were also performed on as received HDPE specimens with no strain gauges attached. A continuous rate of extension testing device was set at cross head speed of 1 mm/min (0.04 in/min), and all HDPE specimens were tested in the HDPE's machine direction.

Figure 8 shows the average stress versus strain responses of the as received HDPE samples and the stress versus strain responses of the HDPE specimens with strain gauges attached. The average modulus of the four specimens with strain gauges attached was found to be slightly less than that of specimens without gauges. This change in the HDPE material property may be attributable to the relief of internal stresses during curing, or to the surface preparation before bonding, as discussed by Giroud and Peggs (1990).

The 2% secant modulus calculated per ASTM D5323 was used to determine the percent difference between the two curves shown on Figure 8. The 2% secant modulus decreased from 433,021 kPa (62,604 psi) to 375,621 kPa (54,479 psi) due to application of the strain gauges to the HDPE. This difference in secant moduli was determined to be 13.2% and the measured strains, being less than 2%, were reduced by this amount to adjust for the effects of the strain gauge attachment protocol.

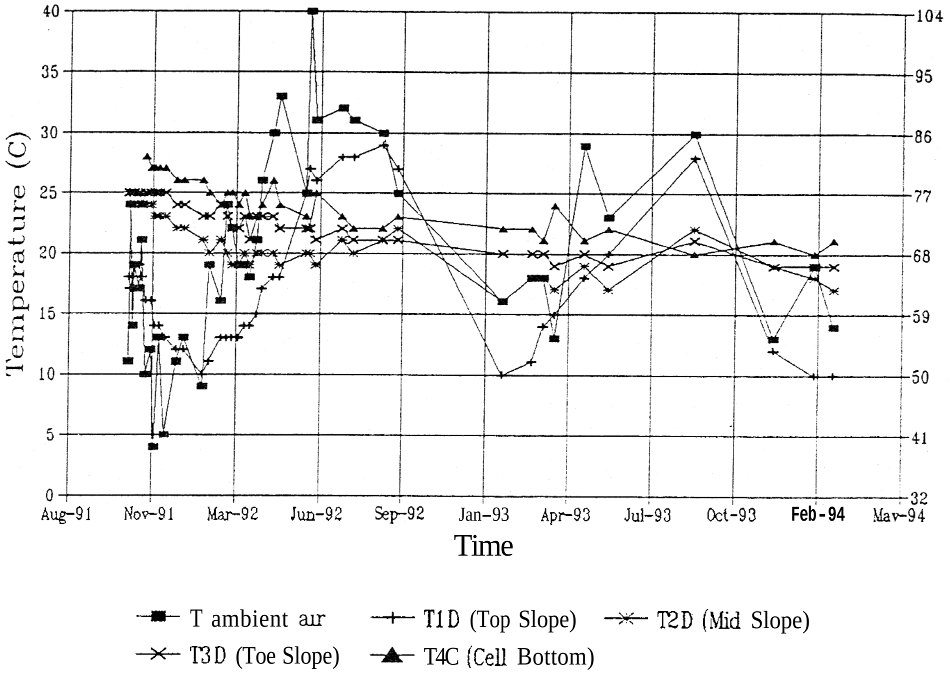

Figure 7. Temperature Responses of Station C and Station D Thermocouples.

