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The state-of-the-practice regarding in-situ monitoring of geosynthetics

Robert M. Koerner
Drexel University, Geosynthetic Research Institute, Philadelphia, Pa., USA

ABSTRACT: The in-situ monitoring of geosynthetics and geosynthetic related systems usually has two goals. One addresses the integrity and safety of the system, the other provides guidance and insight into the design process. Both are obviously important considerations. This paper addresses the state-of-the-practice on the in-situ monitoring of geosynthetics. Thus the techniques and/or devices presented have been used, or are currently being used, in practice. The paper is structured around the various geosynthetic materials by way of their primary function. Numerous projects are described and briefly discussed. The conclusion offers various recommended and optional methods/devices for the various categories addressed in the paper and also provides a checklist for the establishment of an in-situ monitoring program.

1 INTRODUCTION

When geotextiles were known as "filter fabrics" and geomembranes as "pond liners" (ca. 1970's), there was little concern or impetus for in-situ monitoring. The materials were generally viewed as construction expedients and whatever service life could be achieved beyond a few years was a successful application. Most applications of that time were considered to be *temporary* and they invariably were *noncritical* in their end use. With the realization that geosynthetics are generally covered with soil, came the understanding that polymers of the types used for geosynthetics could readily achieve service lifetimes of hundreds of years. This led to the use of geosynthetics in a number of long-term civil engineering applications. With such *permeance*, the obvious extension of geosynthetics into *critical* applications was soon to follow.

Herein lies the dilemma for many potential users of geosynthetics. Since geosynthetic materials have the potential of functioning for hundreds of years, how does one track and quantify the in-situ behavior of the geosynthetic or system depending upon it? The answer, of course, underscores the necessity for in-situ monitoring of the geosynthetic's site-specific performance. Note that this often requires the in-situ monitoring of the associated materials of the adjacent system, e.g., soil, rock, liquid, etc.

Even further, with the formalization of geosynthetics into the relatively mature technology that currently exists, many design models have been developed for a wide variety of applications. Generally, all of these models require some type of field verification. Clearly, actual performance via in-situ monitoring is important in this regard.

Thus, this paper focuses on the in-situ monitoring of geosynthetics for the following interrelated purposes;

- to provide information to the facility owner and/or regulatory agency that the system is performing safely, and
- to provide to the engineer and/or manufacturer that the design models utilized are realistically providing technically sound, yet economical, installations.

2 OVERVIEW

In the organization of a paper on the state-of-the-practice of in-situ monitoring of geosynthetics many approaches can be taken. For example;

- a chronological development of monitoring case histories could be developed,
- the monitoring devices themselves could be categorized and expanded upon,
- the geosynthetic materials and related applications could be followed,
- the primary function of the different geosynthetics could be followed, or
- a combination of geosynthetic material types along with their primary function could be followed.

This latter option will be used in this paper. Thus an overview of the primary functions that geosynthetics can serve must be presented.

The minimum number of primary functions that geosynthetics can serve are the following five; separation, reinforcement, filtration, drainage or as a barrier. Obviously, a geosynthetic can serve more than one function simultaneously, but generally one of them will result in the lower factor-of-safety, thus it becomes the primary function. Placing the various geosynthetic materials into these five functions leads directly to Table 1. It is seen that geotextiles and geocomposites can serve essentially all of the primary functions, whereas geogrids, geonets, geomembranes and geosynthetic clay liners are essentially single function materials.

In this paper, the in-situ monitoring of each type of geosynthetic will be addressed by its primary function in the order of the geosynthetics listed in Table 1. Where appropriate, monitoring of the adjacent soil, rock or total system 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 paper addresses monitoring of the geosynthetic related system, not only the geosynthetic material itself.

