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GRI Standard - GS3[*]

Standard Guide for

Selecting In-Situ Monitoring Methods and Devices for the Evaluation of Geosynthetic Performance

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1. Scope

1.1 This guide presents the various methods and devices that have been successfully used to monitor and evaluate geosynthetic performance in the field.

1.2 While this guide covers all types of geosynthetics, and monitoring for all types of applications, the reinforcement area using geotextiles and geogrids is the most advanced. As such, it supersedes the previous GRI Standard GS3.

1.3 This guides focuses not only on the geosynthetic material, per se, but also on the adjacent soil, e.g., geosynthetics used in separation, filtration and drainage application. In this regard it is the geosynthetic related system that is being monitored.

2. Referenced Documents

2.1 General Reference

Koerner, R. M., 1996, "The State-of-the-Practice Regarding In-Situ Monitoring of Geosynthetics," Proc. Geosynthetics: Applications, Design and Construction, M. B. de Groot, G.

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[*] This GRI standard is developed by the Geosynthetic Research Institute through consultation and review by the member organizations. This specification will be reviewed at least every 2-years, or on an as-required basis. In this regard it is subject to change at any time. The most recent revision date is the effective version.

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den Hoedt and R. J. Termaat, Eds., EuroGeo I, Maastricht, Netherlands, A. A. Balkema Publisher, pp. 71-86.

2.2 Specific References

(see section 14)

3. Summary of Guide

3.1 This guide describes state-of-the-practice (not state-of-the-art) methods and devices for the in-situ monitoring of geosynthetics and geosynthetic related systems. As such, all of the methods and devices that are described have shown successful performance in the past and are referenced in the open literature.

3.2 All of the devices that are included in the guide are commercially available, or can be assembled using commonly available materials.

3.3 The guide contains specific recommendations as to both recommended and optional methods and devices to be used with different geosynthetics.

3.4 The guide also gives selected descriptions and commentary on the various methods and devices that are recommended.

3.5 The guide is organized around each particular type of geosynthetic on the basis of the particular function that the geosynthetic is called upon to serve.

4. Significance and Use

4.1 The guide is meant to provide information to owners and/or regulatory agencies that the geosynthetic or geosynthetic related system is performing safely.

4.2 The guide is meant to provide information to the engineer and/or manufacturer that the methods utilized in design are realistically providing technically sound, yet economical, installations.

4.3 The guide provides information to the potential user of the geosynthetic that is under consideration about the variety of monitoring methods and devices that are available.

4.4 The guide organizes and categorizes the potential methods and devices in such a way as to be compatible with the primary function that the geosynthetic may be called upon to serve.

5. Structure of Guide

5.1 In this guide, the in-situ monitoring of each type of geosynthetic or geosynthetic related system will be addressed by its primary function in the order presented in Table 1.

5.2 Where appropriate, monitoring of the adjacent soil, rock or structure will also be included. When liquid is the medium of interest, e.g., in filtration or drainage, its monitoring will be addressed accordingly. Thus, the guide addresses in some cases the monitoring of the geosynthetic related system, not only the geosynthetic material itself.

Table 1 - Geosynthetics and their Associated Primary Functions

Type of Geosynthetic	Various Primary Functions				
	Separation	Reinforcement	Filtration	Drainage	Barrier
geotextile	-	-	-	-	-*
geogrid					-
geonet			-		
geomembrane					-
geosynthetic clay liner					-
geocomposite	-	-	-	-	-

*when modified to be relatively impermeable

6. Monitoring of Geotextile Systems

This section focuses on geotextile related applications serving the primary functions of separation, reinforcement, filtration, drainage or as a liquid barrier. Each function will be addressed in separate subsections.

6.1 Geotextiles in Separation

Geotextiles as separators are often thought of as being rather minor applications. Yet, they are generally permanent and can be critical in their application. In this section, the monitoring of three specific areas will be described;

- geotextiles as separators in railroad applications,
- geotextiles as separators in highway applications, and
- geotextiles as protection materials for geomembranes.

6.1.1 Railroad Applications

An early project involving the in-situ monitoring of railroad track systems with geotextiles as separators was a full scale comparative test site described by Richardson (1985) and Chrismer and Richardson (1986). Four different needle punched, nonwoven, geotextiles were placed on a soil subgrade with railroad ballast placed above. Each section was 90 m in length. Control sections having no geotextiles were also constructed. The railroad ties and track were placed on the ballast in a uniform and conventional manner. The monitoring associated with the project was extensive, see Figure 1. Included were the following;

- soil water content measurements via electrical resistance transducers and electrical inductance gages,

- pore water pressures via pneumatic transducers and diaphragm sensors,
- track subgrade response via dynamic response earth pressure cells,
- static and dynamic subgrade deformation via vertical LVDT extensometers,
- track tie plate loads via dynamic load cells, and
- track tie strains via electrical displacements gages.

Note that the geotextiles were not monitored directly. The beneficial effects of the geotextiles were evaluated indirectly from the performance of the adjacent soil, water and track system. Monitoring occurred over time and the results were compared to initial readings, to the control sections and (in this case) to the response of other sections with different geotextiles.

6.1.2 Highway Applications

A similar use of geotextiles as separators between soil subgrade and stone base course materials in highway pavements is another major application area. The general focus of monitoring is to gather information for quantification of the benefit/cost ratio of the geotextile solution versus a soil separating layer, or no separator at all. Instead of monitoring the geotextile or soil/water system beneath the geotextile, it is usually the surface of the paved highway that is monitored. In this regard, there are a number of techniques which can be used by themselves or in combination with one another, e.g.,

- physically measuring deflections under load, e.g., Benkleman beam or falling weight deflectometer,
- using truck mounted accelerometers to measure surface roughness,
- using truck mounted ultrasonic height measurements to measure rutting, and/or
- physical measurement of crack lengths and crack density patterns that develop over extended use of the highway.

6.1.3 Protection Applications

In a significantly different application than those described above, geotextiles have long been used as protection materials against the puncture of geomembranes. A common situation is in landfills where the geotextile acts as a separator between overlying coarse drainage stone and the underlying geomembrane hydraulic barrier. A major effort in assessing the performance has been expanded in Germany. While not in-situ monitoring, per se, Heerten (1994) has field exhumed a number of field sites to visually observe the effects of the stones insofar as geomembrane indentation is concerned. Brummermann, et al. (1994), has quantified the geomembrane indentations to arrive at a maximum strain value. Their study is based on graphic methods utilizing the segment of a circle or on a polygon shaped protrusion. Unfortunately, there is no current method of in-situ monitoring other than leak detection of penetrations in the geomembrane from unsatisfactory performance. Such leakage monitoring will be described later. Clearly, the need for protection monitoring material effectiveness is an area for future development.