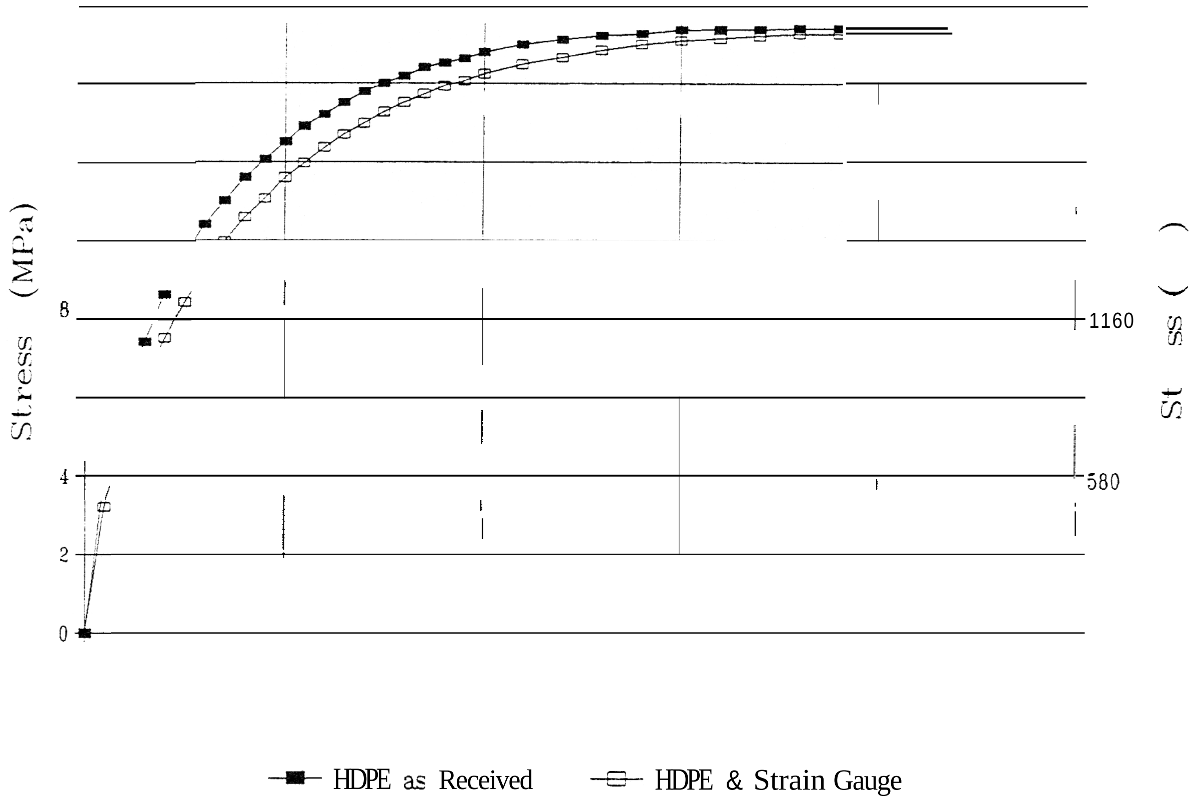

Figure 8. Averaged Stress Verses Strain Responses of HDPE specimens. [Cross-Head Speed of 1 mm/min (0.04 in/min)]

Error Due to Lead Wires. Three lead wires were used to connect each pair of strain gauges to the P-3500 digital strain indicator. The error due to the resistance in the leadwire circuits was corrected by adjusting the gauge factor of the P-3500 instrument, using the measured lead wire resistance at each station.

Error Due to Strain Gauge Thermal Output and Gauge Factor Variation with Temperature. The electrical resistance of the strain gauge varies not only with strain, but with temperature as well. The effects of this variation can be controlled or eliminated by compensation or correction and are significantly mitigated with the use of half-bridge configuration. Approximate correction for thermal variation may be obtained directly from the engineering data sheet supplied by the strain gauge manufacturer, and may be adjusted for HDPE. Figure 7, the observed temperature range during the past three years, indicates that the temperature range at locations S1 through S4 has been between 10 to 30 °C (50 to 86 °F). From the strain gauge manufacturer's adjusted engineering data sheet, the variation in thermal output within this range is less than 100 micro m/m. Similarly, variation of gauge factor with temperature is less than 0.05%. Both of these factors are considered small, and have been ignored in this study.

Errors Due to Wheatstone Bridge Nonlinearity. During strain measurement, an "unbalanced" Wheatstone bridge circuit is used in which the output of the bridge circuit is a nonlinear function of the change in resistance. When measuring small strains, this error is ordinarily small and can be ignored. The magnitude of this error can increase significantly at larger strains. Within the range of strains measured in this investigation, the nonlinearity error was found to be no more than 0.4% of the measured strain, and was therefore ignored.

Error Due to Gauge Orientation. Another error that may be introduced in the measurement of the HDPE strain is the orientation of the gauges with respect to each other and with respect to the maximum principal strain. Great care was taken to ensure that the strain gauges were installed perpendicular to each other and that one gauge was oriented downgrade in the direction of maximum principal strain.

Error Due to Bending Stress. The mounted strain gauge's sensitivity to bending stress can create significant "apparent strains". Once installed, it is not possible to differentiate artificial strain readings from actual strain readings. Installing a pair of strain gauges on both sides of the HDPE would eliminate this error by cancelling the effects of bending. However, attaching strain gauges on the underside of an installed liner system is not practical. To minimize this error, the area in which the strain gauges were to be mounted was inspected to ensure that each pair of gauges was installed on an area of HDPE in good contact with the underlying compacted clay liner.

