Functions and applications of geosynthetics in dams

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Geosynthetics (geotextiles, geomembranes, geonets, geogrids, geomats, geocells, geocomposites, and so on) are increasingly used in dams. The purpose of this paper is to review the different applications of geosynthetics in dams, and, for each application, to summarize the functions which geosynthetics perform.

Twenty years ago, a geotextile was used for the first time in a dam. Since then, a wide variety of geosynthetics has been used in a number of different applications in dams. In the past decade, *Water Power & Dam Construction* has devoted significant space to those applications, thereby providing useful information to designers and constructors of dams. In keeping with this commendable effort, it is hoped that a paper summarizing these applications will also be useful.

Functions of geosynthetics in dams

Traditionally, four functions of geotextiles and related products have been described: filtration, separation, transmission, and reinforcement. This is in addition to the function of fluid barrier performed by geomembranes. In fact, a few more functions can be performed, as shown in Table I (this table also indicates which geosynthetics are typically used for each function). All these functions can be performed in dams and they are briefly defined below; also typical geosynthetics performing each function are mentioned. Definitions of the various types of geosynthetics can be found in other articles [1,2,3] and a book chapter [4] by the author.

Functions of geosynthetics

Category of function	Function	Geosynthetics typically used
Hydraulic functions	Fluid barrier	Geomembranes
	Filtration	Nonwoven and monofilament woven geotextiles
	Transmission	Geonets, geomats, cores of drainage geocomposites, and, to a lesser degree, thick needlepunched nonwoven geotextiles
Interface functions	Separation	Geotextiles
	Interlayer	Geotextiles (and, sometimes geonets or thin geomembranes)
Reinforcement functions	Macro-Reinforcement	Geotextiles, geogrids
	Micro-Reinforcement	Fibres, yarns, and microgrids
	Surface Reinforcement	Geomats, geocells

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Fluid barrier

An impermeable (or, more correctly, quasi-impermeable) geosynthetic (that is, a geomembrane) is used to contain a fluid.

Filtration

A geotextile located between a soil and an open draining material (for example: gravel, transmissive geosynthetic, perforated pipe) allows a liquid to pass while controlling the migration of soil particles.

Transmission

A thick and permeable geosynthetic (that is a transmissive geosynthetic, such as a geonet, a geomat, or a drainage geocomposite) conveys fluids within its plane.

Separation

A geotextile located between a soil containing fine particles and a material (either natural or man-made) with large openings (for example: aggregate, fractured rock, concrete panelling with joints) prevents intermixing of the soil and the adjacent material.

Interlayer

A geosynthetic located between two materials controls stress and strain transfer between the two materials, thereby preventing mutually inflicted damage. Several cases can be considered:

- an interlayer geotextile (or sometimes a geonet), acting as a cushion, prevents a geomembrane from being damaged by adjacent materials such as stones or concrete slabs;
- an interlayer geotextile or thin geomembrane, with a small friction angle and surface adhesion, acts as a slip plane between two materials that must move freely in relation to each other;
- an interlayer geotextile with a high friction angle or surface adhesion acts as a bonding agent to prevent slippage between two materials; and,
- an interlayer geotextile, acting as a support, prevents a geomembrane from intruding into voids of the adjacent material.

The last case is similar to the separation function: the potentially intruding material is a geomembrane in the case of a geotextile support and a soil in the case of a geotextile separator. The case of a support is also similar to the first case of macro-reinforcement discussed below; however, in the case of macro-reinforcement, the geosynthetic supports a soil structure over large voids.

Macro-reinforcement

One, or several layers, of geosynthetics placed in a soil, or between two soils, reinforces the soil(s) as a result of stress transfer from the soil(s) to the geosynthetic. Several cases can be considered:

● a geosynthetic alone or a group of closely associated parallel geosynthetics can help support a soil structure placed on a foundation that is uniformly weak, that contains zones which may collapse or where voids may develop, or that is composed of various areas between which differential settlements may occur;
● a geosynthetic alone or a few parallel geosynthetics anchored at the crest of a slope can improve the stability of a soil layer on a slope; and,
● alternating layers of geosynthetics and soils form a reinforced soil mass.

Micro-reinforcement

Fibres, yarns, or small elements with various shapes (such as microgrids) intimately mixed with soil particles form a reinforced soil mass.

Surface reinforcement

A geomat, a geocell (that is, a synthetic honeycomb structure filled with soil), a geogrid or any other appropriate geosynthetic, placed at the surface of a soil mass and closely interlocked with a layer of soil particles, prevents surface erosion. Mats or loose grid-like fabrics made with natural fibres (for example, geojute) are used where biodegradation is desirable.