6.2 Geotextiles in Reinforcement

Geotextiles as reinforcement materials have been a major topic for in-situ monitoring. Three categories of geotextile reinforcement can be identified: embankments over soft soils, reinforced walls and reinforced slopes. Regarding embankments over soft soils, pioneering work reported by Sluimer and Risseeuw (1982), Risseeuw (1984) and Risseeuw and Voskamp (1984), led to a technique of applying 100 mm long electrical resistance strain gages directly on high strength geotextiles for measurement of strain, see Appendix "A". Critical is the preparation and bonding of the gage to the geotextile, its waterproofing and protection materials and the procedure of extending the wire leads to the monitoring station. This work has lead to the routine use of such geotextile monitoring for a wide range of applications, for example;

- reinforced walls,
- reinforced steep soil slopes,
- reinforced embankments on soft foundation soils,
- reinforcement of unpaved roads,
- reinforcement of new landfills placed on existing landfills,
- bridging over soft foundation areas separated by pile foundations,
- bridging over subsidence prone areas such as karst, thermokarst, backfilled pipelines, etc.

The output of each gage is in strain units. They can usually function up to 8-10% strain at which point debonding begins to occur. To accomplish conversion to stress units, a stress vs. strain calibration curve from a wide width laboratory tensile test of a representative test specimen is necessary. The original survival rate of such gages during construction was low, however, current projects indicate that a 50 to 75% survival rate of such installations should be possible.

Electrical resistance strain gages, however, are not the only method of monitoring geotextiles used as reinforcement. Bourdeau, et al. (1994) report on the use of inextensible flexible cables, which result in deformation at the point of attachment. By comparing adjacent point deformations, strain over a considerable distance can be calculated and converted to stress as deemed necessary. This approach has been used by Guglielmetti, et al. (1996) for monitoring the deformation across the seams of high strength geotextiles. By attaching wire strand to both sides of a sewn seam, the deformations across the seam were monitored. Unfortunately in the case history sited, the results were questionable due to an insufficient slack and lack of dead weight tensioning of the wire strands. Unless all slack is removed in the strand, the accuracy of the measurements will be suspect at least for small deformations.

In the categories of reinforced walls and slopes a very early effort was carried out by Delmas, et al. (1988). They instrumented a 4.0 m high wrap-around geotextile wall with electrical resistance strain gages on the foundation beneath the wall and surveying points on the face of the wall. Short term movement after removal of the falsework and long term movements after placement of a surcharge load were the monitoring objectives. The wall, built in 1971, was one of the earliest attempts at this type of construction and accompanying monitoring.

Graf and Studer (1988) have assessed a number of instrumented walls and slopes where the usual monitoring was for determination of tensile forces in the reinforcement, displacements at various locations in the soil mass and soil pressures at the face and/or foundation interfaces. Their goal was to verify design concepts and assumptions.

More recently Rowe and Gnanedran (1994) report on a number of strain measurement techniques on a high strength geotextile reinforced test embankment. Included were electrical resistance strain gages, mechanical gages for deformation and electromechanical gages consisting of thin metal rings fastened to the geotextile.

Needless to say, the state-of-the-practice of direct monitoring of geotextile reinforcement using strain gages or deformation gages is well advanced at this point in time.

6.3 Geotextiles in Filtration

Since the initially reported cases of using geotextiles as filters in the 1960's (recall that an original name of geotextiles was "filter fabrics") related applications have expanded tremendously. Highway engineers throughout the world regularly use geotextiles instead of the conventional 150 mm thick sand filter layers of the past. Visual observations attest to the viability of their use. In-situ monitoring is essentially a moot point with the notable exception of contaminated liquids like landfill leachates. In such cases the focus of the monitoring is not the geotextile, per se, but the possible head of leachate buildup above the geotextile.

An example of such an in-situ monitoring system is at a Canadian landfill, Pullen (1995). The instrumentation system measured leachate levels above the leachate collection system, (which included a geotextile filter) within the solid waste itself. The system consisted of a level meter and recording system, which pneumatically measured back pressure on the filter. It then converted the analog signal to digital data for continuous display and storage within an internal memory unit. The stored data was downloaded by software to a laptop computer. The data was placed on a spreadsheet for analysis and graphing. All measurements were recorded in real time. Periodically, the memory of the data logger was downloaded and the file analyzed and graphed for long-term records.

Examples such as the above appear to focus on the major concern of geotextile filters, i.e., the possibility of excessive clogging. Clearly, upgradient monitoring of pore pressures is within the state-of-the-practice. Alternatively, outflow from the system could be monitored along with sediment yield. This is routinely done during the collection of leachate from waste facilities. Information on flow rates over time are available for qualitative assessment, Bonaparte and Othman (1996).

6.4 Geotextiles in Drainage

To monitor the performance of geotextiles in drainage applications, the obvious procedure is to actually measure the liquid's flow rate as it passes within and/or through the geotextile. Yet, for most geotextiles such flow rates are relatively small, e.g., in comparison to a geonet or drainage geocomposite. Thus emphasis in geotextile drainage applications is on liquid heads or on pore water pressures within the geotextile or adjacent upstream soil. However, there are no known monitoring case histories focused on geotextile drainage applications at this point in time.

6.5 Geotextiles as Barriers

Geotextiles as moisture barriers have their greatest applicability when used in highways to retard reflective cracking in bituminous overlays. The Liege conference on this topic presented a significant accumulation of literature on the subject, Rigo and Degeimbre (1989). The usual focus of field monitoring has been at the surface of the bituminous overlay. Various papers described the following;

- general visual observations over time,
- detailed crack length and crack density patterns over time,
- comparative behavior with respect to control sections,
- comparative behavior with respect to different materials,
- static load displacement amplitudes,
- falling weight deflectometer readings, and
- rutting measurements using laser devices.

None of the papers, however, described the monitoring of the soil subgrade or stone base course beneath the pavement structural section. Note that there have been two subsequent conferences on this same topic, RILEM (1993 and 1996).

Geotextiles impregnated with bitumen or polymers, and geotextiles used as substrates for factory placed bituminous layers, used as liners for environmental applications will be considered later. In those cases, the focus will be on leakage rates from landfills or surface impoundments where a number of monitoring strategies are possible.

7. Monitoring of Geogrid Systems

The primary function of geogrids is generally that of reinforcement. When the system is permanent and/or of a critical nature, in-situ monitoring may be considered. Numerous studies on walls, slopes and foundation reinforcement applications are available. The focus is usually on the geogrid itself, where short term strains and long term creep and/or stress relaxation are the general monitoring goals.

7.1 Geogrid Wall Reinforcement

By their very nature, vertical walls are critical structures. In-situ monitoring of unitized geogrids using electrical resistance strain gages bonded directly to the longitudinal (high stressed) ribs is an outgrowth of laboratory testing, McGown, et al. (1984). An early field application by Jones is reported in Parkinson (1983). Appendix "B" presents the technique of bonding a strain gage to a unitized geogrid at its minimum cross section whereby stresses are the highest. Many geogrid projects have been monitored in this manner. Alternatively, on flexible geogrids one could use inductance coils, see Appendix "C". While relatively large in size, an LVDT protected within a sliding guide tube has also been used, Barr, et al. (1994).