It should also be mentioned that this paper attempts to address the *state-of-the-practice* of in-situ monitoring of geosynthetics. Thus all of the techniques that will be mentioned have been, or are in the process of being, used on a somewhat regular basis. Monitoring that is considered to be *state-of-the-art* (i.e., research or experimental in nature) will not be focus of the paper. For example, a new technique currently under evaluation using fiber optics for geomembrane leakage and stress monitoring will not be addressed. These relatively advanced techniques are covered by other authors in separate papers in this and other conferences which are organized on a regular basis.

Lastly, it will be noted that most of the monitoring devices that are mentioned in the paper will not be described in great detail. Space limitations precludes such a detailed treatment. As a general recommendation, however, the book by Dunnicliff (1988) presents the theory, concept, functioning and performance of geotechnical instrumentation of the type cited in this paper in a very open and forthright manner. Where special devices or adaptations of conventional monitoring instruments are mentioned for use with geosynthetics, some detail will be provided.

3 MONITORING OF GEOTEXTILE SYSTEMS

This section focuses on geotextile related applications serving in the primary functions of separation, reinforcement, filtration, drainage and as a liquid barrier. Separate subsections address each function.

3.1 *Geotextiles in Separation*

Geotextiles as separators are often thought of as being a rather minor application area. Yet, they are generally permanent and can be critical in their application. 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.

An early application 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 inductance gages.

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

Table 1. Geosynthetics and their associated primary functions.

Type of Geosynthetic	Various Primary Functions				
	Separation	Reinforcement	Filtration	Drainage	Barrier
1. geotextiles	√	√	√	√	√*
2. geogrids		√			
3. geonets				√	
4. geomembranes					√
5. geosynthetic clay liners					√
6. geocomposites	√	√	√	√	√

*when modified with bitumen or elastomer

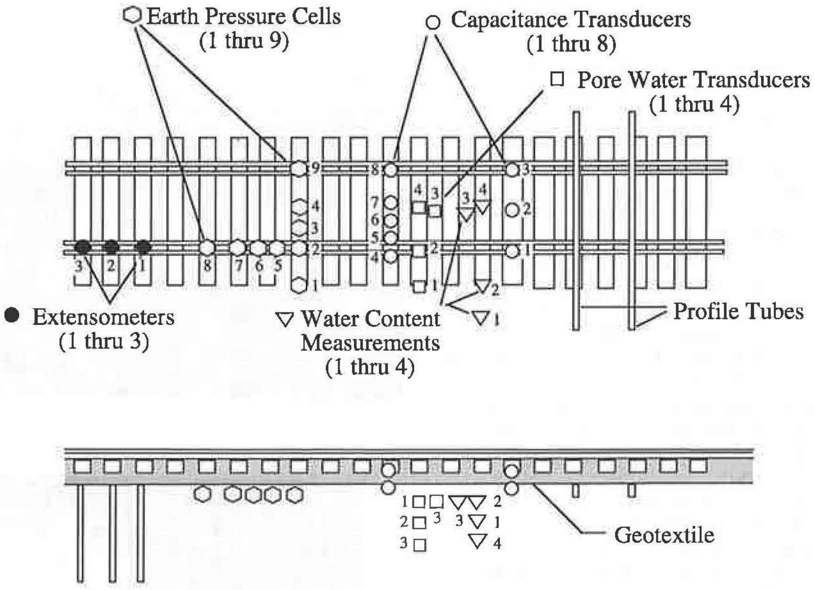


Figure 1. Instrumented railroad test site with geotextiles acting as separators, after Richardson (1985).

A similar use of geotextiles as separators between soil subgrade and stone base course materials in highway pavements is a 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, see Figure 2,
- 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.

In a significantly different application than 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 situations to visually observe the effects of the stones insofar as geomembrane indentation is concerned. Brummermann, et al. (1994), has quantified the indentations to arrive at a geomembrane strain value. Used are graphic methods based on 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.

Figure 2. A falling weight deflectometer, (compl. Corps of Engineers; CRREL).

