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FROM GEOTEXTILES TO GEOSYNTHETICS: A REVOLUTION IN GEOTECHNICAL ENGINEERING

DES GEOTEXTILES AUX GEOSYNTHETIQUES: UNE REVOLUTION DANS LA GEOTECHNIQUE

VON GEOTEXTILIEN ZU GEOSYNTHETICS: EINE REVOLUTION IM GRUNDBAU

Geotextiles now play a major role in geotechnical engineering. Yet thirty years ago geotextiles did not exist, and fifteen years ago they existed but were not recognized. The geotechnical community has advanced considerably in the last fifteen years in terms of usage and attitudes concerning geotextiles. This paper reviews the past and future of geotextiles in geotechnical engineering. First, the history of geotextiles is presented, and basic concepts are discussed, with special emphasis on the functions performed by geotextiles. Second, the technico-economical and fundamental reasons for the growth of geotextiles in geotechnical engineering are discussed. Third, the transformation of geotechnical engineering through the increased usage of geotextiles is reviewed. Fourth, the expected evolution of the geotextile discipline is presented, and the means by which the geotextile community can assist this evolution are described.

Geotextilien spielen nun eine Hauptrolle im geotechnischen Ingenieurwesen. Vor 30 Jahren existierten die Geotextilien nicht und, obwohl sie vor 15 Jahren schon existierten, waren sie jedoch nicht anerkannt. Die geotechnische Fachwelt ist beträchtlich fortgeschritten in ihrem Verhalten gegenüber und in der Verwendung von Geotextilien in den letzten 15 Jahren. Diese Veröffentlichung gibt einen Überblick über Vergangenheit und Zukunft von Geotextilien. Als erstes werden die Geschichte der Geotextilien sowie grundlegende Überlegungen dargelegt, wobei die von diesem neuen Baustoff übernommenen Rollen besonders hervorgehoben werden. Zum Zweiten werden die technisch-ökonomischen Gründe für das Wachstum von Geotextilien im geotechnischen Ingenieurwesen diskutiert. Drittens wird ein Überblick gegeben, wie das geotechnische Ingenieurwesen durch diesen gestiegenen Gebrauch von Geotextilien verändert wurde. Viertens wird die erwartete Entwicklung des Geotextilien-Ingenieurwesens präsentiert, und die Mittel, mit welchen die Geotextilien-Fachwelt diese Entwicklung unterstützen kann, sind geschildert.

INTRODUCTION

Vienna is a symbol.

In Vienna, sixty years ago, geotechnical engineering was born. An art then became a science.

In Vienna, today, this Third International Conference on Geotextiles demonstrates that a major revolution has taken place in geotechnical engineering. In this room there are many leaders of the geotechnical profession, many of whom would have felt uncomfortable attending a geotextile meeting ten years ago. Yet they are pleased to be here today.

Today, we are witnessing the consecration of a discipline which was not taken seriously ten years ago. This same discipline has, however, transformed geotechnical engineering to the point that it is no longer possible to do geotechnical engineering without geotextiles.

Twenty years ago, few geotechnical engineers were aware of geotextiles. Ten years ago, many geotechnical engineers were aware of geotextiles but elected to ignore them: they would not condescend to talk to fabric manufacturers because they had been trained to consider that the only supplier of geotechnical materials was God. Today all geotechnical engineers have heard of geotextiles and have used or expect to use them. It is clear that the attitude of geotechnical engineers has changed as geotextiles have progressively pervaded all branches of geotechnical engineering. This may be one of the most important revolutions to date in the history of geotechnical engineering.

The purpose of this paper is to discuss various aspects of this revolution. First, a brief history of geotextiles will review the development of this revolution, followed by a discussion of basic concepts. Then, the extent and the causes of the revolution will be discussed. Finally, in addition to the revolution of geotechnical engineering by geotextiles, the revolution inside the geotextile community will be discussed. These discussions will be used as a basis to make predictions for the future of geotextiles, as well as recommendations for steps to be taken by members of the geotextile community to ensure complete acceptance of geotextiles by geotechnical engineers. The goal, of course, is continuous growth of the geotextile community, and, consequently, continuous growth of geotechnical engineering.

HISTORY OF GEOTEXTILES

The forerunners

Forms of geotextiles have existed for thousands of years. Reinforced soil was used by the Babylonians more than three thousand years ago to build the ziggurats. One famous ziggurat, the Tower of Babel, collapsed, perhaps because it was not reinforced. As is frequently the case in Europe and the Middle East, the contractor of the Tower of Babel employed foreign laborers. It was then all too easy to blame the failure on them since they could not defend themselves because of language problems, as indicated by the writer of the Bible. In fact, the writer of the story may have had a vested interest in finding a scapegoat since it is possible that, in those days, monk-writer and consulting engineer were one and the same trade (as some modern consulting engineers would agree).

For thousands of years, the Chinese have used wood, bamboo and straw to stengthen soil. The importance of soil reinforcement in ancient China is demonstrated by the fact that the Chinese symbol for Civil Engineering translates as "earth and wood". The concept of soil reinforcement was brought to Japan, from China, about 2000 years ago, and, at the present time, there are reinforced soil structures in China (including portions of the Great Wall) that date from the time of Christ. The use of natural materials for stabilization continued in China into the 1940's, and perhaps to this decade.

The Dutch, in their age-old battle with the sea, have made extensive use of willow fascines to reinforce dikes as well as protect them against wave action. The earliest structures were mounds upon which houses were built. Later, these mounds were connected with dikes. The next stage was the construction of dams to shorten the coastline (circa 1400 A.D.). This action continues into this century, culminating with the Delta Project.

The Romans used reed and wood for soil reinforcement. The same materials, as well as animal hides, were used in the Middle Ages.

Between 1926 and 1935, cotton fabrics were tried as means of strengthening road pavements in the United States [1]. These field trials were not followed by systematic applications.

During World War II, the British Army used armored vehicles specially designed to carry, and lay on the ground, rolls of fascines or canvas. This technique was used in 1944 for the invasion of Normandy.

A revolution in the textile industry

In this century, the textile industry experienced a major revolution, the development of synthetic fibers:

- 1913: First synthetic fiber, made from polyvinyl chloride (PVC), commercially produced in 1934, with limited applications.
- 1930: First "modern" synthetic fiber, a polyamide fiber ("nylon"), by W.H. Carothers of DuPont in the United States. This fiber was commercialized in 1940 with great success.
- 1930's: First polyester fiber, by J.R. Whinfield and J.T. Dickson of Calico Printers Association. Commercial production of polyester fibers began in 1949 in the U.K.
- 1949: Production of low strength, coarse polyethylene filaments by ICI (U.K.). In 1954, production of high strength, fine polyethylene filaments by Ziegler (West Germany), Phillips Petroleum and Standard Oil of Indiana in the United States.
- 1954: First polypropylene fiber by G. Natta of Montecatini (Italy). Commercial production of polypropylene fibers took place in the late 1950's.

Another major step was the development in the mid-1960's of manufacturing processes for nonwoven fabrics made from continuous synthetic filaments ("spunbonded" nonwoven fabrics) by large firms such as Rhone-Poulenc (France), ICI (U.K.), and DuPont (U.S.A.).

Also, in the mid-1950's, the packaging industry was revolutionized by an original technology for manufacturing plastic nets invented in the U.K. by F.B. Mercer.

The first steps of geotextiles

With the advent of synthetic materials, civil engineering experienced a rebirth of the techniques used centuries before. Key dates in this rebirth are:

- 1957: Sand bags made of nylon woven fabrics (Nicolon) were used in the Netherlands at the closing of the Pluimpot. Extensive coastal work had been prompted in the Netherlands by the catastrophic floods that killed 1850 people in 1953. A part of this work is the Delta Project which used more than ten million square meters of geotextiles from the mid-1970's to the mid-1980's. This project, discussed in many technical papers, was made possible by a continuous cooperation between civil engineers and textile specialists, such as Professor van Harten.
- 1958: A synthetic woven fabric produced by Carthage Mills was used between soil and rip-rap for coastal erosion control in Florida (USA). The fabric was made of polyvinylidene chloride monofilaments, and it is still in an apparently good state after 27 years, as shown by a recent visit to the site. This application is considered as the first use of a geotextile. The man responsible for the application, R.J. Barrett, was then involved in hundreds of similar applications. However, the market did not develop significantly because of the cost of the geotextile, and because the applications were relatively small.
- 1958: Installation of synthetic sand bags in groins in West Germany, under the direction of Professor F.F. Zitscher. At the same time, synthetic woven bags were used in Japan to construct embankments and protect slopes.
- 1959: Synthetic sheets, sand bags and woven fabrics were used under the direction of Dr. S. Kanamori, in the construction of dikes, following the catastrophic failure, caused by a typhoon, of sea and river dikes that killed approximately 5000 people in the vicinity of Nagoya (Japan).
- 1960: Use of woven nylon mattresses, filled with sand, for scour protection, in the Netherlands [2].
- 1966: The first use of a nonwoven fabric in civil engineering was for asphalt overlay (U.S.A.). The fabric, composed of staple fibers, was manufactured by Phillips Petroleum. Since then, this application has developed tremendously in the United States, but not in other countries.
- 1967: Synthetic nets (by Netlon Ltd., U.K.) were used for the first time in a civil engineering project. The field trial, reinforcement of soft ground in Japan, was conducted under the responsibility of Professor T. Yamanouchi. This successful trial was followed by many applications, including embankment reinforcement for the Japanese National Railway, and inspired the development of geogrids.

The emergence of a large market

The fantastic growth of the geotextile market began in the late 1960's when the synthetic nonwoven fabrics became available. Some important dates follow:

- 1968: A highly diversified market for geotextiles commenced in Europe, beginning with the use of nonwoven fabrics in unpaved roads in France and in the U.K., and in a canal bank protection system in West Germany. Both nonwoven fabrics used in the unpaved roads were spunbonded, i.e., made of continuous filaments (needlepunched by Rhone-Poulenc of France, and heatbonded by ICI of the U.K.); and the nonwoven used in West Germany was a resin bonded needlepunched fabric made of staple fibers. Key individuals involved were E. Leflaive and J. Puig in France, and A. McGown in the U.K.. These first installations were followed by a variety of applications in road construction, railroad track, erosion control, etc.