Other than monitoring the geogrid itself, horizontal extensometers have been used to monitor long-term creep deformation of the backfill soil. Presumably, if the soil is moving, the reinforcement is not functioning as intended. Additionally, the pressures exerted against the wall facing can be monitored. Berg, et al. (1986) used load cells against two large geogrid reinforced walls and found relatively low lateral pressures. Coupled with low values of measured strains in the geogrid reinforcement, the implications were that current design methods are probably conservative.

The most recent methods being implemented to monitor mechanically stabilized earth (MSE) walls, berms and slopes is the use of laser, lidar or radar to monitor the exposed face over time. Using such techniques one can precisely determine the distance of the face of the structure to a stationary measuring point. This can be done in length sections of any separation distance. Over time the process is repeated and differences from the baseline (if any) can be calculated with extreme precision.

7.2 Geogrid Slope Reinforcement

Paralleling the geogrid wall reinforcement monitoring just described, steep soil slopes have also been monitored. Devata (1984) reports on electrical resistance strain gages bonded directly to unitized geogrids along with horizontal magnetic extensometers to monitor soil creep. Hermann and Burd (1988) report on the instrumentation of a geogrid reinforced steep slope used as a snow avalanche barrier. The geogrids were designed as wrap-around facings on both sides of the barrier, see Figure 2. The instrumentation consisted of the following;

- inductance gages (Bison-type) to measure geogrid extensions (recall Appendix "C"),
- earth pressure cells (Glotzl-type) to measure lateral pressures,
- magnetic extensometers to measure lateral soil displacement, and
- thermometers to measure soil temperature.

The intention was to provide in-situ performance to check on assumptions made during the design process.

7.3 Geogrid Foundation Reinforcement

Geogrids have been used in many foundation reinforcement configurations. Soft soil foundation monitoring reported for geotextiles has a complete parallel when geogrids are used. There are, however, additional cases of foundation reinforcement monitoring that can be presented.

Alexiew, et al. (1995) report on the monitoring of flexible geogrids used to reinforce soil over the pile caps of deep foundations, see Figure 3. The geogrids reinforce the overlying soil between the relatively wide spaced pile caps and eliminate the need for battered piles at the edges of the embankment. The instrumentation, described by Verspohl and Gartung (1995), consisted of the following;

- strain gage elongation measurements of the geogrids between and above the pile caps using both static and dynamic measurements, and
- vertical extensometers to monitor sag in the geogrid at its various levels along with rotation of the pipe caps.

The focus of the study was to assure the adequacy/safety of the system but also to validate the accuracy of the "membrane-effect" design model that was used, see Jones, et al. (1990).

8. Monitoring of Geonet Systems

The primary function of a geonet is its in-plane drainage capability. Generally the medium is liquid, although gas transmission is also a possible application area. Regarding in-situ performance, the geonet's inflow versus outflow is the obvious target to monitor. While various flow monitoring schemes (like tipping buckets) can be used, one large scale case history involving geonets will be described here.

In constructing liners for landfills, the use of double containment is considered by many to be the ultimate in providing for a safe and secure facility. Between the upper and lower barrier layers, a drainage system is required. Its purpose is to monitor (and collect) leakage coming through the upper liner. The drainage layer is often regulated as being a 300 mm thick layer of sand of high permeability. Alternatively, a geonet can be used, if shown to be technically equivalent.

In a case history reported by Eith and Koerner (1992), 25,000 liter charges of water were introduced in a geonet at the upgradient side of a 192 m long rectangular landfill cell and recovered at the downgradient sump. The first charge of water produced an in-situ transmissivity of the geonet calculated as being 45.2 x 10^{-4} m^2/s, see Table 2. After approximately 14 m of solid waste was placed in the 1.5 ha landfill, the flow test was repeated with a resulting transmissivity of 43.5 x 10^{-4} m^2/s. A third flow test was conducted after 28 m of solid waste was placed, with a resulting transmissivity of 40.0 x 10^{-4} m^2/s. The slight decrease of transmissivity was attributed to the increasing geomembrane intrusion into the apertures of the geonet by the increased pressure of the solid waste. The test was a success and resulted in geonets being substituted for the sand drainage layer. The case history represents the ultimate in in-situ monitoring, wherein the entire system to be evaluated is challenged in-toto.

Table 2. Summary of full scale flow tests on a geonet leak detection system, after Eith and Koerner (1992).

Situation or Condition	Dates of Test		
	No-load 18-19 Nov. 1987	Mid -Load 22-23 Dec. 1987	Full-Load 15-16 Mar. 1977
Diameter of HDPE injection pipe, mm	100	100	100
Diameter of HDPE exit pipe, mm	100	100	100
Diameter of detection manhole,	1.82	1.82	1.82
Total cell area, ha	1.54	1.54	1.54
Approximate geonet wetted area, ha	0.87	0.87	0.87
Approximate geonet wetted width (maximum), m	45.7	45.7	45.7
Straight line geonet flow distance, m	192	192	192
Elevation of point of injection, m	95.07	95.07	95.07
Elevation of geonet discharge sump and secondary boot, m	89.95	89.95	89.95
Approximate cell bottom slope, %	2.9	2.9	2.9
Volume of water injected, liters	2612	2321	2268
Approximate time interval for injection, min	18	17	12
Volume of water recovered at 15 hours, liters	2453	2079	1841
Percent of injected water recovered at 15 hours, %	93.9	89.6	81.2
Time interval between injection and arrival at detection manhole, min	100	104	113
Maximum peak instantaneous flow recorded, liters/min	28.2	29.7	29.7
Approximate height of waste (at 10.8 kN/m^3 unit weight), m	1.1	13.9	28.3
Approximate geonet compressive stress, kPa	12	153	311
Calculated transmissivity, m^2/s	45.2×10^{-4}	43.5×10^{-4}	40.0×10^{-4}

9. Monitoring of Geomembrane Systems

The primary function of geomembranes is usually that of a barrier to liquids or occasionally to gases. As such, leakage through the geomembrane is obviously the key parameter to monitor. There are many candidate leak detection systems. In this paper, they will be subdivided into stationary, portable and global systems. First, however, other design related and important geomembrane monitoring concerns such as in-plane and out-of-plane tensile stresses will be described. Temperature monitoring is important and will also be described.

9.1 Geomembrane Stress Monitoring

While general design practice is not to induce tensile stresses in geomembranes, there are two situations where some tensile stressing is inevitable. These are in-plane tensile stresses on side slopes caused by the overlying soil or solid waste, and out-of-plane tensile stresses caused by subsiding soil or solid waste.

Regarding the monitoring of in-plane tensile stresses, the situation is quite straightforward. Electrical resistance strain gages bonded directly to geomembranes have been used, see Koerner and Wayne (1991), see Appendix "B". Yazdani, et al. (1995) have used a series of such gages beneath solid waste from the base up the side slopes and into the anchor trench. Strains were maximum at the top of slope (0.12 to 0.83%) and diminished progressively down the slope. At the base of the slope and along the bottom, the tensile strains were essentially zero.