With the growing use of geosynthetics, there is a need for standardization of the symbols used to represent them in construction drawings and technical papers. Recognizing that proper identification of geosynthetic functions is essential in the design of projects, as well as in the education of potential users, the different functions should be represented by different symbols. To this end, symbols are proposed in Fig. 1 and are used in Figs. 2 to 6. It should be noted that the filtration and separation functions have been combined under the term "transition" because, in dams, even when geotextiles are intended as separators they should be able to act as filters also, since the presence of water should always be considered.

Also shown in Fig. 1 are systems obtained by associating two or more functions. The systems shown can be entirely constructed with geosynthetics or partially with geosynthetics and partially with soils. For instance, a drain can be constructed with gravel and geotextile filter, or it can be a geocomposite comprising a synthetic core and a geotextile filter. Of course, drains can also be entirely constructed with traditional materials such as gravel, sand and pipes.

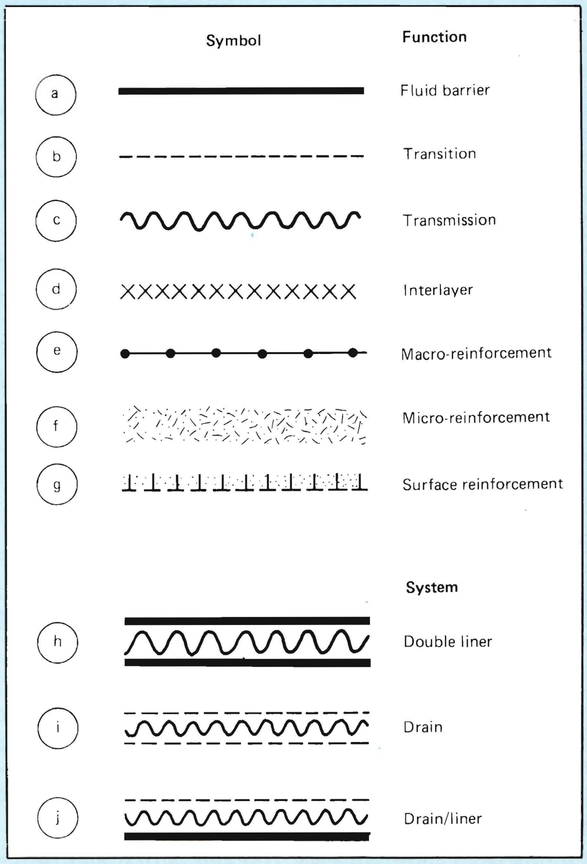

Fig. 1. Representation of geosynthetic functions and systems. (Note: transition combines the filtration and separation functions.)

Applications of geosynthetics in dams

For the sake of clarity, applications of geosynthetics in dams are presented below in five categories. However, some of the applications may be combined with applications from another category (but only experienced designers can do so because some combinations are not appropriate). Additional considerations on design can be found at the end of this paper. It should also be pointed out that Figs. 2 to 6 are only conceptual and are not to scale. Furthermore, the slopes in Figs. 2 to 6 were essentially selected for clarity of the drawings and they are not representative of the slopes in actual dams.

Drainage

Typical cross sections of dams where geosynthetics are used in drainage systems are shown in Fig. 2. Geosynthetic applications presented in Fig. 2(a) include:

● horizontal drains (1) in the upstream zone to prevent porewater pressure buildup in case of rapid drawdown of the reservoir and, sometimes, to accelerate soil consolidation during construction;
● vertical drains (2) under the upstream or the downstream zone to accelerate foundation consolidation during construction and/or to ensure porewater pressure relief;
● chimney drain (3) and drain at the base of the downstream zone (4) to prevent porewater pressure buildup in the downstream zone; and,
● horizontal drains (5) in the downstream zone to prevent porewater pressure buildup in case of malfunction of the chimney drain and, sometimes, to accelerate soil consolidation during construction.

Geosynthetic applications presented in Fig. 2(b) include:

● a drain (1) placed just behind a diaphragm wall (for example: slurry wall, concrete wall, bituminous core) to collect, and detect in a gallery, water leaking through the diaphragm, while the geotextile filter of this drain progressively clogs in front of the cracks of the diaphragm, thereby controlling particle migration and preventing piping; and,
● horizontal drains (2) to prevent porewater pressure buildup in the downstream zone in case of leakage through the diaphragm and into the downstream zone of the dam, which may occur if the system described above does not perform as expected.