- 1970-71: Development of a variety of applications such as: use of a geotextile in road embankments and in vertically-faced multilayer soil/geotextile walls (Leflaive, France); use of a geotextile as a filter for a drain, use of geotextiles in a dam (toe drain and upstream bank), and geotextile/geomembrane association (Giroud, France); use of a thick nonwoven textile for lateral drainage, in a tunnel (Naue-Fasertechnik, West Germany); etc.

- 1972: The European market became well established, mostly as the result of mass production of spunbonded nonwoven fabrics. The first large manufacturers were Rhone-Poulenc (France) and ICI (U.K.), then Chemie Linz (Austria), etc.

- 1972: An early attempt at developing design methods for geotextiles was the development of filter criteria by C.C. Calhoun of the Waterways Experiment Station of the U.S. Army Corps of Engineers (Vicksburg, Mississippi), and by H.J.M. Ogink at the Delft Hydraulics Laboratory (the Netherlands.)

- 1974: A series of full scale trials and installations began under the direction of Professor Bell (U.S.A.). The quality of the testing, documentation, and related analyses had a major impact on the development of geotextile applications in North America.

- 1975: The North-American market began its growth with large manufacturers of nonwovens such as Celanese (Mirafi), Phillips, Dupont, Monsanto, Crown-Zellerbach, and manufacturers of wovens such as Carthage Mills and Nicolon. At the same time, the Japanese market grew with manufacturers bearing such well known names as Mitsui, Mitsubishi, Toray, Teijin, Taiyo Kogyo and Kuraray. Professor M. Fukuoka played a significant role in this development. (He had used vinyl sheets as early as 1957 to provide separation between road base and subgrade; the same technique was used in 1962 by the Japanese National Railway.)

- 1978: Beginning of the construction of large earth dams (approximately 80 m high) incorporating geotextiles in their drainage/filtration system, such as Frauenau Dam in West Germany (with input from F. List, for geotextile design) and Hans Strijdom Dam in South Africa.

The seventies and early eighties saw the development of new types of products such as: mats (Enka, Netherlands, 1972); grids (Netlon, U.K., 1981); and composites for drainage (ICI, U.K.; Enka, Netherlands; Ground Engineering, U.K.; Mirafi, U.S.A.). The term "geosynthetics" has been proposed by J.E. Fluet, Jr. in 1983 to encompass all these synthetic materials, including geomembranes.

The following comments can be made regarding the history of geotextiles:

- Systematic applications (1958) did not immediately follow the first uses of textile fabrics in civil engineering (cotton fabric in 1926), but resulted from the availability of the first adequate product, a synthetic fabric which could resist rot.

- Significant market growth did not result from the first development of an adequate product, but began ten years later when inexpensive fabrics, the spunbonded nonwovens, became available.

These comments illustrate to which extent the development of a technique depends on the availability of products. For thousands of years, human beings have dreamt of flying using their own energy. This only became possible in the 1970's when very light, high strength materials allowed the construction of an extremely light bicycle-plane.

Markets, manufacturers and products

The first significant sales of geotextiles began in the early 1970's and the market has grown strongly since then. In 1984, 300 million square meters of geotextiles were placed in more than 100 000 different projects worldwide [3]. To illustrate the extent to which geotextiles are used, it is interesting to note that, by the year 2000, one-thousandth of Europe is expected to be covered by geotextiles.

At the present time, approximately one-half of the sales are in North America, two-fifths in Europe, and the remainder in Japan (the largest national market after the United States), the South Pacific, South America, South Africa, etc.

The proportion of sales per type of geotextile depends very much on the geographical area, mostly as the result of local habits and influence of local manufacturers. Some examples of proportions, by surface area of geotextile, in 1984, are:

- In North America: approximately two-thirds nonwovens, one-third wovens and a relatively small proportion of other types.

- In Europe, approximately four-fifths nonwovens, one-fifth wovens and a relatively small proportion of other types.

- In Japan: approximately three-fifths wovens; one-fifth nonwovens, and one-fifth nets and grids.

The large European and North American manufacturers mentioned earlier enjoyed big successes in the late 1970's, as a result of their production capabilities. During the same period, some small manufacturers were successful as a result of innovation and special attention to the needs of their customers. Examples are: Nicolon, Naue-Terrafix, and Netlon Ltd.

As in all new fields, shake-ups have occurred. In the early eighties, the North American market experienced the pull out of large firms such as Monsanto and Celanese. However, these corporate decisions did not significantly affect the geotextile industry. In fact, the geotextiles initially produced by these two firms are still produced and marketed by other organizations, which demonstrates the vitality of geotextiles.

As a result of the growth of geotextiles and related products, the already rich vocabulary of geotechnical engineers became augmented by Acosheet, Adva-felt, Adva-fence, Adva-Filter, Alkorflex, Alkorplan, Amerdrain, Amopave, Anticolmat, Appeal, Aqua Screen, Armater, Armorflex, Arm-R-Shield, Bando, Batescape, Baymilex, Betotex, Bidim, Bitech, Broplene, Buideldoek, Butyl, Canvacon, Colbond, Coletanche, Contain, Conwed, Cordrain, Corweb, Culdrain, Dafelt, Datex, Depotex, Drainatex, Drainosyn, Drefon, Drenotex, Driline, D'Tex, Dunseal, Dura-bags, Durethene, Dynalog, Easy Fencin, Ecofelt, Econofence, Eljen, Endoron, Endren, Enkadrain, Enkagrid, Enkamat, Envirofence, Enviromat, Ercomat, Erogard, Erolan, Erotex, Excelliner, Exxon-GTF, Fabricast, Fabriform, Fibertex, Fibretex, Filtan, Filterteppish, Filter-X, Filtram, Filterweave, Flagon, Flexalon, Flexseal, Flexsom, Flotex, Fov, Geobutyl, Geodrain, Geofab, Geofelt, Geofence, Geofeutre, Geofilter, Geoflex, Geoform, Geogrid, Geolon, Geomat, Geonet, Geopave, Geoseal, Geosom, Geotex, Geotextil, Geoweb, Glassgrid, Gobimat, Grade-lok, Greenline, Gridlock, Griltex, Gundline, Gundnet, HaTe, HaTelit, Hitek, Holdgro, Hydrolining, Hydrotec, Hypalon, Hyperlastic, Hypofors, Hytrel, Intermembrane, Internet, Italform, Kraftel, Kureha, Landglas, Liqui-seal, Lotrak, Lucobit, Lutrabond, Lutradur, Lutrapor, Lutrasil, Malla, Manroll, Mantle, Mebradrain, Miradrain, Mirafi, Miramat, Mirascape, Mobal, Monofilter, Monarflex, Monodrain, Mypex, Naltex, Netlon, Nicobag, Nicolon, Nicomat, Nicospan, Nidaplast, Nilex, Nilos, Nudrain, Ovodren, Paragrid, Paralink, Paratie, Paraweb, Penroad, Perma-Bags, Permadrain, Permealiner, Petrogard, Petromat, Petrotac, Plastilene, Plastiliner, Polybac, Polyfelt, Polyfilter-GB, Polyfilter-X, Polyflex, Polynet, Polyscrim, Polytex, Polytrac, Profelt, Propex, Protecsom, Q-trac, Rayvetmat, Reepav, Retain, Rig, Roadglas, Robusta, Rodimperm, Roll-lite, Sackurity, Santoprene, Savalgeo, Scottlay, Sea Carpet, Secutex, Shaumvlies, Shelter-rite, Signode, Silt-Ban, Sodoca, Sodovia, Sodyfelt, Somdrain, Stabilenka, Stabilok, Stabiluko, Storm Mat, Stratum, Stripdrain, Structofors, Supac, Superdrain, Sure-seal, Syntex, Tafnel, Tecnofelt, Tenax, Tensar, Teranap, Terbond, Terbondspun, Tern, Terrafirma, Terrafix, Terralec, Terram, Terratex, Terratop, Terratrack, Tersom, Testudo, Tex-E, Texel, Texpro, Texsol, Trammel, Traxpax, Tremolin, Trevira, Trical, Tricon, Tri-X, True Tex, Typar, Valfeltro, Vannets, Volans, Water Lane, Wayn-Guard, Whaleskin, Yukalon, etc.

Organization of the profession

Progressively, major steps were taken to generate exchange of ideas and to organize the profession:

- 1973: Formation, under the auspices of the German Society for Soil Mechanics and Foundation Engineering, of a working group on "Synthetic Materials for Soil and Hydraulic Engineering" (Professor F.F. Zitscher).
- 1977: An "international conference on the use of fabrics in geotechnics" took place in Paris. It was sponsored by Ecole Nationale des Ponts et Chaussees, and organized under the chairmanship of E. Leflaive. This conference is considered today as the First International Conference on Geotextiles, as proposed by the organizers of the Las Vegas conference in recognition of the major role played by the Paris conference. The terms "geotextile" and "geomembrane" were proposed by J.P. Giroud in a paper presented at the Paris conference.
- 1978: Formation of committees on geotextiles in the United States and France. Both committees have been very active, as have others formed since that time, such as the Canadian committee, formed in 1980, and the Swiss committee, formed in 1981. Also in 1978, the RILEM Committee SM-47 on synthetic membranes, including geotextiles, was formed under the chairmanship of Professor K. Gamski. Progressively, committees on geotextiles were set up by national or international societies dealing with roads, canals, large dams, etc.
- 1978: Associations of nonwoven producers such as EDANA in Europe and INDA in North America organized sessions on geotextiles. In 1980, the Industrial Fabrics Association International (IFAI) formed a Geotextile Division, chaired by J.E. Fluet, Jr.
- 1982: The creation of an international society on geotextiles was proposed in the opening lecture of the First Swiss Symposium of Geotextiles by J.P. Giroud; he then presented the concept at meetings in Europe and North America and organized an assembly during the Second International Conference on Geotextiles to implement this concept.
- 1982: The Second International Conference on Geotextiles was held in Las Vegas. It was sponsored by the Industrial Fabrics Association International (IFAI). The organizing committee was chaired by J.P. Giroud and the technical program committee by J.R. Bell. During the conference, the decision was made to form an international society on geotextiles.
- 1983: Formation of the International Geotextile Society (IGS), with C. Schaerer as president, and G. Massenaux as secretary.
- 1983: First steps were taken to form Sub-committee SC 21 on Geotextiles (related to the existing Technical Committee TC 38 on Textiles) of the International Organization for Standardization (ISO). The first meeting of the sub-committee took place in 1985, with the participation of 17 countries and 3 international organizations.
- 1983: A major step in the recognition of geotextiles by the engineering community was the appointment of a Technical Committee on Geotextiles by the International Society for Soil Mechanics and Foundation Engineering (ISSMFE).
- 1985: First session on geotextiles, chaired by A. Arman, at an international conference of the ISSMFE (in San Francisco).
- 1985: First national chapter of the IGS, the Japanese Chapter, chaired by Professor M. Fukuoka.
- 1986: The Third International Conference on Geotextiles is taking place in Vienna. The chairman of the organizing committee of this conference is Professor H. Brandl who occupies K. Terzaghi's chair at the Vienna Technical University. The mere fact that there is a third international conference on geotextiles is a success for the IGS and the result of a large amount of work. Without the leadership and authority of the IGS, there would have been either no third international conference, or several conflicting conferences claiming that they are the "Third International Conference", either of which would have been harmful for the profession.