Regarding the monitoring of out-of-plane tensile stresses, the same type of electrical resistance strain gages have been used to monitor geomembranes during the densification of the overlying solid waste using deep dynamic compaction. Galenti (1994) reports on twin 2 ha cells (one compacted by standard methods, the other by deep dynamic compaction) where the gages monitored the dynamic pulses and the residual strains in the underlying geomembrane. The pulses were indeed detected, but no residual strains were indicated upon cessation of the compaction activity.

A related concern regarding out-of-plane tensile stresses has to do with vertical and horizontal expansions of landfills. The surcharge load created by the proposed solid waste expansion will cause settlement of the existing solid waste. The concern is not over total settlement which can be estimated, but over differential settlement. Since this type of settlement promises to be quite random in its occurrence, the location of the strain gages represents a major challenge. Clearly, this is an area for additional investigation.

9.2 Geomembrane temperature monitoring

Temperature monitoring of geomembranes used for solid waste landfill containment is another area for which feedback to the design community is necessary. Koerner and Koerner (1995) report on the temperature monitoring of a geomembrane liner, the leachate collection system, the solid waste itself and the geomembrane cover. The temperature was monitored by thermocouples which consist of dissimilar metals in which a continuous current flows. For this case history, the thermocouple wires were bonded to the area of concern and the thermocouple wires were brought to the monitoring station. The system consisted of 20 monitoring units. The only equipment required was a reference junction compensation unit. Thermocouples are robust and quite cost effective for temperature monitoring. Table 3 presents temperatures recorded over a 3-year period at this municipal solid waste landfill which is a 4 ha site with approximately 30 m of waste. The project is still ongoing.

Table 3. Temperatures monitored at a municipal solid waste landfill near Philadelphia over a three year period, Koerner and Koerner (1995).

Location	Min. Temp.	Ave. Temp.	Max. Temp.
geomembrane beneath waste	17°C	21°C	24°C
leachate collection stone beneath waste	14	17	20
within the solid waste itself	15	24	30
geomembrane above waste covered by 3 m of soil	3	24	35

9.3 Stationary Leak Location Monitoring

The concept of placing electrically conducting wires on an orthogonal grid pattern beneath a geomembrane has been brought from the laboratory to the field over the past 10 years, Koerner, et al. (1984). The wires are used as conductors for electrical transmission, time domain reflectrometry or acoustic emission monitoring to sense if, and where, a leak is occurring. The accuracy of location of a leak depends on the spacing of the wires. The wires can also be woven into a geotextile which is placed beneath the geomembrane being monitored. In this case, the wire pattern remains fixed and a puncture protection material is also provided. Stationary electrode placement is another concept which follows along similar lines.

The readout from these systems is an electrical pattern which of itself may give the leak location or may be compared to previous readings to determine if significant changes are occurring.

There are numerous organizations providing monitoring services of this type. Some have proprietary and/or patented systems. The workshop on liner leak monitoring and location technologies in these proceedings provides additional insight into this category of monitoring.

9.4 Portable Leak Location Monitoring

The concept of constructing a geomembrane lined facility, covering it with a nominal amount of water and then creating an electric field dates to the early 1980's; Schultz, et al. (1984) and Darilek, et al. (1989).

An electrical source is used to inject current across the boundary of the geomembrane. When a current is applied between the source and remote return electrodes, current flows either around the entire site (if no leak is present) or bypasses the longer travel path through the leak itself (when one is present). Potentials measured on the surface are affected by the distributions and can be used to locate the source of the leak. These potentials are measured by "walking" a probe in the water. The operator walks on a predetermined grid layout and marks where anomalies exist. The technique must be modified where water does not cover the geomembrane, e.g., on side slopes.

For situations where the liquid is deep, as in existing surface impoundments, or hazardous liquid impoundments, a remote probe can be floated or dragged from one side of the facility to the other. There are many variations on this theme as reported by Peggs (1993).

9.5 Global leak monitoring

Perhaps the most reliable and fail-safe method of monitoring for geomembrane leakage is to provide a complete drainage system, i.e., construct a global lysimeter, beneath the geomembrane in question. This, of course, requires a secondary geomembrane beneath the drainage layer and is the essence of the double liner system. Such double lined systems with an intermediate drainage layer (soil or geonet) are mandated in the USA and Germany for hazardous waste landfills. The drainage layer, aka leak detection layer, flows gravitationally to a sump where a pipe riser is located. This pipe is placed between the two geomembranes and penetrates the primary geomembrane at the surface. It exits accordingly for eventual monitoring using a submersible pump, see Figure 4. This monitoring design is in considerable favor over vertical manhole risers through the waste and gravity flow penetrations passing through the secondary liner system. In the former case, negative skin friction generating large downdrag forces are created by the settling waste mass. In the latter case, the penetration of the secondary liner system is very troublesome from a construction perspective and it occurs at the lowest elevation of the facility where leachate heads are the highest.

Such systems are powerful controls on the performance of geomembranes and are mandated by a number of states in the USA for municipal solid waste as well as for all types of hazardous waste.

The above concept of the double liner strategy with leak detection has recently entered a new era with the advent of the *Vienna Cutoff Double Wall System*, Brandl (1994). The double liner concept is used but now in a vertical deployment as shown in Figure 5(a). It is illustrated for both abandoned waste sites and newly constructed landfills. Figure 5(b) shows the double wall system with a geonet leak detection layer between the two geomembranes. Figure 5(c) shows an important variation of the concept where the primary and secondary geomembranes are segmented by cross walls which compartmentalize the leakage. Thus the leakage can be isolated to specific zones. This concept provides an excellent strategy for monitoring and controlling leakage from waste sites and is felt to be the essence of an environmentally safe and secure containment system.

10. Monitoring of GCL Systems

As with geomembranes, the primary function of geosynthetic clay liners (GCLs) is as a barrier layer. Leakage is again the key monitoring variable and all of the discussion in the previous section is applicable to GCLs as well as with geomembranes. Additionally, one might measure the in-situ permeability of the GCL as is conventionally done with compacted clay liners, see Didier and Cazaux (1996). There is one additional aspect of monitoring GCLs, however, which should be addressed.

GCL's owe their low permeability to bentonite which is contained between two geotextiles or bonded to a geomembrane. With the bentonite hydrated, its permeability is approximately 1 to 5 x 10^{-11} m/sec thus making GCLs excellent barrier materials. Along with this low permeability, however, is a concern over low shear strength. Three interfaces are involved; the upper and lower interfaces, and within the midplane of the GCL. Obviously, steep side slopes are locations of particular concern.

Tanays, et al. (1994) report on geomembrane/ GCL composite lined side slopes of a set of four landfill waste cells. Instrumentation was installed on two cells (at 1:1 and 1:2 slopes) to assess their behavior. The geomembranes were monitored for tensile forces using electronic transducers. Data was provided for up to 100 days. The GCL components were monitored for deformation between points spaced at 0.5 to 0.7 m distance from one another. Each point was brought by a cable protected in a tube extending to the top of the slope. Strain in the lower portion of the GCLs amounted to 1.0 to 1.5 %. At the top of the GCLs, it was zero.