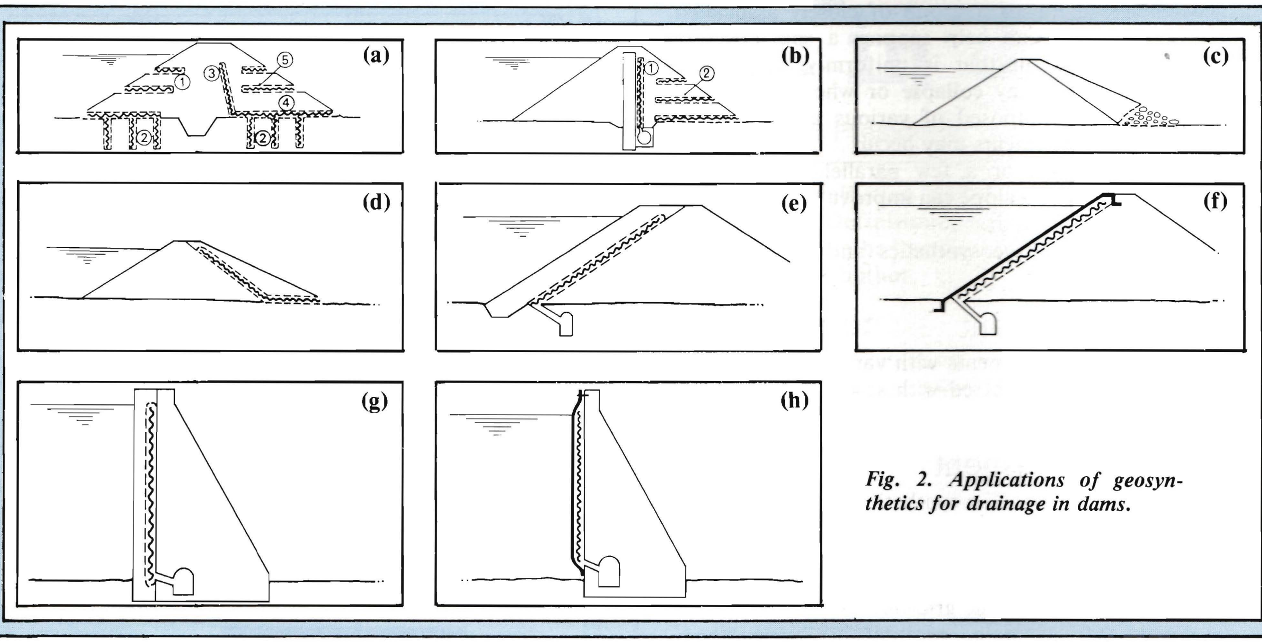

Fig. 2. Applications of geosynthetics for drainage in dams.

An application similar to case (1) in Fig. 2(b) can be considered in flood retention structures, which are embankment dams used to control floods. The reservoirs of these dams are empty most of the time, and cracking of the embankment often occurs. A vertical drain can be constructed in such a dam to control piping which may be caused by water flowing in cracks when there is a flood.

In the cases shown in Figs. 2(a) and 2(b), drains of the type schematically presented in Fig. 1(i) can be used. These include: drainage geocomposites with a geotextile filter and a transmissive synthetic core (such as a geonet, geomat, or any synthetic structure with high transmissivity); sand or aggregate within a geotextile filter (typically a nonwoven geotextile); or, sometimes, a thick needlepunched nonwoven geotextile which performs both the filtration and transmission functions.

Geosynthetics are also used for drainage associated with the repair of existing dams. If the downstream zone of an earth dam is too wet, its stability may be impaired. This can be improved by constructing a drain and adding a wedge of soil, which will result in a less steep, hence more stable, downstream slope. Two cases are shown in Fig. 2(c) (gravel toe drain with geotextile filter) and in Fig. 2(d) (geocomposite drain or, alternatively, gravel drain with geotextile filter). In the case of leaking dams, a low-permeability material (such as clay, concrete, bituminous concrete, metal sheeting, or a geomembrane) can be added on the upstream face of the dam. Drainage may be needed between the low-permeability material and the existing dam to prevent uplifting of the low-permeability material by underpressures resulting from rapid drawdown of the reservoir. Examples are shown in Figs. 2(e), 2(f), 2(g) and 2(h). In cases 2(e) (clay) or 2(f) (geomembrane), either a gravel drain with a geotextile filter or a geocomposite drain could be used. In case 2(g) (between concrete and concrete), the drain must be installed vertically and a geocomposite should be used; in this case, a filter is necessary to prevent clogging of the transmissive material by the concrete when it is cast. In case 2(h) (between geomembrane and concrete), no filter is needed and a geonet or a thick needlepunched geotextile can be used.