3.2 *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 Figure 3. 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 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 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 by Delmas, et al. (1988). They instrumented a 4.0 high wrap-around geotextile wall with electrical resistance strain gages on the foundation beneath the wall and surveying points on

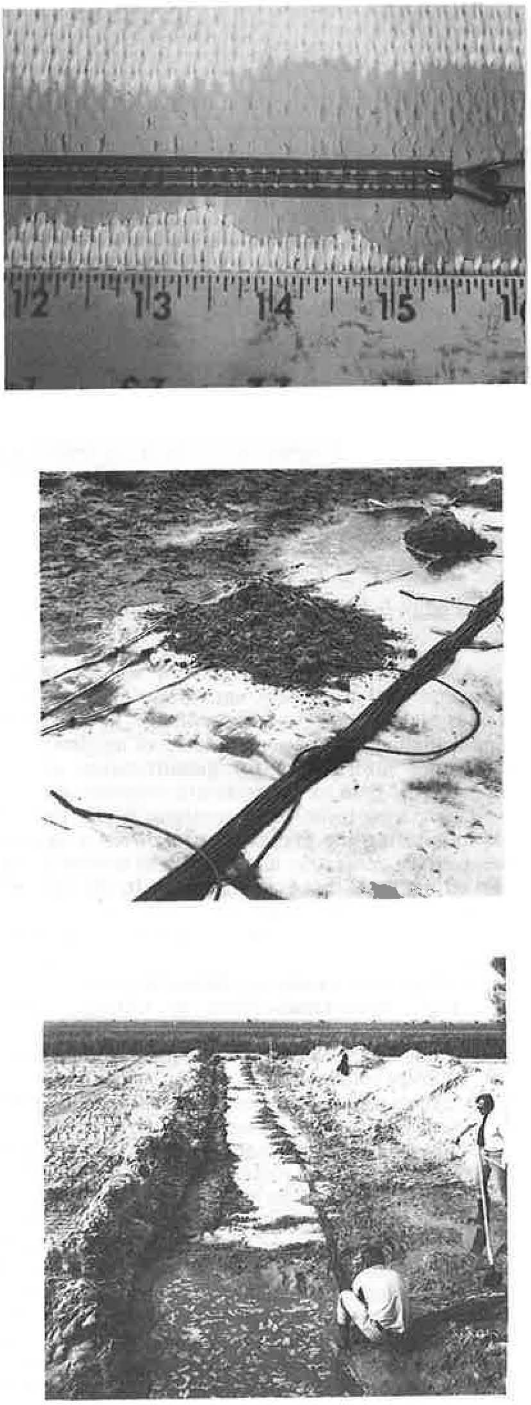


Figure 3. Electrical resistance strain gage monitoring of high strength geotextiles (compl. P. Risseeuw; Akzo).

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.

3.3 *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).

3.4 *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 to the author's knowledge.

3.5 *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. The 1996 RILEM conference on this same topic will be of interest in this regard.

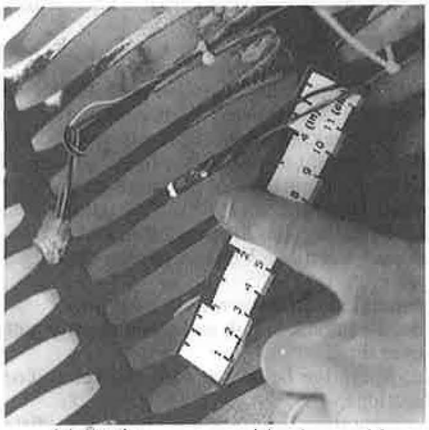
Geotextiles impregnated with bitumen or polymers, and geotextiles used as substrates for factory placed bituminous layers, used as liners for environmental applications will be considered later. In those cases, the focus will be on leakage rates from landfills or surface impoundments where a number of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