Other Sources of Error. The most significant short-coming of these gauges is that they essentially measure strain at a point and only at the surface of the HDPE. In essence these gauges give a microscopic view instead of a macroscopic view of the liner system. If a significant strain gradient exists within the cross-section of the HDPE, or adjacent to the location of the gauge, the response will be overlooked. This makes data difficult to interpret and implies that many gauges are needed to accurately map the response of large facilities.

RESULTS OF FIELD MONITORING

After each pair of strain gauges was installed, initial readings were recorded. For each measurement session, a zero datum was established by connecting the instrument to half-bridge precision resistors, thereby ensuring a constant reference point. Following installation of all of the gauges, monitoring was conducted on a weekly basis. Field monitoring frequency was reduced after the second lift of waste was placed due to the equilibrating effect of this significant normal pressure.

Results of the field monitoring performed as of this writing can be seen in the seven graphs of Figures 9 through 14. Each graph represents the response of a string of strain gauges at one station. During three years of monitoring, only one strain gauge (S2G), has recently given an unstable set of readings. The survival rate of strain gauges has been over 95 percent, which is far better than anticipated.

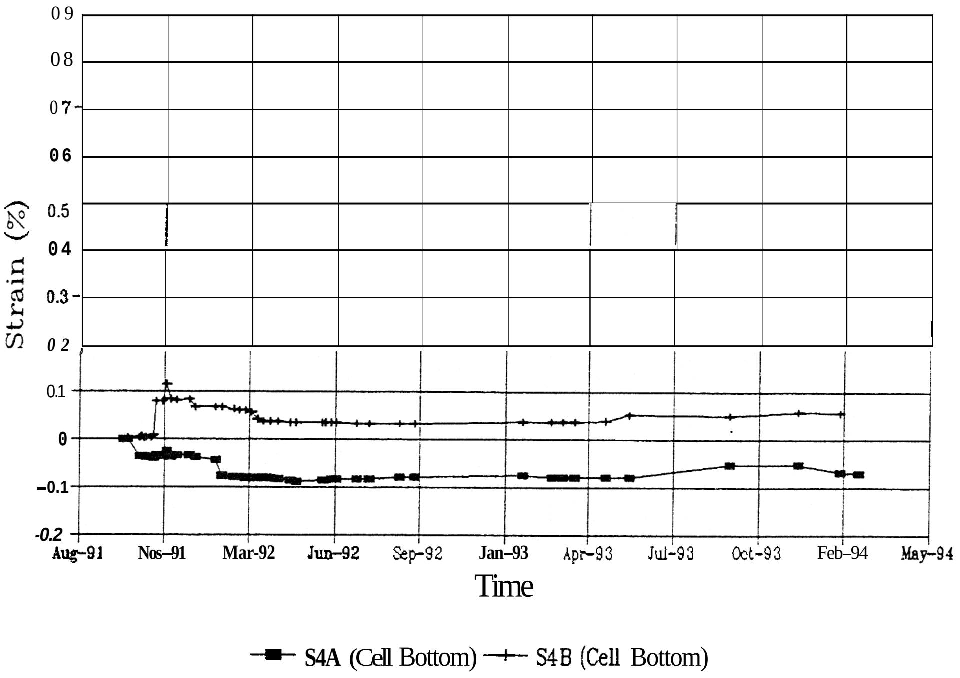

Figure 9. Strain Responses of Station A and Station B Gauges.