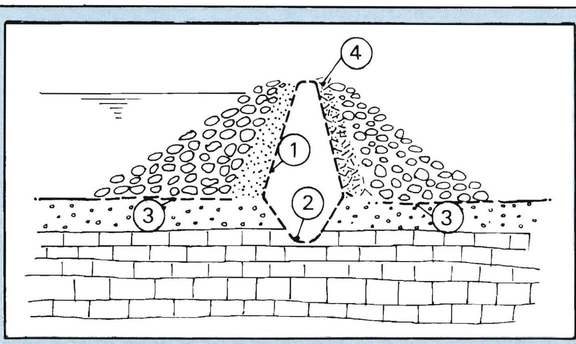

Fig. 3. Applications of geosynthetics for transitions in zoned dams.

Transitions in zoned dams

Geosynthetic applications presented in Fig. 3 include:

- transition between the impervious core (typically clay) and the next transition zone (typically sand) (1);
- transition between the impervious core and fractured bedrock (2);
- transition between rockfill and foundation soil (3); and,
- micro-reinforced sand filter that does not liquify during earthquakes and does not crack (4).

To these applications should be added the use of a geotextile for upstream slope protection, as presented in Fig. 6(a), case (2), since this application is often referred to as a transition layer.

The geosynthetic typically used in Fig. 3, cases (1), (2) and (3), is a needlepunched nonwoven geotextile; a woven geotextile can also be used in cases (2) and (3) if significant strength is required. Should cracking of the clay core occur, geotextiles (1) and (2) should be able to retain a significant fraction of the clay particles carried by leakage water so as to prevent massive piping.

In case (4), micro-reinforcement would most likely be done with continuous yarns.

Reinforcement

Typical cross sections of dams where geosynthetics act as reinforcement are presented in Fig. 4.

In Figs. 4(a) to 4(e), multilayer reinforcement is used to construct slopes that are steep and even vertical. In case 4(c) the spillway is very short, which is interesting for small dams where the cost of the spillway is often a significant part of the total cost. Case 4(d) can be considered when the height of an existing dam must be increased; one may consider cross section 4(e) to increase the height of an existing dam or to construct a new dam, taking advantage of the fact that, with soil having both friction and cohesion, the "ideal" slope (with the same factor of safety at all levels) has a concave shape. In cases 4(a) to 4(e), a variety of geotextiles and geogrids can be used; also, in these cases, the multilayer macro-reinforced soil mass can be replaced, at least for small dams, by a micro-reinforced soil mass (most likely using continuous yarns). It should also be noted that reinforcement using continuous yarns was already considered in Fig. 3, case (4).

In Figs. 4(f), 4(g) and 4(h), a geosynthetic alone or a group of closely associated parallel geosynthetics is used to support a dam or a portion of it. Case 4(f) can be considered for a small dam built on a very soft foundation, and case 4(g) for a small dam built on a soil that can locally collapse. The reinforcement layer shown in Fig. 4(h) helps prevent cracking of a low-permeability layer (such as clay or bituminous concrete) over a boundary between two zones of soil or different compressibilities (for instance a fill zone and a cut zone in the case of a partially excavated reservoir). In cases 4(f), 4(g) and 4(h), high-strength/high-modulus geosynthetics are usually required (typically, geogrids and multifilament woven geotextiles). If two or more layers of geosynthetics are used, they must not be placed on top of each other, so as to minimize the risk of a slip surface. A layer of high-friction soil (for instance, angular aggregate) must always be placed between two parallel reinforcement layers to ensure stress transfer.

In Fig. 4(i), a geosynthetic alone, or a few parallel geosynthetics anchored at the crest of the dam, improve the stability of an inclined clay layer used as an impervious barrier for a small dam. (Applications where the geosynthetic reinforcement plays a similar role are described in Figs. 6(c) and 6(e) for upstream slope protection.)

Waterproofing

Since the essential function of a dam is to retain water, the use of geomembranes in dams is logical. Typical uses are shown in Fig. 5.

The basic cross section shown in Fig. 5(a) has already been used in many dams. A double liner can be used when it is essential to minimize leakage, Fig. 5(b). In this case, the reservoir will also probably be lined, or, at least, a large area of it will be lined in the vicinity of the dam. To minimize leakage from a reservoir on pervious soil, one might provide the reservoir with a double liner and line the upstream face of the dam with a single geomembrane placed directly on a layer of low-permeability soil, Fig. 5(c). A geomembrane and a layer of low-permeability soil in contact with each other form a composite liner. If there is a hole in the geomembrane, the rate of leakage through a composite liner is much less than through a geomembrane placed on a pervious soil[5]. Composite liners are often used in waste disposal landfills.