4 MONITORING OF GEOGRID SYSTEMS

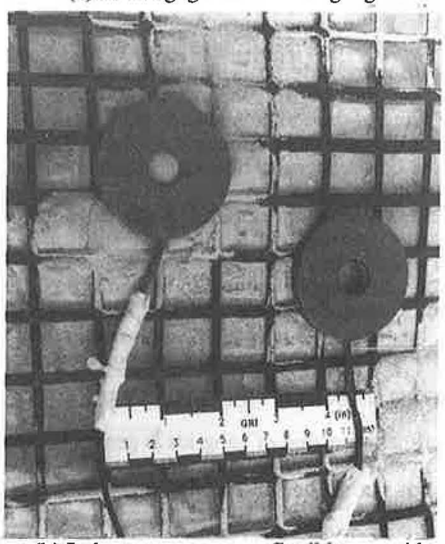
The primary function of geogrids is generally that of reinforcement. When the system is permanent and/or of a critical nature, in-situ monitoring may be considered. Numerous studies on walls, slopes and foundation reinforcement applications are available. The focus is usually on the geogrid itself, where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

4.1 *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). Figure 4a shows a typical strain gage bonded to a unitized geogrid at its minimum cross section where by stresses are the highest. Many geogrid projects have been monitored in this manner. Alternatively, on flexible geogrids one could use inductance coils, see Figure 4b. While relatively large in size, an LVDT protected within a sliding guide tube has also been used, Barr, et al. (1994).



(a) Strain gage on unitized geogrid.



(b) Inductance gages on flexible geogrids.

Figure 4. Monitoring of geogrids in reinforcement applications.

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.

4.2 *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 5. The instrumentation consisted of the following;

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

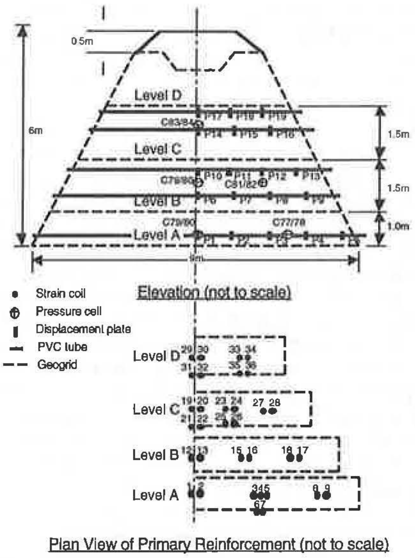


Figure 5. Instrumentation layout of geogrid reinforced steep soil slope, after Hermann and Burd (1988).

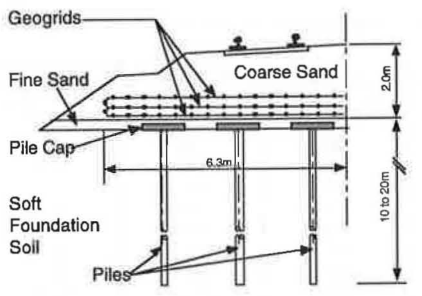


Figure 6. Geogrid reinforcement of a railroad embankment over soft foundation soil spanning pile caps, Alexiew, et al. (1995).

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

4.3 *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 6. 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).

5 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 can be used (they will be described later with drainage geocomposites), 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), 2500± 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 45.2×10^{-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 43.5×10^{-4} m^2/s. A third flow test was conducted after 28 m of solid waste was placed, with a resulting transmissivity of 40.0×10^{-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.

6 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.

6.1 *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). 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

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

Situation or Condition	No-load	Mid-load	Full-load
Dates of test	18-19 Nov. 1987	22-23 Dec. 1987	15-16 Mar. 1988
Diameter of HDPE injection pipe, mm	100	100	100
Diameter of HDPE exit pipe, mm	100	100	100
Diameter of detection manhole, m	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}

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.

6.2 *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 thermocouple monitoring of a geomembrane liner, the leachate collection system, the solid waste itself and the geomembrane cover. Thermocouples consist of dissimilar metals in which a continuous current flows. When broken at the monitoring location, the open voltage is a function of the junction temperature. For this case history, the thermocouple wires were bonded to the area of concern and the coaxial 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. It is a 4 ha site with approximately 30 m of waste. The project is ongoing.