In another case history, the focus of the monitoring program was the midplane shear deformation of GCLs, Koerner, et al. (1996). Fourteen full scale test plots had five different types of GCL's deployed on 1:2 and 1:3 slopes. Various landfill cover situations were simulated by using GCLs in association with geomembranes, drainage geonets and erosion control materials. Monitoring included gypsum cylinders for subgrade moisture content, fiberglass wafers for bentonite moisture content and wire "telltales" for GCL midplane deformation monitoring. Ten sets of telltales were placed on the GCLs at each of the fourteen test plots. Each set consisted of a deformation monitoring point on the top and a companion point on the bottom of the GCL. Thus deformation differences between top and bottom indicated differential movement of the GCLs within their midplane. The monitoring points were flattened fish hooks embedded in the geotextiles and geomembranes and epoxy bonded in the localized area. Connected to each point were stainless steel wires protected in plastic tubes extending to the top of the slope. By observing movement of the wires on a measurement table, relative deformation of each set of top and bottom points was obtained. Table 4 presents the differential deformation at the toe of slope of the various test plots 330 days after construction and 160 days after cutting the upper geosynthetics to transfer stresses to the midplanes of the GCLs involved. Plot "F" is in a obvious state of major movement with the top surface moving with respect to the bottom. It has recently slid as a complete soil/upper geomembrane mass.

Table 4. Relative deformation of GCLs at Cincinnati test plots at toe of slopes 330 days after construction, Koerner, et al. (1996).

Plot	Product	Bottom of Left Panel (mm)	Bottom of Right Panel (mm)	Average (mm)
A	Gundeal	+13	-8	+2
B	Bentomat	+23	-13	+5
C	Claymax	-8	+5	-1
D	Bentofix II	+5	-5	0
E	Gundseal	+20	-5	+7
F	Gundseal	+18	+500	+340
G	n/a	--	--	--
H	n/a	--	--	--
I	Bentofix I	0	-25	-13
J	Bentomat	+8	-25	-8
K	Claymax	+25	+25	+25
L	Bentofix I	+15	-5	-5
M	n/a	--	--	--
N	Bentofix II	-8	+8	0

"+" = top of GCL moves with respect to bottom
"-" = bottom of GCL moves with respect to top

11. Monitoring of Geocomposite Systems

The primary functions that geocomposites can serve are obviously product specific. Since geocomposites used in reinforcement, filtration and barrier applications are similar to those described previously they will be referenced to the appropriate section. Thus, this section only considers separation and drainage functions which have some unique monitoring schemes.

11.1 Geocomposites as Separators, i.e., Geosynthetic Erosion Control Materials

There are literally hundreds of geosynthetic erosion control materials. They combine polymeric geotextiles, geonets and geogrids with natural materials (straw, hay, mulch, coir, etc.) in very interesting and innovative products. When deployed on slopes, their effectiveness is usually monitored by the measurement of water runoff and sediment yield at the toe of the respective slopes. For open channels, vegetation density increases over a specific period and resistance to velocity and shear stresses also increases. Many studies of this type have been conducted; Armstrong and Wall (1991), Fifield and Malnor (1990) and Northcutt (1993). In all cases, the results are comparative from one system to another, and to a control section with no erosion control protection. The latter is used as the base line. Many of these projects are focused on product categorization and selection, but others are intended to provide input to formulating design methods for predictive purposes. It is an active area of research.

11.1.1 Slope/Bank Protection

Hundreds of field studies have been conducted since the early 70's that measure sediment loss and vegetated density increases on geosynthetic-protected and unprotected soil slopes. Monitoring of these slopes vary from immediately after installation to a three year "resting" period. Included in the data collection should be: plant height, percent seed germination, sediment loss, infiltration rate, rill/gully depth and visual observations.

11.1.2 Open Channels

Studies of the effectiveness of geosynthetic flexible channel lining materials have been made since 1980. Although most have shown the benefits of reinforced vegetation, the studies are either: (1) conducted shortly after installation; or (2) made using rain gauge data from major storm events. In either case, data used in the evaluation should include design storm discharges, vegetative coverage/establishment, average height before mowing, depth of accumulated sediment, total rainfall during storm events, depth of erosion (if any) and visual observations.

11.2 Geocomposites in Reinforcement

This category is similar to that of geotextiles in reinforcement (section 6.2) and geogrids in reinforcement (section 7.1, 7.2 and 7.3).

11.3 Geocomposites in filtration

This category is similar to that of geotextiles in filtration (section 6.3).

11.4 Geocomposites as highway edge drains

Geocomposite drains usually fall into categories of sheet drains, wick drains and edge drains. Of these, edge drains result in very cost effective systems providing they function for the lifetime of the associated highway system. Concerns over core blockage and geotextile clogging are often expressed and in-situ monitoring is one way to assess the performance behavior.

Dempsey (1988, 1989) has measured numerous highway edge drain installations. The basic unit is a tipping bucket at the outlet of the edge drain. When full, the bucket empties and a counter is engaged. The number of bucket tips provides the needed data to calculate a flow rate. For higher flow rates, outflow monitoring weirs can be setup along with a data logger for the desired data. For very high flow rates, automatic flowmeters can be used.

11.5 Geocomposites as barriers

This category is similar to that of geotextiles as barriers (section 6.5).

12. Summary

This standard guide has provided a wide range of in-situ monitoring methods/devices which have generally resulted in reliable data. While not known for sure, their survival rate is high, at least on a relative basis to other field monitoring methods. Note, however, that in some harsh construction installation situations, a 50% survival rate might be considered as being an acceptable survivability rate.

In order to summarize the wealth of information that exists, the format of Table 1 is preserved and superimposed on it are the methods described in this paper, see Table 5(a). The monitoring methods or devices are somewhat arbitrarily divided into recommended and optional categories. Table 5(b) gives a further description of the various methods/ devices listed in Table 5(a).

As mentioned in the introduction, the purpose of in-situ monitoring is generally to provide information as to the adequacy/safety of the installation or to provide design feedback. Both are important reasons to recommend or require in-situ monitoring. Clearly, such monitoring is the sign of a maturing industry which can assess itself and report to the user community accordingly.

13. Conclusions

It should be noted that the cost of monitoring was never mentioned. This is for a number of reasons, among which are the following;

- geosynthetic and soil materials require different levels of monitoring according to their application,
- installation costs are highly variable,
- readout equipment varies considerably,
- the duration and subsequent cost of monitoring is always an issue, and
- site location and logistics are extremely variable.

Hence each situation is site-specific and costs must be assessed on a case-by-case basis.