A geomembrane upstream blanket can be used to minimize leakage under a dam, Fig. 5(d). If the blanket is installed on a soil containing areas that are weak or likely to collapse (for example: karstic formations), a layer of soil reinforced with a geosynthetic (geogrid or high-strength/high-modulus geotextile) can be used under the geomembrane, Fig. 5(e).

The construction of a geosynthetic vertical cutoff, Fig. 5(f), requires: either the excavation of a trench using drilling mud followed by insertion of geomembrane panels connected by a special technique; or, the use of rigid synthetic sheet piles driven into the soil (generally using a protective steel mandrel). A diaphragm in a dam can either be vertical, Fig. 5(g), and constructed after completion of the embankment using one of the cutoff construction techniques mentioned above, or it can be constructed as the embankment construction progresses. In the latter case, the

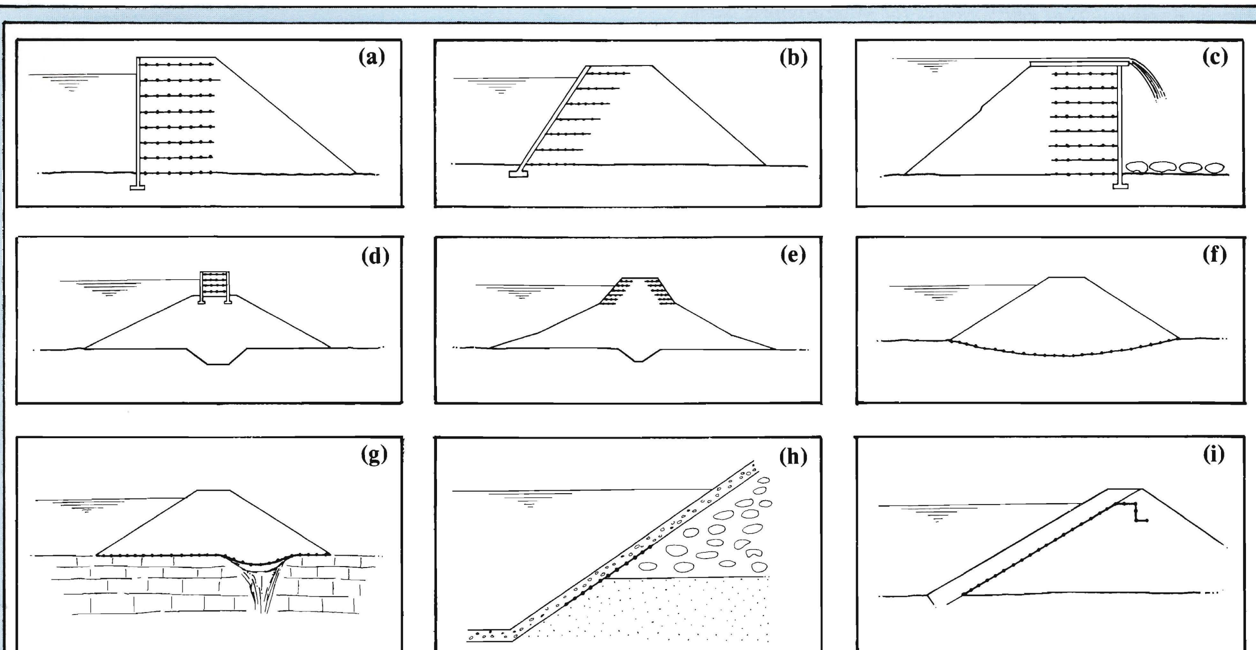

Fig. 4. Applications of geosynthetics for reinforcement in dams.