BASIC CONCEPTS

Geotextile functions

At first glance, it seems clear that the mats of palm fronds used to construct the ziggurats were intended to reinforce the structure. However, some of the mats used were thick enough to convey a significant amount of water within their plane, and one may wonder if the mats were not also used to laterally drain the excess water from the clay. Such drainage would have accelerated consolidation of the clay and minimized the risk of failure during construction, a problem which had attracted much undesired attention to the Tower of Babel.

In modern structures too, a geotextile can perform several functions, and the first step of design is certainly to identify the functions required of the geotextile in the considered application. Therefore, a list of functions is needed. In order to compile a list of such functions, it is first necessary to define the term "function". The following definition is therefore proposed: "A geotextile function is a specialized action of the geotextile which is required to achieve a design purpose and results from a unique combination of geotextile properties." Relationships between properties, functions and purposes are given in Table 1 (which can be found at the end of the paper). The six functions presented in this table can be defined as follows:

. Fluid Transmission. A geotextile provides fluid transmission when it collects a liquid or a gas and conveys it, within its own plane, toward an outlet. (Note: this function is usually called "drainage" which creates a lot of confusion with the "drainage applications" discussed in Table 2; therefore the terms "fluid transmission", or simply "transmission", are recommended.)

. Filtration. A geotextile acts as a filter when it allows liquid to pass normal to its own plane, while preventing most soil particles from being carried away by the liquid current. Two cases can be considered: (1) A geotextile, placed across a flow of liquid carrying fine particles, stops most of the particles (which therefore accumulate on the filter) while allowing water to pass through; (2) A geotextile, placed in contact with a soil, allows water seeping from the soil to pass through, while preventing any movement of soil particles (with the exception of a very small amount of the finest particles located near the filter).

. Separation. A geotextile acts as a separator when, placed between a fine soil and a coarse material (gravel, stones, blocks, slabs, boards, etc.), it prevents the fine soil and the coarse material from mixing under the action of repeated applied loads.

. Protection. A geotextile protects a material when it alleviates or distributes stresses and strains transmitted to the protected material. Two cases can be considered: (1) Surface Protection - A geotextile, placed on the soil, prevents its surface from being damaged by such actions as weather, light traffic, etc.; (2) Interface Protection - A geotextile, placed between two materials (such as, asphalt overlay/cracked pavement, or geomembrane/stony ground), prevents one of the materials (e.g., the overlay or the geomembrane) from being damaged by concentrated stresses applied by (or strains imposed by) the other material.

. Tensioned membrane. A geotextile functions as a tensioned membrane when it is placed between two materials having different pressures, and its tension balances the pressure difference between the two materials, thus strengthening the structure.

. Tensile member. A geotextile acts as a tensile member when it provides tensile modulus and strength to a soil with which it is interacting through interface shear strength (i.e., friction, cohesion-adhesion, and/or interlocking between geotextile and soil).

Most properties indicated in the left column of Table 1 are self explanatory. However, the following comments are necessary:

. The permeability involved in the "fluid transmission" function is the permeability in the plane of the geotextile, while the permeability involved in the filtration function is the permeability normal to the geotextile.

. Continuity is an essential property which results from the structure of geotextiles. It means that geotextiles cannot be dispersed, while granular materials can be dispersed since they are made of discrete particles. It is implied that geotextiles are able to retain their continuity, which includes appropriate resistance to tear, puncture, burst, localized tensile stresses (grab), etc.

. The term tensile strength has been chosen for the sake of simplicity. It refers to all pertinent aspects of the tensile behavior such as strength, modulus, limited creep, etc.

. The term friction has also been chosen for the sake of simplicity. It encompasses all mechanisms by which shear stresses are transferred between soil and geotextile, such as friction, cohesion/adhesion, and interlocking.

Functions and applications

It would be simple for both professors and designers if only one function were performed in each type of application. In reality, a geotextile often performs several functions, as indicated in Table 2, which can be found at the end of the paper. From a practical viewpoint, it is interesting to group the application types in six areas: drainage, erosion control, containers, geomembrane support, soil reinforcement, and roadways (defined here to include all types of traffic supporting structures). From Table 2, the dominant functions appear to be:

. In hydraulic applications (drainage and erosion control): the fluid transmission and filtration functions.

. In geosynthetic construction (containers, geomembrane support): the tensioned membrane and protection functions.

. In geotechnical structures (roadways and soil reinforcement): the tensile member and separation function, and, to a lesser extent, the tensioned membrane and protection functions.

Application types mentioned in Table 2 are presented in [3, 4].

The emergence of geotextile functions

The need for identifying and describing geotextile functions appeared when geotextiles began to be used in a variety of applications. Therefore it is not surprising that the first papers discussing geotextile functions were published by those who were involved in the diversification of geotextile applications: A. McGown [5], and E. Leflaive and J. Puig [6]. Incidentally, it is interesting to note that:

- The "fluid transmission" function (then called "drainage" function) was identified by Leflaive and Puig in France, where needlepunched nonwovens (with high transmissivity) were the only geotextiles available at that time, but was not identified by McGown, working in the U.K. with heatbonded nonwovens which have negligible transmissivity.
- The "protection" function, although it was mentioned in some manufacturers' brochures, was not included in these early papers because geotextiles performing this function were used in applications that were not in the mainstream of early European applications (e.g., geotextiles in asphalt overlays have always been used almost exclusively in the United States; similarly, the protection of geomembranes by geotextiles, developed as early as 1971, was not considered at that time to be an integral part of geotechnical engineering because geomembranes were used to line small ponds, with no real design - today, lining systems incorporating geomembranes and geotextiles are used in major geotechnical structures such as dams, canals and waste disposal facilities).

The above comments illustrate that early concepts were derived from the observation of available products, which is often the case in a new discipline.

In the past, several charts have been proposed which showed relationships between properties and functions. The first one included only four functions (drainage, filtration, separation, reinforcement) [7], and, later, more complete charts included eleven functions [8]. The chart given in Table 1 seems to be an acceptable compromise: it is simple and includes, at least as subcases, the eleven functions indicated in [8].

Discussion of geotextile functions

As indicated in Table 1, geotextiles provide reinforcement to geotechnical structures through both the "tensioned membrane" and "tensile member" functions. In fact, these are often combined into one function, called "reinforcement". It appears more appropriate to consider them as two different functions ("the reinforcement functions") since they involve different combinations of geotextile properties, and play different roles as discussed below.

Relationships between functions and materials likely to perform them are presented in Table 3. In this table, not only geotextiles, but all types of geosynthetics are considered and one function has been added, "fluid barrier", which can be performed by geomembranes or by low permeability soils such as clay. Also, the protection function has been separated into two parts: surface protection (such as the use of geosynthetics for erosion control mats, temporary landing strips, etc.) and interface protection (such as use of geotextile between asphalt overlay and cracked pavement, or as a cushion between geomembrane and stony ground, etc.).

The discussion below refers to the materials presented in Table 3, as well as the three key properties presented in Table 1, namely: permeability, continuity and tensile strength.

Regarding permeability, soils offer a wide range of possibilities from very low (clay) to very high (gravel), and they are well-suited to perform the hydraulic functions, i.e., fluid barrier, fluid transmission and filtration. Consequently, to perform these functions, the designer may choose between geosynthetics or soils. In addition, to perform the fluid transmission function, choices may be made between pipes and synthetic drainage products such as nets, mats and waffles.

Soil layers have some measure of continuity when they are carefully placed and when they are not dispersed by erosion, traffic, etc. They can therefore perform functions where continuity is required such as surface protection (gravel), and filtration, separation and interface protection (sand). However, geotextiles have the advantage of better continuity, which facilitates their installation and enhances their performance. For example, geotextiles are successfully used for:

- filtration, especially when the installation of a sand filter is difficult , e.g., in French drains;
- separation , especially when the continuity of a sand layer could be disrupted by large deformations, e.g., in unpaved roads; and
- interface protection, especially when a thin layer of sand would lack the required continuity, e.g., in asphalt overlays (where the continuity of a sand layer would be progressively disrupted by repeated traffic loads) or in protecting a geomembrane on a slope (where the continuity of a sand layer would be disrupted by sloughing, erosion, etc.).

Soils, obviously, cannot provide the two reinforcement functions, tensioned membrane and tensile member, since tensile strength is required for these two functions. Regarding the tensile member function, the only competition at the present time for geosynthetics comes from steel strips and rods that have been successfully used as tensile members in thousands of structures in the past twenty years.

The tensioned membrane function is the only function for which geotextiles have virtually no competition: soils lack tensile strength and steel strips lack bi-dimensional continuity. Steel grids or steel fabrics could theoretically be used but, to be economical, they would have to be thin and would corrode. The tensioned membrane function appears therefore as the most original function of geotextiles, resulting from a unique combination of the two key properties of geotextiles, continuity and tensile modulus/strength. No wonder that the fantastic growth of the geotextile market started with their use in unpaved roads where the tensioned membrane function plays an essential role.