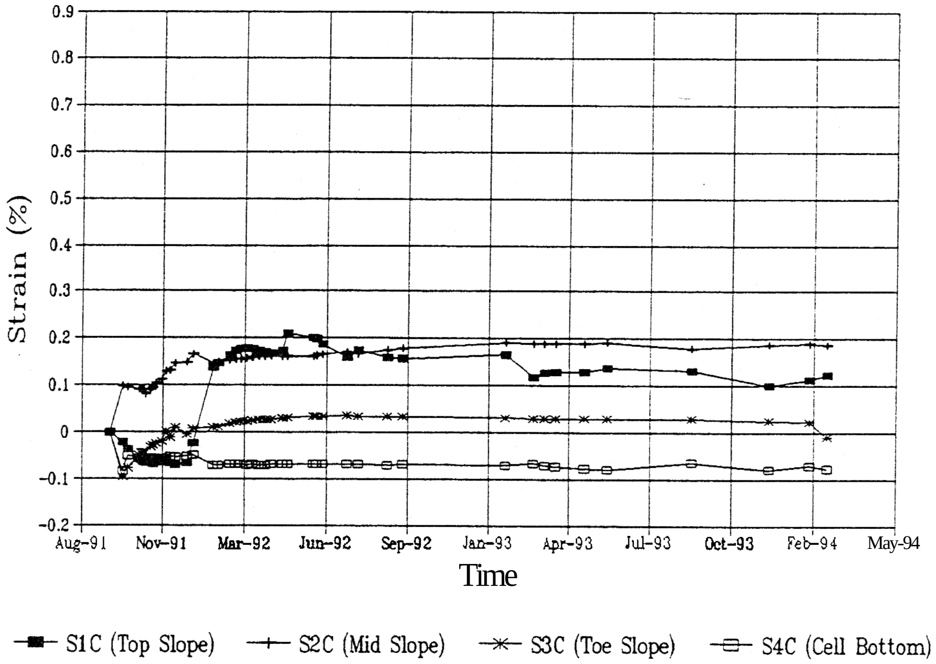

Figure 10. Strain Responses of Station C Gauges.

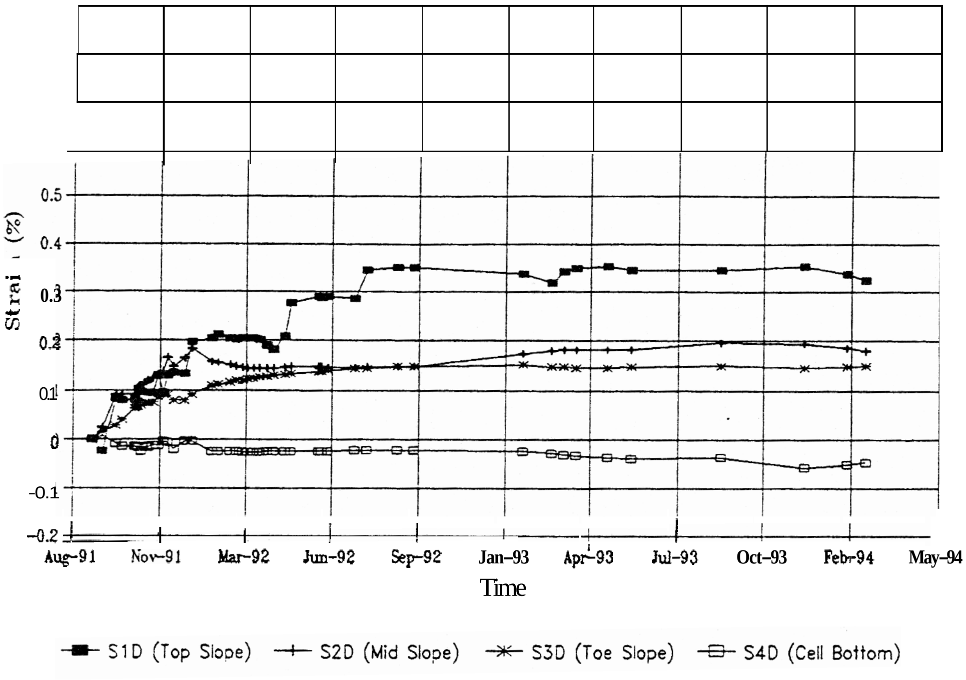

Figure 11. Strain Responses of Station D Gauges.