6.3 *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

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

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.

6.4 *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). The workshop on liner leak monitoring and location technologies in these proceedings gives additional details into this monitoring concept.

6.5 *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

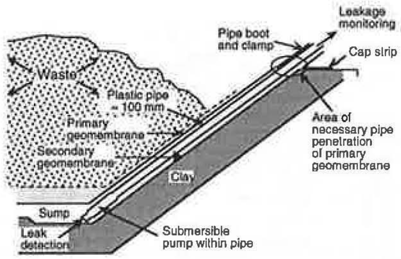


Figure 7. Leakage monitoring via submersible pump within a sideslope pipe riser.

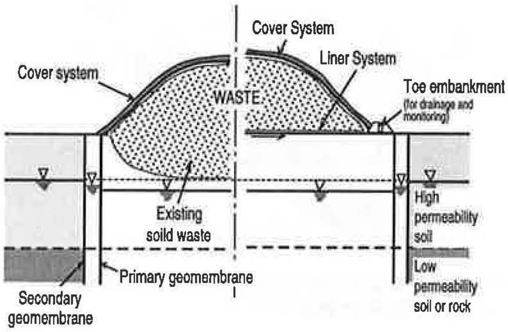
where a pipe riser is located. This pipe is placed between the two geomembranes and penetrates the primary geomembrane at the surface. It exits accordingly for eventual monitoring using a submersible pump, see Figure 7. This monitoring design is in considerable favor over vertical manhole risers through 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.

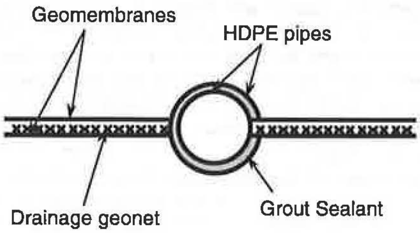
The above concept of the double liner strategy with leak detection has recently entered a new era with the advent of the *Vienna Cutoff Double Wall System*, Brandl (1994). The double liner concept is used but now in a vertical deployment as shown in Figure 8(a). It is illustrated for both abandoned waste sites and newly constructed landfills. Figure 8(b) shows the double wall system with a geonet leak detection layer between the two geomembranes. Figure 8(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.

7 MONITORING OF GCL SYSTEMS

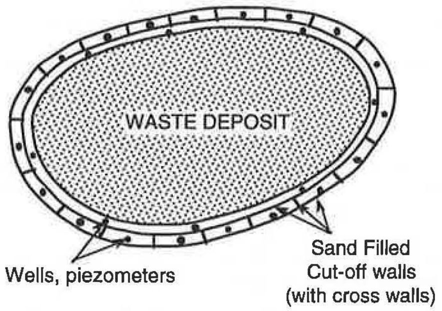
As with geomembranes, the primary function of geosynthetic clay liners (GCLs) is as a barrier layer. Leakage is again the key monitoring variable and all of the discussion in the previous section is applicable to GCLs as well as with geomembranes. Additionally, one might measure the in-situ permeability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



(a) Double vertical cutoff wall for abandoned sites with no liners (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 8. Vienna cutoff double wall system, after Brandl (1994).

(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 × 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, Anonymous (1996). Fourteen full scale test plots had five different types of GCL's deployed on 1:2 and 1:3 slopes, see Figure 9a. 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, see Figure 9b. 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/ geotextile mass. Monitoring of the remaining plots will continue for at least another year.