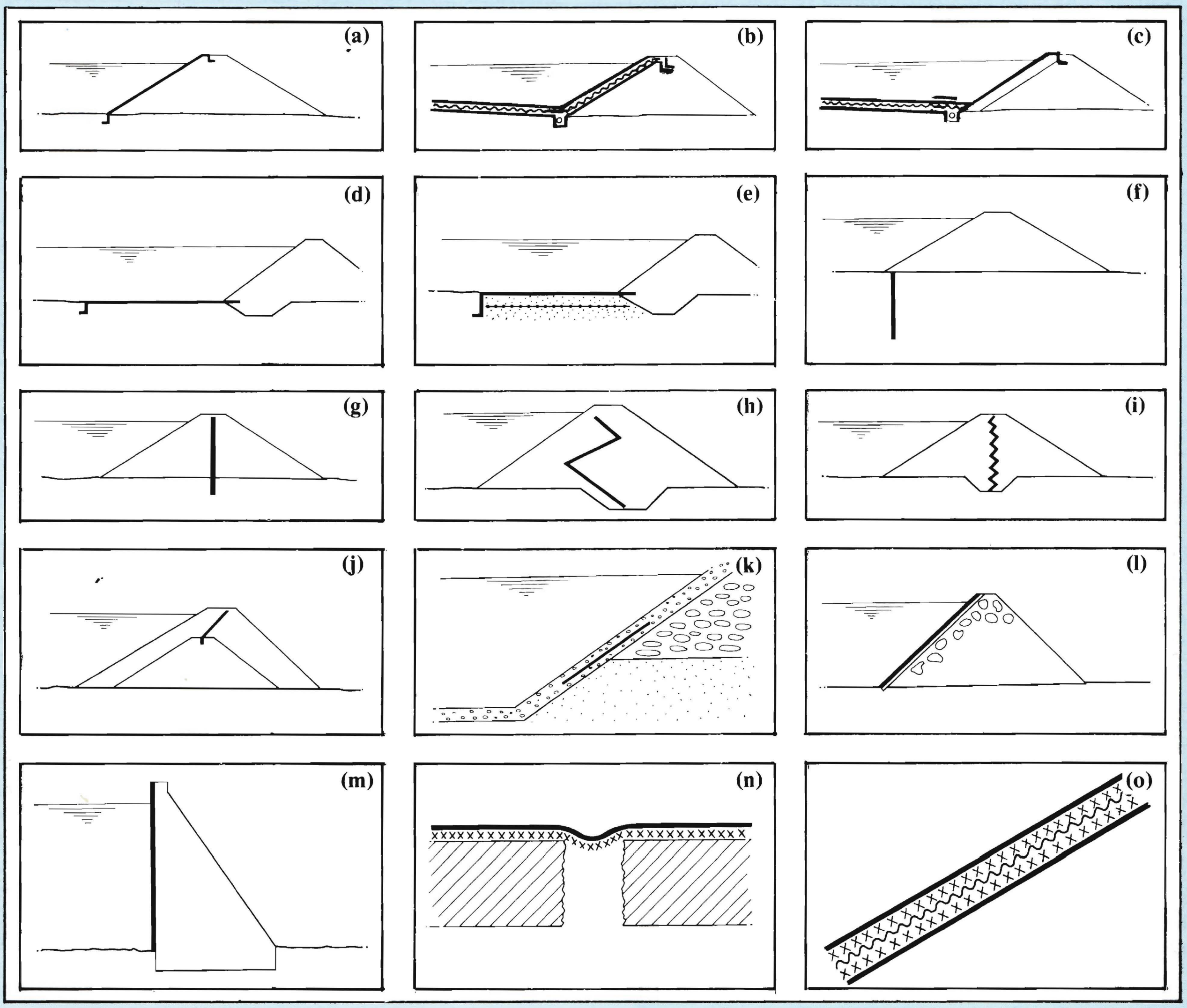

Fig. 5. Applications of geosynthetics for waterproofing dams.

cross section shown in Figure 5(h) can be considered: the embankment is constructed in several stages and, at the end of each stage, a geomembrane is placed and seamed to the previous one. A zig-zag shape such as the one shown in Fig. 5(i) can lead to numerous construction problems.

Geomembranes can be associated with traditional construction techniques to heighten earth dams, Fig. 5(j), or to complement a bituminous concrete liner in an area where it may crack, Fig. 5(k), for example, over a boundary between two zones of different compressibilities. In both cases, it is essential to make sure that the geomembrane does not promote the development of a slip surface. In the case of Fig. 5(j), stability analyses must be performed. In the case of Fig. 5(k), shear tests should be conducted and it may appear that the best choice is a bituminous membrane, perhaps one that is made in situ.

Finally, geomembranes are used to repair dams. For instance, a geomembrane can be placed on the upstream slope of a leaking earth dam, according to the basic cross section shown in Fig. 5(a), or the cross section shown in Fig. 2(f). Geomembranes are increasingly used to repair dams faced with metal sheeting, concrete or bituminous concrete, Fig. 5(l), or concrete dams, Fig. 5(m); in these applications, geomembranes are either glued to the face of the dam or mechanically attached, using metallic strips. Transmissive geosynthetics (such as geonets or thick needlepunched geotextiles) are sometimes used between the geomembrane and the original face of the dam, as illustrated in Fig. 2(h).

Techniques used for dam repair can also be used for the construction of new dams. For example, the same application as shown in Fig. 5(m) has been used to waterproof the face of roller compacted concrete dams.