INVASION OF GEOTECHNICAL ENGINEERING BY GEOTEXTILES

The market data presented previously show that large quantities of geotextiles are being used. Geotextiles have, in fact, pervaded almost all branches of geotechnical engineering, and ninety different types of applications have been described [4].

What are the reasons for the success of geotextiles? First, and most obviously, geotextiles have been successful because manufacturers have aggresively developed and marketed them, and because contractors, designers and owners have elected to use them. The reasons for early usage of geotextiles are discussed below.

Reasons which interest contractors

Early successes of geotextiles may be credited to a large extent to contractors. They have adopted geotextiles very rapidly because they found immediate benefits in using them. Construction has become easier, and both earthwork and transportation time and costs have been reduced, as discussed below:

- In some projects, the use of geotextiles allows construction which would otherwise be difficult, if not impossible, such as road construction over a very soft soil. Also, road construction with geotextiles is less weather-dependent (trucks are less likely to get bogged down when a geotextile is used). In applications such as filtration, construction time is reduced because a geotextile is easier to install than a granular filter.

- When using geotextiles, the amount of earthwork is often reduced, e.g., geotextile drains and filters are less bulky than their granular counterparts and geotextile reinforcement allows the construction of smaller structures. Alternatively, the cost of earthwork is reduced if geotextile reinforcement permits the use of soils of a lesser quality, which are of course less expensive.

- Transportation costs can be dramatically reduced by replacing hundreds of tons of granular material by a few rolls of geotextile. Transportation costs can be further reduced if the incorporation of geotextiles in a structure results in the use of local soils. Reduced quantity of transportation is also beneficial from an environmental standpoint since the noise and dust associated with transportation of construction materials are reduced.

The above comments apply primarily to road construction, an area where the influence of contractors on the development of the use of geotextiles was significant. Road construction was the first large market for geotextiles (while the first applications of geotextiles were in coastal protection, where the need for geotextiles is clear, as is discussed hereafter, but the market is smaller).

Reasons which interest designers

Designers have not been as quick as contractors to adopt geotextiles because they do not have the same opportunity to enjoy immediate benefits. Furthermore, they often do not even have an incentive to recommend less expensive solutions. However, with the emphasis now placed on "value engineering", incentives are more and more often present for designers to prepare less expensive designs. Contractors, on the other hand, have traditionally had a high incentive to decrease the cost of a project, and they are also in the best position to evaluate savings resulting from easier and more efficient construction procedures. This is especially true in road construction where access to the construction site is of prime importance.

The impact of geotextiles in design is discussed later in this paper and is also discussed in the following paper by Professor R. Floss. Accordingly, only reasons for some of the early uses of geotextiles by designers are listed here:

- Geotextiles present an easy solution to problems with which designers have long been struggling, such as filters for coastal protection. Sand filters wash away and are difficult to construct under water while geotextiles are secure and easy to place. Therefore, it is not surprising that the first uses of geotextiles were in coastal protection.

- Geotextiles open new possibilities for innovative design and, in some of the first uses of geotextiles, the motivations of the designer were nothing but sheer curiosity and desire to try something different. This was more possible in countries where there was no prevalent litigious atmosphere, unlike some countries today where a prime motivation of designers is to avoid being sued.

- Geotextiles may increase the reliability of a structure in which they are incorporated because: (i) the quality control of their placement is easy; (ii) their installation is not significantly affected by weather; (iii) their properties are more uniform and reliable than soil properties; and (iv) they mitigate some soil defects by bridging weak spots, separating layers which would tend to mix, etc. As a result, the designer knows that the structure is built as designed and will likely perform as predicted.

This topic is discussed in detail in a paper devoted to the rationale and the future of geotextiles [9].

Reasons which interest owners

To a large extent, the success of geotextiles is due to owners who dared to use them in the early days. Motivations of owners are a combination of contractors' and designers' motivations. Like contractors, owners are interested in low cost, and, like designers, they are interested in reliability and, sometimes, in experimentation. Some of the most spectacular geotextile installations can be credited to daring and visionary owners playing the same role as the Babylonian Church three thousand years ago. Examples are: the Deltadienst Rijkswaterstaat (with K.A.G. Mouw) in the Netherlands; the Ponts et Chaussees in France; the Corps of Engineers (with J. Fowler) and the Forest Service (with J.E. Steward) in the U.S.A.; the Bundesanstalt fur Wasserbau in Germany; the Department of Water Affairs in South Africa; the Japanese National Railway; Hydro-Quebec and the Ontario Ministry of Transportation in Canada; and the West Yorkshire Metropolitan County Council (with Dr. C.J.F.P. Jones) in the U.K. In addition, many smaller, often private, owners were equally daring when they authorized the use of geotextiles in projects such as: coastal protection in the Netherlands, Japan and the United States; dams in Germany and France; waste management facilities in the United States; canals in the Middle East; land reclamation in Brazil and Japan; harbor construction in Belgium; tailings dams in South Africa; etc.

In some early applications of geotextiles, the main motivations of owners was the reduced maintenance and corresponding savings associated with the use of geotextiles. This was the case, for example, with the use of geotextiles in railroad track. In North America, where maintenance is critical because of very high loads, soft subgrades, and degradable ballast, the introduction of geotextiles (which extended maintenance cycles by several years) was hailed as revolutionary, and the market for geotextiles in railroads has grown rapidly. It should not be concluded that geotextiles are used only to maintain railroad tracks that are in critical condition. For example, in France and Japan, the high performance tracks for the fastest trains in the world also incorporate large amounts of geotextiles.

Fundamental reasons

In addition to the technico-economical reasons discussed above, there are other reasons for geotextiles (and geomembranes) to be used in geotechnical engineering. These are fundamental reasons.

The first fundamental reason is that there is a need for membrane-like materials in geotechnical engineering:

- Geotechnical structures are built with granular materials, whose properties are obviously complemented by those of membrane-like materials (e.g., the integrity of layers of granular soils can be disrupted by erosion, settlements, and earthquakes, while a geotextile layer remains continuous).
- Geotechnical structures are often large masses including layers of materials, and thin bi-dimensional materials are obviously useful, either as an interface between layers, or as a liner or a protection at the surface of the mass.
- Geotechnical structures are flexible and subjected to differential movements. Therefore, materials used in geotechnical structures should be flexible. By definition, membranes are bi-dimensional and flexible. Therefore, membrane-like materials are well-suited to geotechnical structures.

There was a lack of appropriate membrane-like materials, and geotextiles have proved to be the best materials to fulfill the needs indicated above:

- There are very few natural membrane-like materials. Animal hides have been used in earth construction in antiquity and in the Middle Ages, but they are small and usually biodegradable.
- Fascines made of willows, coarse mats made of palm fronds, jute fabrics, etc., have been used in soil structures since antiquity. These materials can be made as large as needed, but they are usually biodegradable, and they are expensive because their fabrication is labor intensive.
- Geotextiles are flexible bi-dimensional fabrics, they can be made as large as needed and they are not biodegradable. Therefore they fulfill all requirements to satisfy the need for membrane-like materials discussed above. This is the most fundamental reason explaining their success. In fact, all geotextile functions presented in Table 1, except tensile member and drainage, are "interface functions" where a "membrane-like" material is needed.

Another fundamental reason that explains the success of geotextiles, especially in soil reinforcement, is that many structures built in geotechnical engineering are tri-dimensional. (Tri-dimensional structures are much more difficult to design than uni-dimensional (beams) and bi-dimensional (slabs) structures used in structural engineering: this is one of the reasons why geotechnical engineering lagged behind structural engineering for many years. It has only been in the last twenty years that geotechnical engineering has caught up, principally because of the sophisticated methods of analysis which have become available.) An efficient way to build a tri-dimensional structure is to reinforce it with bi-dimensional elements (i.e., materials with one of the three dimensions - the thickness - much smaller than the two others). Similarly, an efficient way to make bi-dimensional materials is to combine uni-dimensional materials (fibers) because making fibers is one of the most efficient ways to use a given amount of matter since, as a result of molecular orientation, the strength of a fiber is much higher than the strength of the original polymer. In summary, building a tri-dimensional mass using bi-dimensional elements, made from uni-dimensional elements, is an efficient way to use matter, especially if the uni-dimensional elements have high molecular orientation. This is one of the reasons for success, in soil reinforcement, of geotextiles and other molecularly oriented materials such as polymer grids.

The above discussion on the efficient use of matter in geotextiles, using soil reinforcement as a example, is corroborated by the following comments on the performance of a nonwoven geotextile used for filtration. Calculations show that a nonwoven geotextile and a sand having the same opening size (i.e., distance between fibers or particles that govern the filtration capability) have approximately the same permeability. The same calculations also show that the density of the geotextile would be about one-tenth of that of the sand because the geotextile has a much higher porosity that the sand, and polymer density is much lower than mineral particle density. As a result, a geotextile has the same filtration characteristics as sand, but with ten times less matter. (In addition, the thickness of a geotextile filter is usually 100 to 1000 times smaller than the thickness of a sand filter, which is possible because of the continuity resulting from the structure of the geotextile. As a result, the weight of a geotextile filter is typically 1000 to 10 000 times smaller than weight of a sand filter having the same filtration characteristics.)

In conclusion, when used as reinforcement, drainage or lining, geotextiles and geomembranes are, respectively, the muscles, the veins and the skin of the Earth. Never before have construction materials displayed such versatility and performed such fundamental functions. Geotextiles and geomembranes are therefore here to stay.

INFLUENCE OF GEOTEXTILES ON GEOTECHNICAL ENGINEERING

Geotextiles have invaded geotechnical engineering for many reasons, as discussed above. Beginning as a minor technique, their influence on geotechnical engineering has elevated their status to that of a true discipline. The following discussion traces the development of that influence.