It is important to conceive and execute a monitoring plan with clear objectives in mind. Dunnicliff (1988) provides a methodology for organizing a monitoring program in geotechnical instrumentation. The checklist of specific steps that are recommended follows;

1. define project conditions,
2. predict mechanism(s) that control behavior,
3. define the question(s) that need answering,
4. define the purpose of the instrumentation,
5. select the parameter(s) to be monitored,
6. predict the magnitude(s) of change,
7. devise remedial action,
8. assign relevant tasks,
9. select the instruments,
10. select the instrument locations,

11. plan for factors influencing the measured data,
12. establish procedures for ensuring corrections,
13. list the purposes of each instrument,
14. prepare a budget,
15. write an instrument procurement specification,
16. plan the installation,
17. plan for regular calibration and maintenance,
18. plan for data collection, processing, presentation, interpretation, reporting, and implementation,
19. write the contractual arrangements for field services, and
20 update the budget as the project progresses.

Table 5a. Summary of monitoring methods/devices revised in this paper and categorized accordingly.

Geosynthetic Type	Function or Property	Recommended	Optional
geotextiles	separation	• water content measurement • pore water transducers	• level surveying • earth pressure cells • inductance gages
	reinforcement	• strain gages • movement surveying • inclinometers • extensometers	• earth pressure cells • inductance gages • pore water transducers • water content measurements • settlement plates • temperature
	filtration	• water observation wells • pore water transducers	• flow meters • turbidity meters • probes for pH conductivity and/or dissolved oxygen
	drainage barrier (e.g., reflective cracking)	same and geotextile filtration • surface deflections • level surveying • surface roughness measurements • profilometry (for rut depth) • crack surveying	• water content measurements
geogrids	walls	• strain gages • inclinometers • extensometers • monument surveying	• earth pressure cells • piezometers • settlement plates • probes for pH • temperature readings
	slopes	• strain gages • inclinometers • extensometers	• earth pressure cells • piezometers • monument surveying
	foundations	• strain gages • level surveying • extensometers	• earth pressure cells • piezometers • settlement plates

geonets	drainage	• flow meters • turbidity meters	• probes for pH, conductivity and/or dissolved oxygen • piezometers
geomembranes	tensile stress temperature	• strain gages • temperature measurement	•
	stationary leak monitoring	• See Peggs (1996)	•
	portable leak monitoring	• See Peggs (1996)	•
	global leak monitoring	• flow meters • downgradient wells	• turbidity meters • probes for pH, conductivity and/or dissolved oxygen
geosynthetic clay liners	global leak monitoring	• flow meters • downgradient wells	• turbidity meters • probes for pH, conductivity and/or dissolved oxygen
	shear strength	• extensometers • deformation telltales	• gypsum cylinders • fiberglass wafters • strain gages (inductance coils)
geocomposites	separation (e.g., erosion control)	• flow meters • turbidity meters	• level surveying
	reinforcement drainage (e.g., edge drains)	(same as geotextiles and geogrids) • flow meter • turbidity meters	• probes for pH, conductivity and/or dissolved oxygen
	barrier	(same as geotextiles, geomembranes and GCLs)	

Table 5b. Selected description and commentary on the methods/devices listed in Table 5a.

Category	Methods/Device	Resulting Value/Information
surveying	monument surveying level surveying settlement plates	lateral movement of vertical face vertical movement of surface vertical movement at depth
deformation	telltales	measures movement of fixed rods or wires can accommodate any orientation
	inclinometers	measures vertical movement in a casing inclined movements up to 45 deg.
	extensometers	measures changes between two-points in a borehole
strain measurement	electrical resistance gages • bonded foil • weldable inductance gages (coils) • static measurements • dynamic measurements LVDT gages	measures strain of a material over gage length, typ., 0.25 to 150 mm measures movement between two embedded coils up to 1000 mm distance apart
stress measurement	earth pressure cells • diaphragm - type • hydraulic - type	measures total stress acting on the cell, can be placed at any orientation, can also measure stress (pressure) against walls and structures
soil moisture	water observation wells	measures stationary groundwater level
	gypsum cylinders	measures soil moisture content up to saturation
	fiberglass wafers	measures soil moisture content up to saturation

groundwater	piezometers • hydraulic type • pneumatic type • vibrating wire type • electrical resistance type	measurements pore water pressures at any depth can be installed as single point or in multiple point array can be placed in any orientation
temperature measurement	bimetal thermometer	measures temperature in adjacent area to +/- 1.0 deg. C
	thermocouple	measures temperature at a point to +/- 0.5 deg. C
	thermistor	measures temperature at a point to +/- 0.1 deg. C
liquid quantity	tipping buckets	measures flow rates (relatively low values)
	automated weirs	measures flow rates (relatively high values)
	flowmeters	measures flow rates (very high values)
liquid quality	turbidity meters pH probes conductivity probes dissolved oxygen probes	measures suspended solids measures pH of liquid measures conductivity of liquid measures dissolved oxygen in liquid

Clearly, such a checklist should be considered in planning for the in-situ monitoring of geosynthetics whenever *permanent* and/or *critical* installations are under consideration or are being otherwise challenged.