8 MONITORING OF GEOCOMPOSITE SYSTEMS

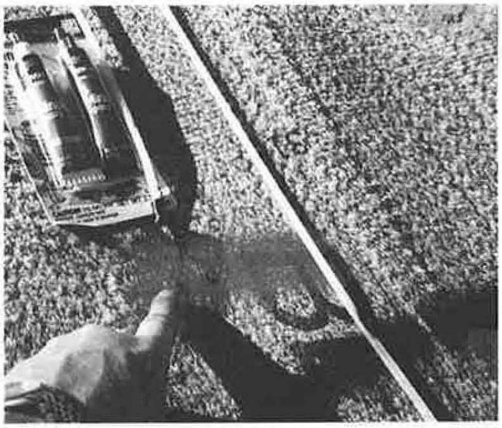
The primary functions that geocomposites can serve are obviously product specific. Since geocomposites used in reinforcement, filtration and barrier applications are similar to those described previously they will be referenced to the appropriate section. Thus, this section only considers separation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

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

Plot	Product	Bottom of Left Panel (mm)	Bottom of Right Panel (mm)	Average (mm)
A	Gundseal	+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	+180	+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

(a) Overview of 2:1 test plots.



(b) Epoxy bonded fish hook in upper geotextile of GCL.

Figure 9. GCL test plots and deformation monitoring of GCL midplane behavior on steep slopes (compl. G. Koerner; GRI).

8.1 *Geocomposites as separators in erosion control*

There are literally hundreds of geocomposite 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. 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.

8.2 *Geocomposites in reinforcement*

This category is similar to that of geotextiles in reinforcement (section 3.2) and geogrids in reinforcement (section 4.1, 4.2 and 4.3).

8.3 *Geocomposites in filtration*

This category is similar to that of geotextiles in filtration (section 3.3).

8.4 *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, see Figure 10. 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.

8.5 *Geocomposites as barriers*

This category is similar to that of geotextiles as barriers (section 3.5).

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

Geosynthetic Type	Function or Application	Recommended	Optional
geotextiles	separation	• water content measurements • 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	• flowmeters • turbidity meters • probes for pH conductivity and/or dissolved oxygen
	drainage	same as geotextile filtration	
	barrier (e.g., reflective cracking)	• surface deflections • level surveying • surface roughness measurements • profilometery (for rut depths)	• 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	• flowmeters • turbidity meters	• probes for pH, conductivity and/or dissolved oxygen • piezometers
geomembranes	tensile stress	• strain gages	
	temperature	• temperature measurement	
	stationary leak monitoring	• see workshop report in these proceedings	
	portable leak monitoring	• see workshop report in these proceedings	
	global leak monitoring	• flowmeters • downgradient wells	• turbidity meters • probes for pH, conductivity and/or dissolved oxygen
geosynthetic clay liners	global leak monitoring	• flowmeters • downgradient wells	• turbidity meters • probes for pH, conductivity and/or dissolved oxygen
	shear strength	• extensometers • deformation telltales	• gypsum cylinders • fiberglass wafers • strain gages (inductance coils)
geocomposites	separation (e.g., erosion control)	• flowmeters • turbidity meters	• level surveying
	reinforcement	(same as geotextiles and geogrids)	
	drainage (e.g., edge drains)	• flowmeter • turbidity meter	• 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	lateral movement of vertical face
	level surveying	vertical movement of surface
	settlement plates	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°
	extensometers	measures changes between two-points in a borehole
strain measurement	electrical resistance gages • bonded foil • weldable	measures strain of a material over gage length, typ., 0.25 to 150 mm
	inductance gages (coils) • static measurements • dynamic measurements	measures movement between two embedded coils up to 1000 mm distance apart
	LVDT gages	measures movement between two fixed points 100 to 200 mm 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 pressure	piezometers • hydraulic type • pneumatic type • vibrating wire type • electrical resistance type	measures 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°C
	thermocouple	measures temperature at a point to ± 0.5°C
	thermistor	measures temperature at a point to ± 0.1°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	measures suspended solids
	pH probes	measures pH of liquid
	conductivity probes	measures conductivity of liquid

Figure 10. Tipping bucket arrangement for monitoring flow for a geocomposite highway edge drain, (compl. B. Dempsey; U. of Ill.).

9 SUMMARY AND CONCLUSIONS

Reviewed in this paper has been 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.

In conclusion, 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.

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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