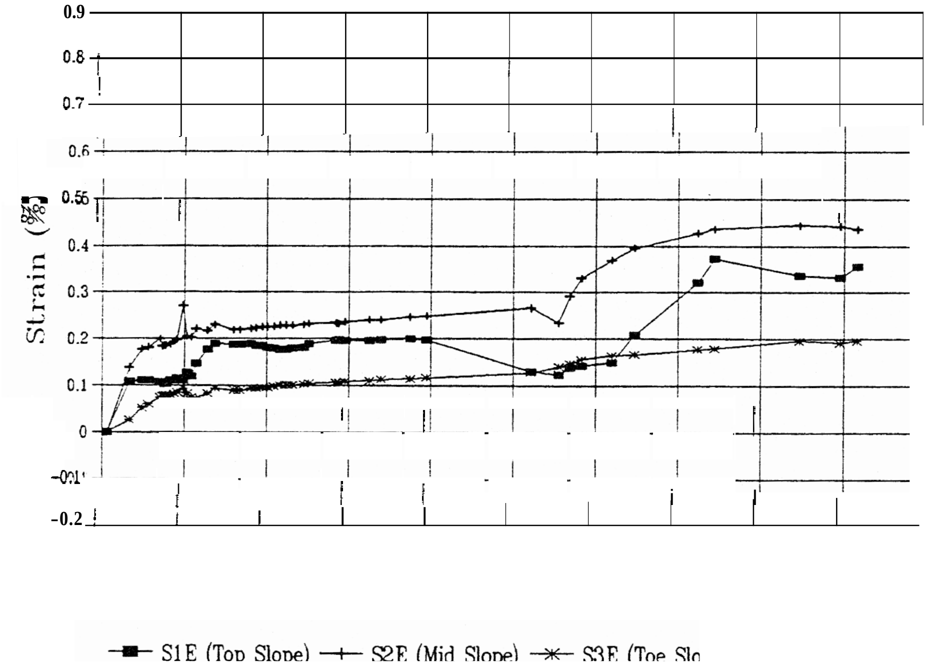

Figure 12. Strain Responses of Station E Gauges.

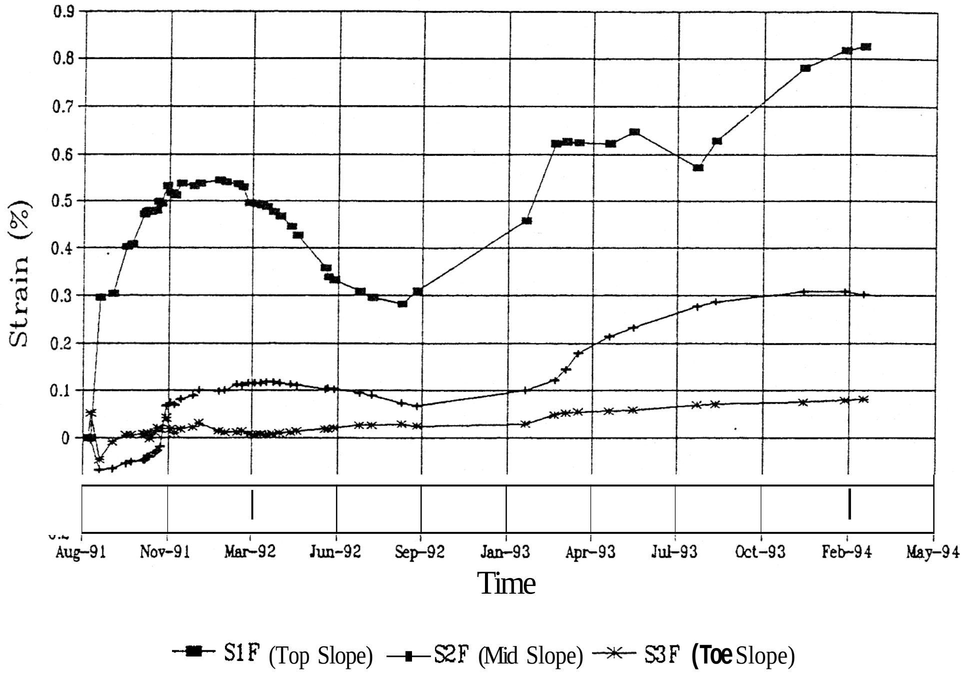

Figure 13. Strain Responses of Station F Gauges.