In all geomembrane applications in dams, geosynthetic interlayers can be used. The most typical case is a geotextile cushion preventing puncture and abrasion of a geomembrane by adjacent materials such as stones or concrete slabs. Other interlayer applications (mostly using geotextiles) include:

- a support interlayer to prevent a geomembrane from intruding into cracks or joints of the underlying concrete when water pressure is applied, Fig. 5(n);
- a bonding interlayer geotextile placed between some types of geomembranes and some types of geonet to minimize the risk of slippage between the geomembrane and the geonet, which may be useful when double liners are used, Fig. 5(o); and,
- a slip surface interlayer to allow free relative movement of a concrete protection with respect to the geomembrane, as discussed in the next section, see Fig. 6(d).

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Erosion control and slope protection

Typical examples of geosynthetic systems used for erosion control and slope protection are presented in Fig. 6. These applications are briefly discussed below:

- In Fig. 6(a), case (1), a geosynthetic is used on the downstream slope of a dam to prevent surface erosion while vegetation grows. Geosynthetics typically used in this application include geomats and geocells. Geojute is also used if biodegradation is desirable. Erosion of the downstream slope is typically caused by rainwater; however, it is possible to design a protection which can withstand a certain amount of flow caused by overtopping of the dam.
- In Fig. 6(a), case (2), a geotextile filter is used under rocks (riprap), concrete blocks, or concrete slabs for upstream slope protection. When large rocks or blocks are used, a layer of gravel is often placed between this material and the geotextile to protect the geotextile and to ensure uniform contact between the geotextile and underlying soil, Fig. 6(b).
- In Fig. 6(c), a geogrid anchored at the crest of the dam is used to reinforce the layer of gravel discussed above and to prevent it from sliding along the slope. Also, the geogrid may act as a macro-filter, preventing gravel particles from migrating through the large rocks or blocks.
- In Fig. 6(d), a geotextile interlayer (with a low friction angle and surface adhesion) allows concrete slabs to move freely in relation to the underlying material (often a geomembrane) if they need to do so.
- In Fig. 6(e), a geogrid is used to reinforce a layer of soil, concrete, or bituminous concrete placed on a slope. A number of applications of this type can be envisaged in dams and reservoirs: reinforcement of a protective soil layer placed on a geomembrane liner, reinforcement during the placement of a cast-in-place concrete slab or liner, and reinforcement of a bituminous layer used for protection or waterprooofing.
- In Fig. 6(f), a geosynthetic drain is used to evacuate excessive water (laitance) from concrete during its placement, thereby preventing the development of underpressures that may cause instability of the concrete layer during its placement. This is especially useful when a concrete protection is to be cast on top of a geomembrane liner. Because of the small amount of water released during concrete placement, a needlepunched nonwoven geotextile may be used. This geotextile must be anchored at the crest of the dam to withstand the shear stresses exerted by the concrete when it is poured.
- In Fig. 6(g), the use of fabric-f slab is presented. Concrete is poured between two layers of fabric, kept parallel by separator yarns, thus producing a mattress-like slab. The slabs may incorporate prefabricated weep-holes to prevent underpressure buildup in case of rapid drawdown of the reservoir. In this application, high-strength woven geotextiles are used to withstand the tensile stresses that occur during concrete pouring.

In cases 6(c) and 6(e), a single geogrid is typically used. If two or more geogrids are needed, they should not be placed in contact with each other to prevent the development of a slip surface.

Design considerations

The applications presented in this paper are only conceptual and require a significant amount of detailed design to be successfully implemented.

First, the design must ensure that the geosynthetics will adequately perform their intended functions. From this viewpoint, it is important to note that geosynthetic design methods are now available which can be adapted to all applications of geosynthetics in dams. Therefore, today, using geosynthetics in dams without conducting design analyses and calculations is inexcusable, and being systematically opposed to the concept of using geosynthetics in dams is unjustifiable.

Second, it should be borne in mind that, when performing a necessary function, a geosynthetic in a dam may have detrimental secondary effects. For example, since geosynthetics can promote the development of slip surfaces, their location, extent, and slope can be selected only after appropriate stability analyses have been conducted;