Geotechnical engineering and the textile industry

One primary mechanism by which geotextiles are influencing the field of geotechnical engineering is the introduction of geotechnical engineers to textile specialists. Using earth as a construction material (geotechnical engineering) and weaving cloth to make garments (the textile industry) are among the oldest professions on earth, and it is surprising that they ignored each other until the middle of the 20th century. This attitude is all the more surprising when we realize the extent to which geotechnical engineering and textiles are part of our everyday universe: many large features of our landscapes (road embankments, retaining structures, landfills, canals, dams and reservoirs) result from geotechnical engineering; each country on earth has selected a piece of fabric as a national symbol; when we see a human being we usually see more textile than flesh; the fabrics they wear are the most convenient way to distinguish between a soldier and a civilian, a clergyman and a layman, and, sometimes, a man and a woman; and when Magritte wants to represent death, he does not show the soul being separated from the body, but the body being separated from the clothes.

In their early efforts to test and eventually to sell their first geotextiles, representatives of the textile industry approached geotechnical engineers, who often reacted negatively. As indicated in the introduction, geotechnical engineers are trained to consider God as the only supplier of geotechnical materials and they may find it difficult to talk to other suppliers, especially if they might be associated with the "frivolous" garment industry. Also, geotechnical engineers, accustomed to designing prototype structures and to considering themselves as creative, have a certain reluctance to cooperate with representatives of a mass-production industry. As a result, geotechnical engineers have often complained about the fact that the properties of available geotextiles were imposed upon them, and these did not fit their needs. Consequently, many geotechnical engineers felt that geotextiles were made to satisfy manufacturer's criteria rather than user's criteria. Such a criticism might have been valid in the early days, especially in countries dominated by one manufacturer, but, with the development of competition, a very large variety of geotextiles is now available. From the textile industry's viewpoint, it should also be noted that the same geotechnical engineers have always accepted the limited variety of soils available at each given site.

Because of the success of geotextile sales, many textile specialists have been in contact with geotechnical engineers during the process of project design, field installation, committee work or conferences. This interaction has been and continues to be very profitable for geotechnical engineers. In fact, when they establish relationships with textile specialists, geotechnical engineers commonly find the experience to be intellectually and professionally rewarding. Textile specialists, and the geotechnical engineers who have cooperated with them, have certainly brought a new spirit to geotechnical engineering. Geotechnical engineers are now learning about new materials and are extending their creativity. This is quite a change from the days when geotechnical engineers considered materials as given and devoted all their creative skills to design concepts and calculations.

Today, it is not uncommon for a geotechnical engineer to work for a geotextile manufacturer, and those bright engineers who have elected to do so have found challenging and rewarding careers. This is quite a change from the good old days when God, then the sole supplier of geotechnical materials, never made a job offer.

Revolution in design

A second mechanism by which geotextiles are revolutionizing geotechnical engineering is by causing geotechnical engineers to change their design habits. A few examples are discussed below:

- When geotextiles are used, some structures can be stable and perform satisfactorily while they are theoretically at the verge of failure. This is the case of unpaved roads (or other similar structures) where, under repeated loads, the soil can work safely at its plasticity limit, which is possible only if a geotextile provides confinement to the subgrade. It is interesting to note that confinement results from the tensioned membrane function which, in turn, is governed by the two most fundamental properties of geotextiles: continuity and tensile characteristics.

- A second example is the influence of soil-geotextile interaction on design. The nature of the interaction of a geotextile with its environment (liquids and/or solids) is as important as its physical and mechanical properties. Geotechnical engineers are becoming knowledgeable about the various aspects of interaction between geotextiles and soils: permeability to fluids, retention of solids, and mechanical interaction which includes friction, surface adhesion and interlocking, etc. All the work being done on these subjects can only lead to a better understanding of geotechnical engineering in general.

- A third example is the importance of detailed design, which results from high specialization of functions. Geotextiles are placed at a certain location to perform a precise function. As a result, there often is a gradient of stress in the vicinity of this location (i.e., gradient of liquid pressure, gradient of mechanical stresses). A zone of high stress gradient is a zone that may deteriorate faster by erosion, mechanical fatigue, etc. Let us consider a traditional example without geotextiles. In a zoned dam, functions are specialized, i.e., imperviousness is provided by the clay core, and strength by the rockfill zones. The interface between the core and rockfill zones is the delicate portion of the dam because of stress gradients (gradient of water pressure likely to cause piping, gradient of shear stresses likely to cause cracking), and carefully designed transition zones are needed. This is also valid for geotextile applications. For example, in a multilayer geotextile reinforced embankment, there are stress gradients, and methods of design should be developed to take these facts into account. This is a general process: structures, like societies, become more efficient by specializing functions but thereby generate interaction problems. A primitive society where everyone is simultaneously farmer, cook, doctor, engineer and teacher has a simple organization. A modern society, on the other hand, experiences stress because of friction between the various categories of specialized individuals.

In conclusion, geotextiles are transforming geotechnical engineering by placing geotechnical engineers in contact with textile specialists, and by having an influence on the design practice of geotechnical engineers. So far, this has primarily affected the pioneers in the field, but all geotechnical engineers are progressively being involved.

INFLUENCE OF GEOTECHNICAL ENGINEERING ON THE GEOTEXTILE COMMUNITY

As discussed in the previous section, geotechnical engineering has been transformed by geotextiles. Conversely, the world of geotextiles has changed significantly because of the influence of geotechnical engineering. The prime cause of this change was that, in spite of early successes, geotextiles encountered a great deal of resistance from certain circles of the geotechnical community. It was a challenge to which the geotextile community responded brilliantly.

The challenge

As indicated in the previous section, one of the reasons for the slow acceptance of geotextiles by many geotechnical engineers was the lack of communication between the textile and geotechnical communities in the early days of geotextiles. This reason is linked to the people involved. In addition, there are reasons linked to the products, the geotextiles. Many geotechnical engineers were slow in accepting geotextiles because: (i) they did not like synthetic polymers; (ii) they did not know how to use geotextiles; and/or (iii) they were confused by the diversity of available materials.

In the beginning, many geotechnical engineers were reluctant to use geotextiles because they are made from synthetic polymers, materials that are not traditionally used in civil engineering. Geotechnical engineers easily accept inclusions in the ground made of concrete (piles) or steel (piles, sheet piles) because they are familiar with the behavior of these materials. They did not easily accept synthetic polymers because they knew very little about them and were not comfortable using them. This lack of knowledge also made some geotechnical engineers suspicious regarding the durability of synthetic polymers. ("Plastics" have a bad reputation: "it is plastic therefore it is not good". This bad reputation results from everyday uses where plastics are used to replace high quality traditional materials such as leather. Synthetic materials used in other applications are respected and trusted: who would dare using a parachute that is not made with synthetic fabric? Also, in the early days, some manufacturers contributed to the poor reputation of plastics when they denigrated polymers used by their competitors.) Today, most geotechnical engineers are comfortable using synthetic materials because the durability of geotextiles in the ground has been established by almost thirty years of experience. Also, there are many cases where the design life of the geotextiles is rather short, either because the structure incorporating the geotextile is temporary, or because the role of the geotextile decreases with time. For example, the amount of reinforcement required from a geotextile in a given structure often decreases with time, as soil consolidates and progressively carries a larger fraction of the load.

Many geotechnical engineers, especially designers, did not know how to use geotextiles as a result of one or more of the following legitimate reasons: (i) lack of information about the mechanisms by which geotextiles work; (ii) lack of design methods; (iii) lack of data regarding geotextile properties; and/or (iv) lack of data regarding performance of structures incorporating geotextiles. The latter factor was perhaps the most important. As a result, engineers who wanted to use geotextiles were very demanding and asked many questions regarding the mechanisms through which geotextiles perform. For example, many geotechnical engineers have asked many more questions about the functioning of geotextile filters than they would have asked about the functioning of sand filters. To quote McGown, "The principal difference between soils and geotextiles is that we are far more familiar with the former than the latter." [10].

In the mid-1970's, as a result of free competition, a number of geotextiles, wovens and non-wovens, appeared on the market. Many geotechnical engineers, disoriented by the diversity of brand names and pressured by salesmen, were not comfortable with what they considered a commercial atmosphere and became skeptical about geotextiles. Others who thought that it was sufficient to learn the difference between wovens and nonwovens became disillusioned as selection of the optimum product for a project became more difficult when new types of products appeared: mats, nets, grids, webbings, composite geotextiles (a detailed description can be found in [3]). Today, there is a very wide diversity of products, whose typical ranges of properties are given below:

- Mass per unit area, from 0.1 to 1 kg/m^2 or more.
- Opening size: 0.05 to 0.5 mm for nonwovens; 0.1 to 1.0 mm for wovens; 5 to 10mm for mats; 5 to 100 mm for nets and grids.
- Hydraulic transmissivity: negligible for most wovens and heatbonded nonwovens; 10^{-6} to 10^{-5} m^2/s for needlepunched nonwovens; 10^{-4} to 10^{-2} m^2/s for nets; 10^{-4} to 10^{-1} m^2/s for drainage geocomposites.
- Tensile strength: 10 to 30 kN/m for the most commonly used nonwovens; 30 to 100 kN/m for strong nonwovens; 20 to 50 kN/m for for the most commonly used wovens; 50 to 100 kN/m for strong wovens; 100 to 1000 kN/m for very strong wovens and webbings; 30 to 200 kN/m for the most commonly used polymer grids; 200 to 400 kN/m for very strong polymer grids.

The response of the geotextile community was equal to the multiple challenge described above: it included several aspects such as research and development of understanding, education of potential users of geotextiles, and organization of the profession.

Research and development of understanding

Research was initially sponsored by manufacturers, and much of the early work was devoted to proving that specific fabrics would work in given applications. Although this approach may have been criticized by purists, it was very useful because a lot of work was done which would not have been possible without manufacturers' support. The engineering community is certainly indebted to manufacturers for their early and continuing dedication to research. Progressively, an increasing amount of research was sponsored by independent organizations, and at present, research with geotextiles has become part of normal research work in many research centers and universities. Some of them have already acquired a solid reputation in the field of research on geotechnical applications of geotextiles. Some examples are: University of Strathclyde, Scotland, U.K. (Professors A. McGown and K.Z. Andrawes), Oxford University, U.K., (Professor C.P. Wroth), University of Birmingham, U.K. (Professor D.J. Hoare), Transport and Road Research Laboratory, U.K. (R.T. Murray), Queen's University, Belfast, U.K. (Professor A.L. Bell), Science University of Tokyo, Japan (Professor M.