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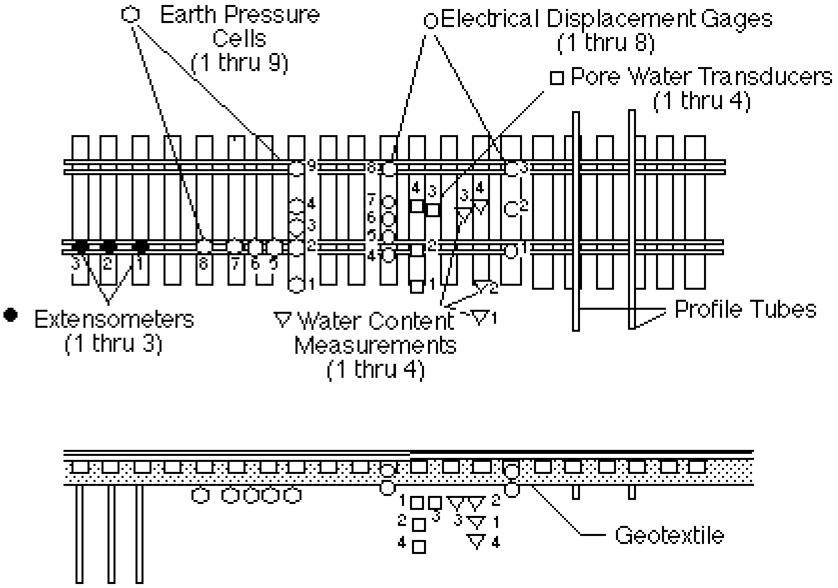
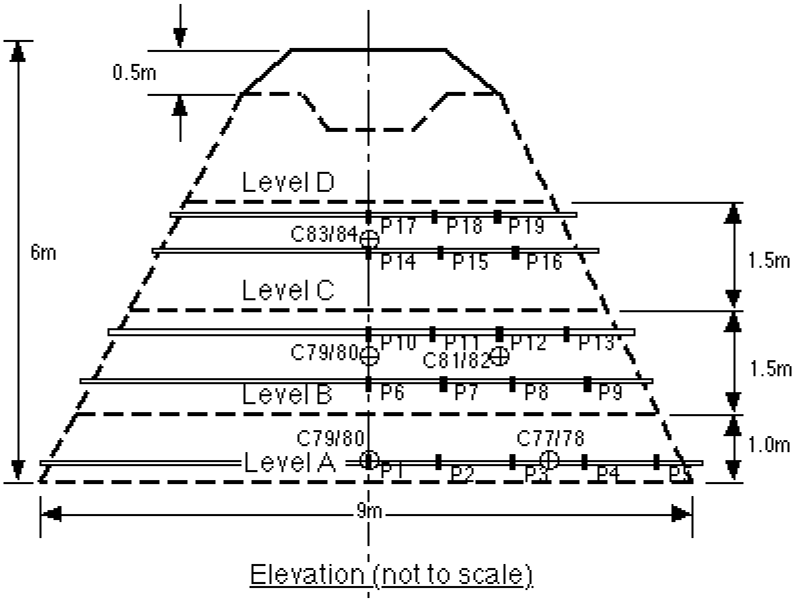
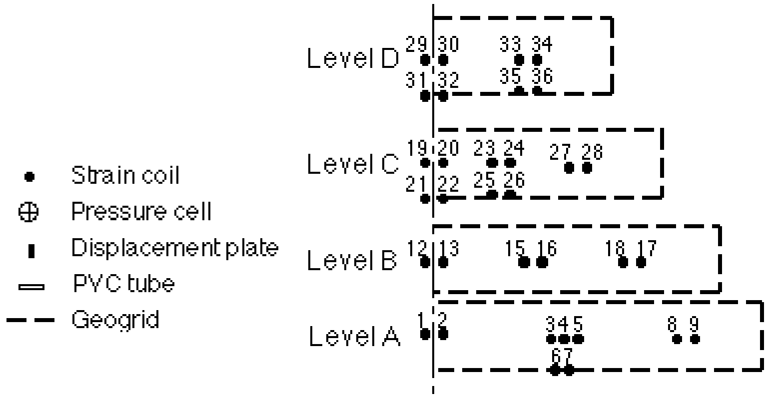


Figure 1. Instrumented railroad test site with geotextile acting as separators, after Richardson (1985).



Elevation (not to scale)



Plan View of Primary Reinforcement (not to scale)

Figure 2. Instrumentation layout of geogrid reinforced steep soil slope, after Hermann and Burd (1988).

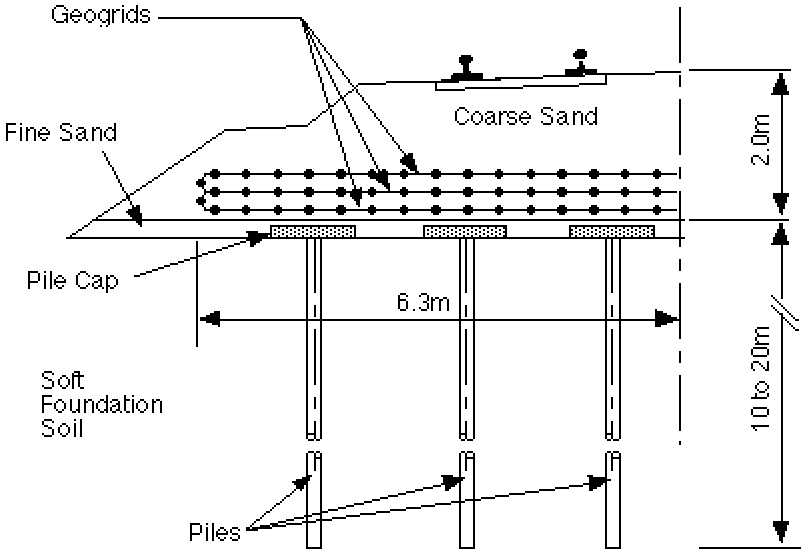


Figure 3. Geogrid reinforcement of a railroad embankment over soft foundation soil spanning pile caps,
Alexiew, et al. (1995).

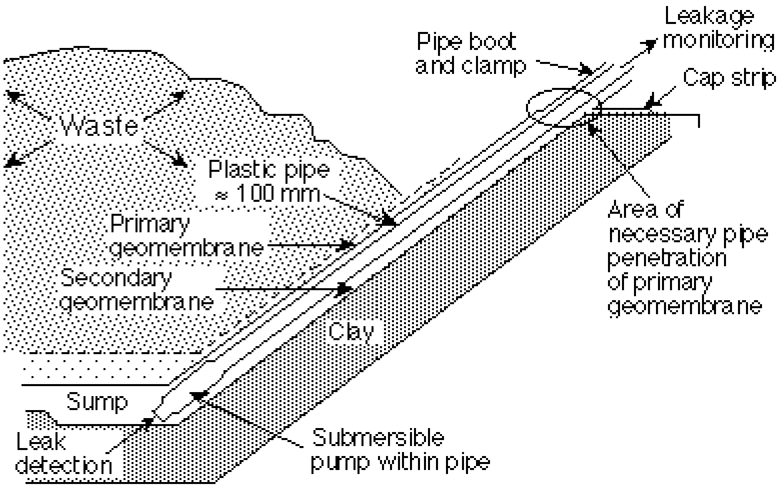
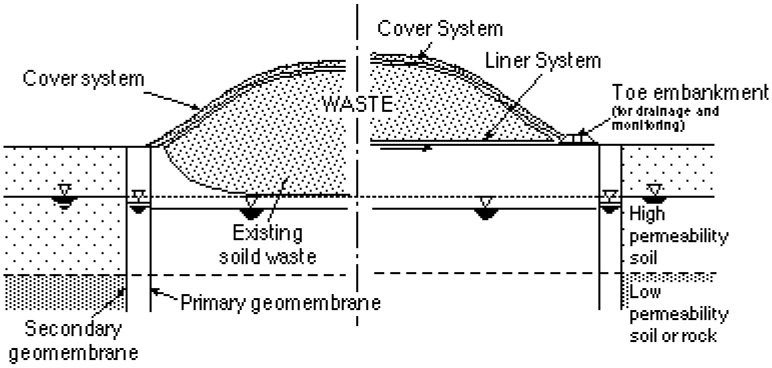
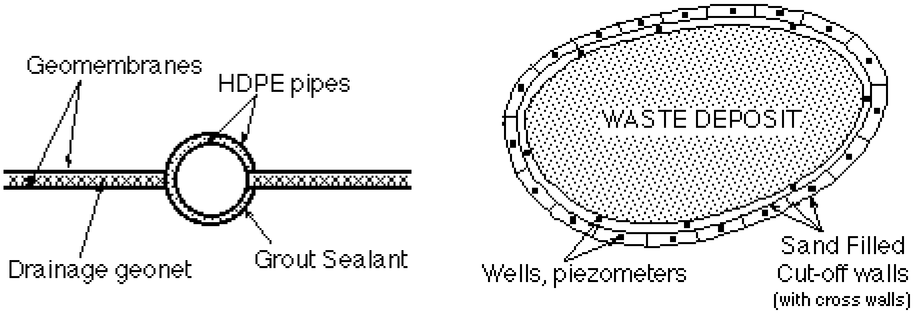


Figure 4. Leakage monitoring via submersible pump within a side slope pipe riser.