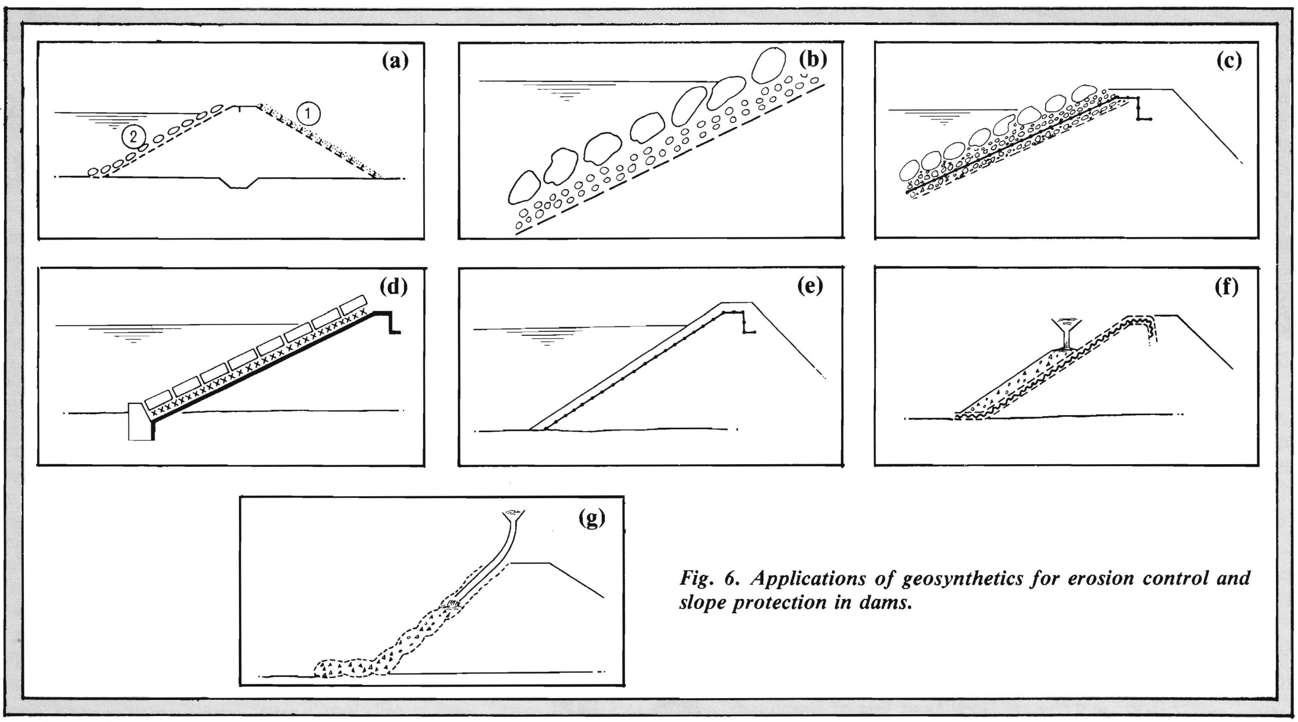

Fig. 6. Applications of geosynthetics for erosion control and slope protection in dams.

from this viewpoint, strip drains should be preferred to large blanket drains if design calculations show the strip drains provide the required amount of drainage. Another example is that of geosynthetic reinforcement which extends from upstream to downstream; since water may find preferential paths along the geosynthetics and leakage through the dam may thus occur, precautions must be taken to prevent leakage (such as using a geomembrane upstream facing). Also, it is important to know that geotextiles used as interlayers often have some transmissivity and may therefore cause leakage or convey water to locations where it has a detrimental effect.

Third, for the geosynthetic to perform adequately, it must be applied properly. This requires that the design be constructible and that the geosynthetic has the required properties to survive installation. (These properties are commonly referred to as "survivability characteristics".) Significant experience has been gained in the past two decades and, today, designers can specify reliable construction techniques and select geosynthetics with adequate survivability characteristics. Also, designers should know that the impressive experience accumulated in the past five years in the practice of construction quality assurance for geosynthetic-lined waste disposal facilities is available for the construction of dams with geosynthetics, and therefore, high-quality geosynthetic installation can be achieved in dam construction. Furthermore, it should be noted that excellent methods have been developed in the past decade for installing geosynthetics to repair existing dams.

Finally, geosynthetics must be durable and must perform their intended functions for the entire design life of the dam. This essential question was discussed by the author in a previous article in *Water Power & Dam Construction*[6]. It should also be noted that, in many of the applications mentioned in this paper, geosynthetics are accessible and can be inspected.

Conclusion

Versions of all geosynthetic applications described in this article have been successfully constructed, and many of them a number of times. Many case histories have been presented in *Water Power & Dam Construction* and many more will be. The wide variety of applications of geosynthetics in dams illustrates the versatility of geosynthetics and the creativity of designers. Both factors make it easy to predict that many more dams will be constructed and repaired using geosynthetics. □

Acknowledgements

For the preparation of this paper, the author's personal experience was supplemented by information obtained in documents published by the International Commission on Large Dams[7, 8] and many papers published in *Water Power & Dam Construction*, including papers by Bertacchi and Cazzuffi[9, 10].

The author is indebted to D. Cazzuffi, J.E. Fluet, Jr., and R.M. Taylor for their thorough review of the manuscript, and R. Rodriguez for her assistance in the preparation of the paper.

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