Fukuoka), Kyushu University, Japan (Professor T. Yamanouchi), Institut du Genie Civil, University of Liege, Belgium (Professors K. Gamski and J.M. Rigo), Technical University of Vienna, Austria (Professor H. Brandl), Technical Research Center of Finland (H. Rathmayer), Laboratoires des Ponts et Chaussees, France (E. Leflaive, J. Puig, P. Delmas), Institut Textile de France (M. Sotton, B. Leclercq), Grenoble University, France (Professor J.P. Gourc), CEMAGREF, France (D. Fayoux), Centro Ricerca Idraulica e Strutturale, ENEL, Milano, Italy (D.A. Cazzuffi), Delft University of Technology, the Netherlands (Professor K. van Harten), Plastics and Rubber Research Institute, TNO, Delft, the Netherlands (with a large research team), the Delft Hydraulics and Soil Mechanics Laboratories, the Netherlands (with large research teams), EMPA, St. Gall, Switzerland (E. Martin), Technical University of Munich, West Germany (Professor R. Floss), Bundesanstalt fur Wasserbau, West Germany (H.J. List), Politechnika Gdanska, Poland (Professor E. Dembicki), Civil Engineering Institute, Bucharest, Romania (Professor S. Andrei), Federal University, Rio de Janeiro, Brazil (Professor J.A. Ramalho-Ortigao), The New South Wales Institute of Technology, Australia (Professor M. Hausmann), University of Western Ontario, Canada (Dr. R.K. Rowe), Ecole Polytechnique de Montreal, Canada (Professor A.L. Rollin), Queen's University, Canada (Professor G.P. Raymond), Royal Military College of Canada (Professor P.M. Jarrett), Drexel University, U.S.A. (Professor R. M. Koerner), Louisiana State University, U.S.A. (Professor A. Arman), Georgia Institute of Technology, U.S.A. (Professors G.F. Sowers, R. Barksdale, and N.D. Williams), Oregon State University, U.S.A. (Professor J.R. Bell), Purdue University, U.S.A. (Professor R.D. Holtz), Illinois Institute of Technology, U.S.A. (Professor R.K. Saxena), University of Illinois, U.S.A. (Professor E. Barenberg), New York State Department of Transportation, U.S.A. (L.D. Suits), and the Waterways Experiment Station of the U.S. Army Corps of Engineers with a large research team.

Research has been successful in many areas such as: demonstration of the durability of geotextiles in the ground, development of an understanding of mechanisms by which geotextile function, and preparation of design methods. Of course, much more work is needed and will be done since research on geotextiles is moving in the right direction. Also, research is being done using the well established means and structures of the geotechnical community (such as universities and research centers mentioned above). This leads to even greater acceptance by potential users since geotechnical engineers ascribe great credibility to research performed by other geotechnical engineers.

The amount of research and the development of understanding are reflected by the number of publications on geotextiles. To date, approximately 2000 publications on geotextiles have been documented [3, 11] since the papers by R.J. Barrett (1966) [12] and T. Yamanouchi (1967) [13] discussing the first applications of fabrics and nets, respectively.

Education of potential users of geotextiles

Education of the potential users of geotextiles has been, and continues to be, a key factor in the development of the uses of geotextiles. During the early stages of geotextile development, manufacturers printed informative brochures and sponsored lectures and seminars. Today, one- to three-day training courses ("short courses") are sponsored by universities and official organizations such as the Federal Highway Administration in the United States. Audiences attending short courses are increasingly large because engineers can no longer afford to ignore geotextiles. As a complement to short courses, manuals have been written [14,15] and audio-visual shows have been prepared.

Education of potential users of geotextiles is also achieved through papers written for publication: they contribute to dissemination of (usually) unbiased information on geotextiles. Unfortunately, much of the early geotextile literature was published in other than traditional geotechnical sources and was not read by many geotechnical engineers. Then, papers on geotextiles began to appear in classical geotechnical journals, such as the "Journal of Geotechnical Engineering" of the American Society of Civil Engineers (ASCE) where the first paper devoted to geotextiles was published in 1981. Another step was the commencement, in 1983, of the trade magazine "Geotechnical Fabrics Report" published by the IFAI, and, in 1984, of the technical journal "Geotextiles and Geomembranes" published by Elsevier, with Professor T.S. Ingold as the editor. These two publications, exclusively devoted to geotextiles, geomembranes and related products, are a major contribution to the education of engineers and other potential users. Books have also been published on geotextiles in 1971, 1980, 1981, and 1984 [16, 17, 18 and 19].

The educational process includes a major task, which is to give a clear picture of the range of products available and of their potential uses. This was one of the goals of the report prepared by the Technical Committee on Geotextiles of the International Society for Soil Mechanics and Foundation Engineering [3]. With a clear view of the types of products, the diversity of products is no longer a problem, but becomes an advantage. To have a clear picture, a consistent terminology is necessary. Considering the proliferation of new types of materials, one may ask if the term geotextile is still appropriate. The phrase "geotextiles and related products" was proposed by Giroud and Carroll [20] and adopted by the American Society for Testing and Materials (ASTM). The term geosynthetics was proposed by Fluet to ASTM in June 1983, to encompass geotextiles, geomembranes, and related products. The term geosynthetics is now increasingly used in North America. However, although most geotextiles and geomembranes are made from synthetic materials, some are not and the term geosynthetics is not quite as comprehensive as it is intended. Also, the development of polymer grids (geogrids) makes it impossible to exclude steel grids which perform the same function. A general term such as "geoproduct" may encompass all considered products, but this term may be too vague. Does it include concrete piles, sheet piles, anchor plates? An even more general term would be "geomaterials". Such a term would undoubtedly include man-made products ("geoproducts") as well as natural materials (soils, rocks). A tentative classification of geoproducts is presented in Table 4.

The education of potential users of geotextiles will continue to play a crucial role in the future. Potential users of geotextiles and related products, especially the designers, should be kept abreast of new developments, but the priority is to educate the large number of people who do not know the basics of geotextiles. There are still many of those in countries where geotextiles are commonly used, and there are many, of course, in countries where geotextiles are not used. A continuous effort should be made to demonstrate to geotechnical engineers that geotextiles are part of geotechnical engineering (this was the theme of the report presented in 1985, in San Francisco, at the International Conference on Soil Mechanics and Foundation Engineering by the Technical Committee on Geotextiles of the International Society for Soil Mechanics and Foundation Engineering [3]). Many concepts familiar to geotechnical engineers are similarly used for geotextiles and, after all, the difference between wovens and nonwovens is similar to the difference between rocks (organized) and soils (random).

Educational programs should include workshops on construction methods because it is important that design engineers become familiar with the installation of geosynthetics. Too often, it is impossible to implement construction as indicated on the design drawings because the designer does not know how geotextiles are installed. As a result, the performance of the structure may be affected. For example, it is misleading for the designer to believe that geotextiles and earthworks are as straight in the field as are the lines representing them in the design drawings. A geotextile reinforcement installed with wrinkles, or a geotextile filter that is not in close contact with the jagged edges of a drainage trench certainly will not perform as designed.

The education of geotechnical engineers will have to draw much from the knowledge and the experience of textile specialists. Geotechnical engineers will need to be familiar with such subjects as the chemistry of polymers and the effect of temperature on geoproduct properties (and knowledge of temperature distribution in soils and structures becomes necessary). The geotechnical engineers of the world should listen to Vienna now as they did sixty years ago; they should listen to Vienna today if they want to become the leading geotechnical engineers of tomorrow.

Organization of the profession

The efforts undertaken to organize the profession have included committee work to develop standards and the formation of the International Geotextile Society.

The development of standards for geotextile testing has been undertaken by many committees in most countries using geotextiles. A first result of this effort is that there is now a general agreement on the types of geotextile tests that are needed. However, so far, standards have been published on only a few tests and much additional effort is needed to complete this task. In the meantime, many tests inherited from the textile industry are still used.

To date, most of the standardization work completed has been done by separate national committees. International coordination with a view to the preparation of international standards is necessary since geotextiles are easily transported from one continent to another. For the first time, in 1985, representatives from committees of various countries met under the umbrella of the International Organization for Standardization (ISO) to start a very useful and necessary work. Although some groups may object to specific methods of operation of the ISO, and others may want to slow down the development of international standards for national or commercial reasons, it is fortunate that the concept is now gaining momentum. Hopefully, international standards will evolve which are based on an international view. Such standards will be a very valuable tool for all members of the geotextile community and will bring international recognition to the contributions made by a variety of committees from different countries.

The organization of the geotextile community was a major challenge because of the initial differences, discussed above, between geotechnical engineers and textile specialists. The formation of the International Geotextile Society (IGS) in 1983 is the essential element for the organization of the profession. The society now has members in 25 countries. The Vienna Conference is the first official event sponsored by the IGS. This causes us to reflect some sixty years in our past and follow the path of a man in Vienna who inspired many of us: he had understood that soil and equations were a good match, but understanding was not enough; he had written equations, but writing was not enough; he published the equations, but publishing was not enough; he travelled the world teaching, but teaching was not enough; he organized an international conference and attracted the world, but attracting the world was not enough; finally, he was the leading force in creating the International Society for Soil Mechanics and Foundation Engineering, and that kept the people together, kept the momentum.

Looking at the relatively short history of geotextiles, it is amazing that the process by which the geotextile community has become organized is similar to that of geotechnical engineering, with, however, one important difference: it is the action of a number of people, not the leadership of one person, that led our profession to where it is today, a situation we can all be proud of. More importantly, beyond the action of people, the main factor responsible for the success of geotextiles is the geotextile itself, this piece of fabric that works when it is placed in the ground. Success has been achieved because geotextiles work: they work because of their properties, they work even without the theories of experts or the claims of salespeople.

To reinforce the important difference mentioned above, it is interesting to notice that the Austrian Post Office has recently issued two stamps, one showing a man, Terzaghi, the other, a product, a roll of geotextile.