(a) Double vertical cutoff wall for abandoned sites (left) and new sites with liners beneath waste (right)



(b) Double geomembrane wall with geonet leak detection layer

(c) Double geomembrane wall with cross walls for leak location monitoring

Figure 5. Vienna cutoff double wall system, after Brandl (1994).

Appendix "A"

Method to Bond Electrical Resistance Strain Gages to Geotextiles

This procedure for bonding electrical resistance strain gages to geotextiles is written around the following assumptions.

- The geotextile is a relatively high strength fabric and is reasonably robust, e.g., its wide width tensile strength is greater than 50 kN/m (300 lb/in.)
- The strain gages are relatively long, e.g., 50 or 100 mm in length, such that a representative length of fabric can be monitored.
- The fabric is clean and dry, i.e., no soil is on or embedded in the fabric and no water is present in its voids or on its yarns.
- The assembly area for attaching the strain gages is flat and rigid, e.g., a factory or shop floor makes a good assembly area. In the field, a flat wooden board can be used.

<u>Recommended procedure for attaching a single strain gage is as follows</u>:

1. A thin layer of silicone glue is applied to the fabric surface at the desired monitoring location. [Terostatt 33 from Teroson GmbH, Heidelberg, Germany and Dow Corning 3145 RTV MIL A-46146 adhesive/sealant, Midland, Michigan have been successfully used]

2. The strain gage and bondable terminal (for attachment of the leads) are pressed into the silicone using a thin PE cover film so as to remove all entrapped air. [Strain gages Type EP-08-40, CBY-120 from Micromeasurements, Inc., Romulus, Michigan have been successfully used]

3. The gage, terminal and silicone adhesive/sealant is subjected to a light compression loading and allowed to cure for a period of 24-hours.

4. After the adhesive has dried, the dead load is removed and the PE cover film is peeled away from the gage and terminal. Jumper wires with adequate slack are soldered from the gage to the adjacent terminal.

5. The required length of cable is spliced and soldered to the terminal.

6. After all electric connections are made, the gage and terminal areas are waterproofed with the adhesive sealant. While adequare waterproofing is essential it should be noted that excessive adhesive sealant can reinforce the affected area and mask the true response.

7. The cable leads are extended to the monitoring area with sufficient slack to account for distortion during backfilling and subsequent long term settlement or movement of the geotextile. A loop of wire may be included near the gage so that stress is not applied to the terminal connection.

8. Resistance is checked and recorded after installation is complete (and before backfilling) to ensure that the system is operable.

9. Readings are taken over time per the monitoring plan.

Appendix "B"

Method to Bond Electrical Resistance Strain Gages to Unitized Geogrids or Geomembranes

This procedure for bonding electrical resistance strain gages to unitized geogrids or geomembranes is written around the following assumptions.

- The strain gages are relatively small for geogrid monitoring, e.g., 10 mm or less, since the specific location for monitoring is generally known (as with uniaxial homogeneous geogrids). For geomembranes, the gages can be as long as desired, e.g., 50 to 100 mm, since the entire sheet of material is homogeneous.
- The geogrid or geomembrane surface upon which the strain gage is to be bonded is clean and dry.

- The assembly area (for attaching the strain gages) is flat and rigid, e.g., a factory or shop floor makes a good assembly area. In the field, a flat wooden board can be used.

<u>Recommended procedure for attaching a single strain gage is as follows</u>:

1. The location on the geogrid or geomembrane where the gage is to be mounted is lightly buffed with No. 8 sandpaper. Grinding and loss of cross sectional thickness is not permitted since it will lead to erroneous results.

2. The surface is brushed lightly with a cleaner and degreaser typically used for electrical equipment. National Chemsearch Lexite of Irving, Texas has been used with success.

3. An industrial adhesive is applied to the surface [Permabond 910reg. alpha cyanoacrylate ester has been successfully used]

4. The strain gage is pressed into the adhesive with an overlying thin plastic film being careful to work out all entrapped air. [Strain gages type Y11-FA-5-120 from Showa Measuring Instruments Co. (for geogrids) and Type EP-08-20CBW-120 from Micromeasurements, Inc., Romulus, Michigan (for geomembranes) have been successfully used]. Note that these are small strain gages and usually have the terminal attached to them from which the leads are extended.

5. The required length of cable is spliced and soldered to me terminal.

6. The strain gage, terminal and lead connection must be made watertight by using a flexible silicone waterproofing. A rubber jacket covering the spliced connection is considered good practice. Hot air shrink-fit sleeves have been used.

7. The cable leads are extended to the monitoring area with sufficient slack to account for distortion during backfilling and subsequent long term settlement or movement of the geogrid or geomembrane.

8. Resistance is checked and recorded after installation is complete (and before backfilling) to ensure that the system is operable.

9. Readings are taken over time per the monitoring plan.

Appendix "C"

Method to Use Inductance Coils to Measure Deformations of Flexible Geogrids

This procedure for using inductance coils to measure deformations of flexible geogrids is written around the following assumptions.

- The geogrid is relatively flexible and is in its installed position at the site.

- The inductance coil pairs are each circular and positioned in a known orientation pattern. The options are parallel to one another, planar to one another or perpendicular to one another, per the instrument manufacturer's instructions.

Recommended procedure for attaching a pair of coils is as follows:

1. Select the proper diameter coils on the basis of the intended separation distance. (Inductance coils are available from Bison Instruments, Inc., Minneapolis, MN, under the designation Model 4101 A "Soil Strain Gage").

2. Develop a calibration curve between the original separation distance of the two coils and the anticipated maximum movement distance during the monitoring time. The orientation of the coils with respect to one another must be compatible with that to be used in the field. (The instrument manufacturer markets a calibration device).

3. With the geogrid installed in its intended position in the field, attach the paired inductance coils to the geogrid at the desired locations. The attachment must be made with non-metallic ties, e.g., plastic electrical ties, and be secure enough so that the orientation remains fixed during the monitoring period.

4. Using the portable meter, record the amplitude reading and check that it properly correlates with the calibration curve for that distance and orientation.

5. Carefully hand backfill the gages and the lead cables and recheck the amplitude reading to verify that the coils were not moved or distorted out of alignment.

6. Backfill at least 300 mm of soil over the geogrid at the location of the coils using light weight construction equipment and take the initial amplitude readings. This value should be close to the calibration and as-installed amplitude readings.

7. Extend the cables to the monitoring area with adequate slack to account for subsequent long term settlement or movement of the geogrid.

8. Readings are taken over time per the monitoring plan.