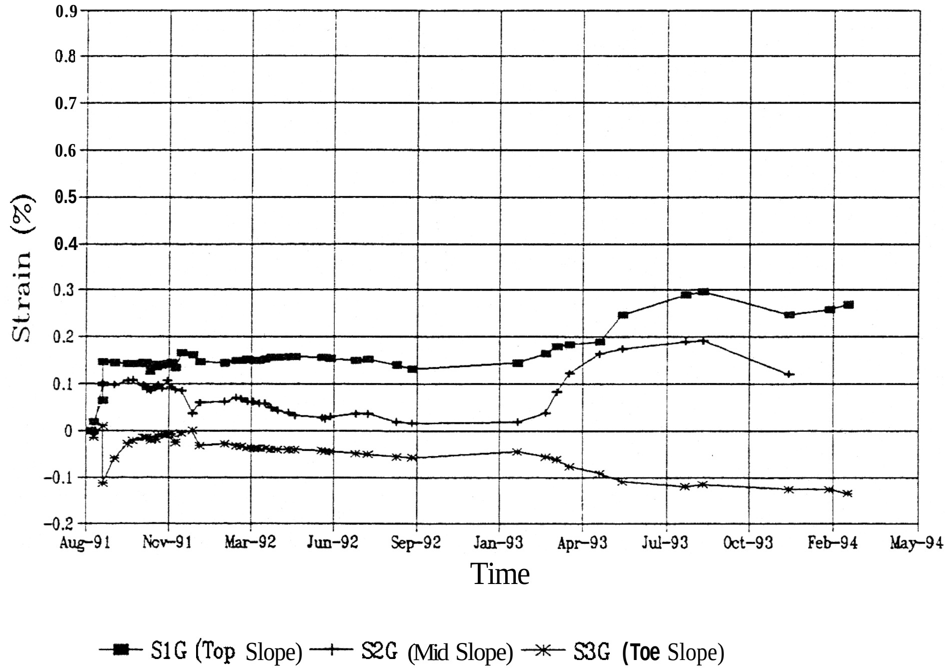

Figure 14. Strain Responses of Station G Gauges.

Presented in Table 1 is a summary of the results of this investigation.

Station	S1	S2	S3	S4	Comments
A	---	---	---	-0.07%	Stable
B	---	---	---	0.06%	Rising
C	0.12%	0.19%	0.02%	-0.08%	Stable
D	0.32%	0.18%	0.15%	-0.05%	Stable
E	0.36%	0.44%	0.20%	---	Rising
F	0.83%	0.30%	0.08%	---	Rising
G	0.27%	0.12%	-0.13%	---	Rising
Average	0.38%	0.25%	0.06%	-0.04%	

Figure 12 shows the response of the three gauges installed at station E. The gauge at the top of the slope (S1E) had residual strain of approximately 0.36%. The initial five month response of this gauge was predictable due to waste placement operations, and then about two years into the data collection the strain jumped from 0.24% to 0.44%. This jump in strain can be attributed to an access ramp that was built directly over the string of gauges. The gauge at the middle of the slope (S2E) was actually straining more than the gauge at the top of the slope (S1E), at about 0.44%. The gauge at the toe of the slope (S3E) had residual strain of 0.20% at this station.

Figure 13 shows the response of the three gauges installed at station F. The gauge at the top of the slope (S1F) had residual strain of approximately 0.83%. This strain reading was the highest measured during the investigation. The gauge at the middle of the slope (S2F) was strained at about 0.30% while the gauge at the toe of slope (S3F) was strained at 0.08%.

Figure 14 shows the response of the three gauges installed at station G. The gauge at the top of the slope (S1G) was strained at about 0.27%. The response of this gauge a year and a half into the data collection jumped from 0.14% to 0.30% strain due to an additional lift of waste placed above this station. The gauge at the toe of slope (S3G) was strained in compression at 0.13%. This is the first time that one of the gauges on the side slope has gone into compression and could be indicative of the geomembrane shifting down the slope and bunching up at the toe of the slope.

SUMMARY AND CONCLUSION

From the collective strain gauge responses it was evident that a full scale operating landfill can successfully be instrumented with strain gauges over a long period of time. The gauges were dependable in all but one case.

As can be seen by the average residual strains in Table 1, gauges at the top of the slope were straining more than the gauges at the bottom of the slope. This finding confirms theoretical speculation throughout the technical literature as discussed by Giroud, Morel (1993) and Roerner (1987). In the cases where gauges showed an abrupt peak and then a lengthy residual response, it is believed that the initial peak was due in large part to the stresses caused by the placement of overlying material and the residual response was due to relaxation of material over time. In most cases the response can be explained by daily operational procedures at the facility.

Site specific design of the composite landfill liner system using the methodology presented by Koerner (1990) predicted a residual HDPE strain at the S1 stations of 0.19%. Given the difficult nature of in-situ strain measurements, the average recorded strain at the S1 locations of 0.38% validates the design methodology used, and indicates that the lining system at YCCL is performing as designed.

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- Micro-Measurement staff for their technical assistance.

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