Clearly, the organization of the geotextile profession has been influenced by the organization of the geotechnical profession. One of the major tasks of the International Geotextile Society (IGS) is to organize international conferences, as does the International Society for Soil Mechanics and Foundation Engineering (ISSMFE). Also, an important tool, ensuring coherence in the geotextile community, is a list of symbols [21] consistent with those adopted by the ISSMFE.

Committees are far from having completed their work, but the evolution of the profession is so rapid that some committees have already changed their scope and name. For example, the French and the Canadian committees on "Geotextiles and Geomembranes" were formerly on "Geotextiles" only; the ASTM Committee on Geotextiles, Geomembranes and Related Products was formerly on "Geotextiles and Related Products", and, before that, on "Geotextiles". This committee may soon become the ASTM Committee on Geosynthetics. The International Geotextile Society, less than a year after its creation, formed a committee to study a modification of its scope and bylaws to include geomembranes.

National Committees and the International Geotextile Society should remember that they work in a fast growing and changing field. Therefore, all their proceedings should be sufficiently flexible to include new products. Flexibility and open-mindedness should be the rule. The pioneers of today should not become the conservatives of tomorrow.

THE ROAD AHEAD

As indicated above, a great deal of work is still needed in research, education, and organization of the profession. Developments resulting from research can be expected in the areas of available materials, construction methods, evaluation of geosynthetic properties, and design methods.

Materials

In classical geotechnical engineering, only natural materials such as soils and rocks are used. Types and properties of natural materials are limited, while the human imagination is unlimited and can thereby produce a wide variety of products which may intrinsically lead to new design concepts. These products include not only geotextiles but many other types of geosynthetics such as grids, mats, nets, meshes, etc., and new types of products will certainly appear.

The growing geosynthetic market will attract more and more manufacturers. These manufacturers will come not only from the traditional textile industry, but also from the plastics industry. Already, new manufacturers have appeared who are specifically organized for the production of geosynthetics. This transformation of the profession will bring new ideas and create new products. Some of the production lines will be sufficiently versatile to allow designers to obtain custom-made geosynthetics to fit special design needs. For example, synthetic drainage materials are already gaining wide acceptance. However, to provide large drainage capacity, these products must contain very large voids, and they are therefore bulky and difficult to transport. Expansive geosynthetics (possibly made of a permeable foam, or similar in principle, if not in use, to honeycomb products), which assume their final shape and occupy their final volume only when expanded on the site, will be developed to minimize transportation costs. The use of waste products (such as reclaimed tires) for soil reinforcement will grow, thereby requiring the development of special testing and design methods. The development of the use of fibers, yarns [22] and microgrids [23] directly combined with soil has already led to a new design concept, micro-reinforcement, i.e., small scale reinforcement which is intimately associated with soil particles (in addition to the concept of macro-reinforcement already in use with large elements such as geotextiles, geogrids, steel strips, etc.).

The use of such small elements as filaments, yarns and microgrids will not be limited exclusively to reinforcement. One may envision using them for filtration: there are cases where a thick filter is needed but it is difficult to obtain close contact between a thick geotextile filter and the soil to be filtered (which is required to prevent clogging). One solution to this problem would be to make the filter on site by spraying many fibers or filaments onto the soil, thus assurring good contact. A further refinement of this technique could be obtained through utilization of sophisticated equipment to vary either concentration of fibers in the sprayed mixture or thickness of the mixture in designated areas. Another refinement would be to fulfill an old dream of the geotechnical engineer: the cohesive material with high permeability. This would be achieved by mixing into the soil a large number of high porosity micro-inclusions with high mechanical interlocking with the soil. Such materials would be ideal for the construction of filters in earth dams in seismic areas, where liquefaction of granular filters during earthquakes is a major problem.

Construction methods

New construction methods will create new possibilities for conceptual design, especially for soil reinforcement applications.

For the installation of elements of macro-reinforcement, such as geotextiles and geogrids, pretensioning will be used more and more systematically, with specialized equipment to stretch the geosynthetic in the field. Today's geotechnical engineer can utilize current construction techniques to pretension geosynthetics to a certain extent. Simply having an understanding of geosynthetic behavior enables the design engineer to specify installation sequences which will make the geosynthetic work more efficiently. The key factor to consider in such attempts is the fact that geosynthetics have strain-dependent behaviors.

The developments in micro-reinforcement will probably have a great impact on construction methods, especially development of such items as computerized equipment controlling density and orientation of micro-reinforcement during placement of fibers or micro-grids in the ground. As a result of this technology, it will become possible to construct the "ideal least expensive structure" by placing micro-reinforcement in the appropriate direction with respect to the expected strain field. The corresponding method of design will have to be developed.

Many applications can be envisioned where macro-reinforcement and micro-reinforcement will be combined. Macro-reinforcement will be preferred in applications where the analysis of the stress and strain field in the unreinforced structure shows that reinforcement is needed in one or two well-defined directions. Micro-reinforcement can be used in all cases but is expected to find its broadest use in applications where tensile stresses and strains may appear in several directions or in directions that vary with time.

Use and evaluation of geosynthetic properties

Computerized databanks will be used to store and retrieve properties of existing geosynthetics and, by comparing properties to selection criteria, will automatically select geosynthetics whose properties match those determined by the designer to be required for a project. The efficacy of such systems will depend on the development of international standards, but many factors impede progress in this area. For example:

- Standards organizations are notoriously slow (although for good reasons) to develop national standards, so it will be even more difficult to establish accepted international standards.
- Slowness of standards organizations may be even more of a problem in a fast-growing discipline. New products appear and are used - or misused - before relevant standard test methods are available. As a result, designers too often choose between testing with irrelevant but available standards, or not testing. A better choice in this case would obviously be a relevant test based on non-standard procedures, which requires knowledge and/or imagination on the part of the designer.
- International standardization efforts are severely hampered by the persistent use, in the country with the largest geotextile market, of an illogical and impractical system of units. It is of utmost

importance that all influential organizations in the field of geosynthetics take a firm stance on the matter of recommending and promoting the use of the SI system of units in all countries without any exception. All those who keep presenting papers, publishing articles, and writing brochures and reports with the exclusive use of a system other than the "Systeme International" should stop this practice because they do a disservice to the profession and to themselves. In our century, perpetuating a practice that restricts communication between people is a mistake from a technical, economical, and even ethical standpoint. The geotextile community must adopt a universal language. Let it be inspired by Vienna, where Haydn, Mozart and Beethoven taught the world its most universal language.

International standardization of symbols as well as units is critical to a smooth growth of knowledge and efficient exchange of information. As mentioned earlier, the International Geotextile Society has adopted a list of symbols [21] that is consistent with the list of symbols of the International Society for Soil Mechanics and Foundation Engineering, which illustrates the cooperation between the geotechnical and geotextile communities. This list of symbols will have to be continuously updated, which will require continued cooperation between textile specialists and geotechnical engineers.

Methods of design

In the early stages of geotextile development, applications were, at best, crudely designed. The initiative belonged to manufacturers and contractors. Methods of design have progressively appeared and, in the future, the initiative should clearly belong to designers.

Design developments based on ongoing research can be expected in two major areas: development of sophisticated analytical design methods, and development of empirical or semi-empirical methods for those applications which elude analytical methods of design. In both cases, essential information will have to be obtained from the evaluation of the performance of carefully monitored structures.

Sophisticated analytical design methods will permit the design engineer to take into account complex parameters such as strain-dependent and time-dependent geosynthetic properties, influence of confinement stresses on geosynthetic tensile properties, soil-geosynthetic interaction (especially strain compatibility between soil and geosynthetic), influence of small changes in strain field or in stress inclination on the behavior of a soil mass incorporating geotextiles, effect of temperature, etc. The development of sophisticated analytical design methods will happen almost automatically because of the following pre-existing factors:

- These types of methods are particularly well adapted to soil reinforcement design, so economic incentives will cause manufacturers of geosynthetics used for reinforcement to sponsor their development.
- Many researchers are already in a position to develop such methods because they have been involved in the development of similar methods for traditional geotechnical applications.
- The development of analytical methods can be done by small teams with standard equipment typically available in universities and research centers.

Such methods will require:

- tests to better quantify geosynthetic properties such as tensile characteristics (including creep) when confined in soil;
- mathematical tools such as finite element computer programs which can model geosynthetic behavior; and
- a new approach to evaluating the safety of a structure by using a spectrum of partial factors of safety (since a unique factor of safety has little meaning for a composite material such as a reinforced soil).

Results expected from this approach include:

- design methods based on a rational analysis for reinforced soil structures such as vertical walls, steep slopes, embankments on weak foundations, etc.; and
- methods which optimize orientation and density of micro-reinforcing elements, such as fibers or micro-grids, to design the least expensive structure and direct the automated equipment used to place the reinforcing elements.

The development of analytical methods for some types of applications is difficult. This is typically the case for traffic supporting structures (roads, railway track structures) because fatigue of materials, natural as well as synthetic, under the effect of repeated loads is not well understood. Highway pavements, for example, are designed today using empirical methods which were developed from extensive full scale testing conducted over the past several decades. It is necessary that similar full scale testing be undertaken to establish design methods for geosynthetically reinforced paved and unpaved roads.

A first step towards that goal has been the development of an empirical method for the design of unpaved roads using available data from twelve years of experience [24]. The next step should be to carry out extensive full scale testing for unpaved as well as paved roads. Governmental agencies, geosynthetic manufacturers, research centers, professional and trade organizations should all be encouraged to combine their resources to sponsor and/or conduct such research.

More generally, areas where empirical and semi-empirical design methods are useful include design situations where concentrated stresses are important, transient conditions prevail, or time dependent effects are critical. Such situations occur in many geotextile applications.

The use of empirical or semi-empirical methods of design usually requires the use of a classification of materials. Classification of materials requires an accepted set of index properties, and therefore accepted testing procedures to evaluate index properties. For example, Atterberg limits are used worldwide to classify soils, and standard recommended procedures exist. Unfortunately, at the present time, there is a great deal of confusion regarding geosynthetic index properties. In particular, too many different tests and test procedures are currently in use. The confusion concerning index tests for geosynthetics must be eliminated as soon as possible through cooperation between all parties involved. Again, international cooperation is sorely needed. A first step could be the adoption by all manufacturers of a standard format to present the properties of their products, a common practice in other competitive industries.

In conclusion, it can be predicted that a comprehensive and consistent body of knowledge for designing with geosynthetics will be developed in the next decade. As a result, an increasing number of large structures will incorporate geosynthetics. Also, the use of geosynthetics will be safer than it is today because design engineers will be better informed and less likely to design exclusively on the basis of information provided by manufacturers. An ideal situation will be reached when design engineers will have, for each type of application, a choice of design methods at their disposal.

As a result of the development of design methods, designing geotextile applications will become more and more sophisticated. And, we will surely see the disappearance of early designs which consisted mostly of drawing a dashed horizontal line to show the location of the geotextile determined from magic formulas, such as cost of geotextile smaller than cost of aggregate saved.

CONCLUSION

The road ahead includes a great deal of work. Nevertheless, it is encouraging to consider how impressive is the distance already travelled.

Ten years ago we were the eccentrics of the geotechnical profession. We are now one of the most active groups, enjoying full recognition. Those who have contributed to this exceptional success should be proud: textiles specialists because of their technical achievements, manufacturers who have made available a variety of high quality products, sales and marketing persons who expanded the market by their unflagging efforts, designers and contractors who have attracted attention to geotextiles by incorporating them in major projects, owners and governmental agencies who have taken risks and set the examples, authors writing about geotextiles, and all of those who devote time to committees and conference organization.

Vienna is a symbol for all geotechnical engineers, as I said before, because of the birth of geotechnical engineering in this city. Vienna now becomes a symbol of the birth of a new discipline. Geotextiles, geosynthetics, or geoproducts are not only a convenient technique, they have become a discipline.

Geotextiles, geosynthetics, geoproducts are a discipline because they have a long and consistent history and their own language - terminology and symbols.

Geotextiles, geosynthetics, geoproducts are a discipline because they have influenced the thinking and the practice of engineers.

Geotextiles, geosynthetics, geoproducts are a discipline because there is an active international community committed to progress by the way of technical development, professional organization, and education.

Finally, geotextiles, geosynthetics, geoproducts are a discipline because they have many disciples.

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The author realizes that the history of geotextiles presented at the beginning of this paper may unwittingly omit some important facts, and would appreciate any information which would enable him to prepare a completed and updated version for eventual publication.

DEDICATION

This paper is dedicated to twelve young professionals who are actively engaged in geotextile engineering and with whom the author has been personally involved, as well as to their peers in the same generation and those even younger, whom they have the responsibility to educate. The twelve - K.Z. Andrawes, C. van den Berg, R. Bonaparte, D.A. Cazzuffi, J.P. Gourc, G. Heerten, R.A. Jewell, H.G. Rathmayer, J.M. Rigo, R.K. Rowe, J.C. Vertematti, and G. Werner - are from twelve different countries and can be considered as a cross-section of a generation which has a unique opportunity to accomplish much for our profession.

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References quoted in this paper are listed on the last page, after the tables.

TABLES

For the sake of clarity, the tables are presented together in the next two pages. These tables are:

Table 1. Relationships between properties and functions of geotextiles, and their purpose and location

Table 2. Relationships between applications and functions of geotextiles

Table 3. Relationships between functions and materials

Table 4. Proposed classification of geoproducts

Table 1. Relationships* between properties and functions of geotextiles**, and their purpose and location.

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PROPERTIES***	FUNCTIONS	PURPOSES	LOCATIONS
Thickness	FLUID TRANSMISSION****	Removes excess water	INCLUSION
Permeability	FILTRATION	Prevents piping	INTERFACE
	SEPARATION	Prevents mixing	INTERFACE
Continuity	PROTECTION	Prevents damage	INTERFACE
	TENSIONED MEMBRANE*****	Provides reinforcement	INTERFACE
Tensile Strength	TENSILE MEMBER*****	Provides reinforcement	INCLUSION
Friction			

* Only the principal relationships are shown (e.g., the thickness also has some influence on the filtration and the protection functions).

** This table is applicable not only to geotextiles, but to all geosynthetics except geomembranes.

*** The three key properties are underlined.

**** The fluid transmission function is often called drainage function, which can be misleading (see Table 2).

***** Tensioned Membrane and Tensile Member are the two reinforcement functions.

Table 2. Relationships* between applications and functions of geotextiles.

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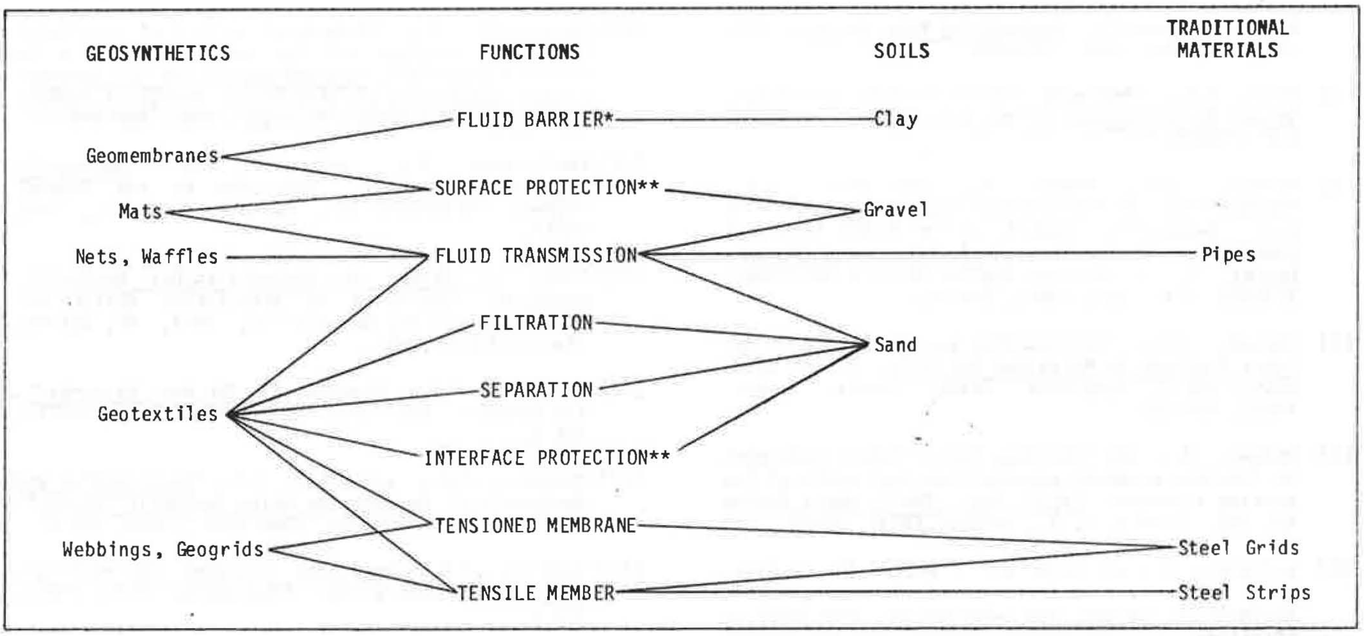
APPLICATION CATEGORY	APPLICATION AREA	APPLICATION TYPE	FUNCTIONS: Fluid Transmission	Filtration	Protection	Separation	Tensioned Membrane	Tensile Member
Hydraulic Applications	DRAINAGE	Geosynthetic drains without filter	X					
		Geosynthetic drains with filter (geocomposites)	X	X				
		Gravel drains, Pipes		X				
	EROSION CONTROL	Bank revetment		X				
		Erosion mat			X			
		Silt Fence, Silt curtain		X			X	
Geosynthetic Construction	CONTAINERS	Concrete forming, Sand bags (hydraulic fill)		X			X	
		Gabions, Sand bags					X	
	GEOMEMBRANE SUPPORT	Bridging					X	
		Cushion			X			
Geotechnical Structures	ROADWAYS**	Asphalt overlay			X			
		Unpaved road (large deflection)				X	X	
		Base course (small deflection), Ballast				X		X
	SOIL REINFORCEMENT	Reinforced walls, slopes and embankments						X

* For each application type, only the most important functions are indicated (e.g., the table does not show that the fluid transmission function may be involved when a geotextile is placed under flat concrete slabs in a bank revetment, or when a geotextile is used in a railroad track on a saturated subgrade, etc.)

** Here, roadways are considered to include all types of traffic supporting structures such as roads, parking lots, staging areas, railroad tracks, etc.

Table 3. Relationships between functions and materials. © J.P. Giroud, 1985



* The fluid barrier function (e.g., liners for dams and reservoirs) was not included in Table 1, since it is not performed by geotextiles.

** The protection function has been separated into two parts: (i) surface protection (e.g., erosion control mats, landing strips); and (ii) interface protection (e.g., geotextile between asphalt overlay and cracked pavement, geotextile as a cushion between geomembrane and stony ground).

Table 4. Proposed classification of geoproducts. © J.P. Giroud, 1985

<table>
<tr><th>SCALE</th><th>DIMENSIONS</th><th colspan="2">TYPES</th><th>MATERIALS</th></tr>
<tr><td rowspan="2">Micro-geoproducts</td><td>Uni-dimensional</td><td colspan="2">Fibers, Filaments, Yarns</td><td rowspan="3">Synthetics
Steel
Glass</td></tr>
<tr><td>Bi-dimensional</td><td colspan="2">Microgrids</td></tr>
<tr><td rowspan="6">Macro-geoproducts</td><td rowspan="2">Uni-dimensional</td><td colspan="2">Cables
Strips</td></tr>
<tr><td colspan="2">Rods ("Nails")</td><td rowspan="2">Steel</td></tr>
<tr><td rowspan="4">Bi-dimensional</td><td rowspan="4">Geofabrics*</td><td>Grids</td></tr>
<tr><td>Geotextiles
Webbings
Mats
Nets
Formed sheets</td><td rowspan="2">Usually synthetic
("Geosynthetics")</td></tr>
<tr><td rowspan="2">Geomembranes</td></tr>
<tr><td>Asphalt (usually with synthetic fabric)</td></tr>
</table>

* Here, the term "geofabrics" is not limited to fabrics but is applicable to all planar structures made of polymers, steel, etc.

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