

IGS Education Committee

Mini-lecture Series on Geosynthetics:

Geosynthetics in dams

Lecture Notes

prepared by

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01 INTRODUCTION

Among the various types of large man-made structures (with containment function), dams have surely the most important impact on the environment, due not only to the size of the structure itself, but also to the creation of water storage reservoirs, often of very large size.

02 In the past 40 years, a wide variety of geosynthetics have been used, with different functions, in virtually all types of dams, both for new construction and rehabilitation purposes. The different types of geosynthetics and biodegradable natural products included in the enclosed Table have been defined by Cancelli and Cazzuffi (1994).

This lecture is dedicated to a review of geosynthetic applications in dams, according to the performed functions, i.e. barrier (to fluid), drainage, protection (of geomembranes), filtration, reinforcement and surficial erosion control; in the frame of each function, the review will consider the different types of dams in which geosynthetics have been used, i.e. embankment dams (both earth and rockfill), concrete and masonry dams, and roller compacted concrete dams, respectively.

BARRIER (TO FLUIDS)

The function of barrier (to fluids) represents the ability of a geosynthetic to prevent migration of fluids.

Embankment dams

03 A geomembrane was first used as the waterproofing element of a dam in 1959 at Contrada Sabetta dam in Italy (Cazzuffi, 1987). This rockfill dam, 32.5 m high, has performed successfully to date: two sheets of a polyisobutylene geomembrane (2 mm thick), protected with concrete slabs, were installed on the 1V:1H upstream face of the dam during initial construction.

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In 1997 it was decided to initiate the rehabilitation of the dam and in 1998 some samples of the original polyisobutylene geomembrane were taken: the general behaviour of the geomembrane itself was still good, as laboratory tests clearly showed (Cazzuffi, 1999).

Since then, a number of embankment dams have been realised with geomembrane waterproofing (ICOLD, 1991): in the most of cases, geomembranes are externally protected from atmospheric agents by the superposition of a cover layer, like concrete slabs, precast concrete elements, geosynthetic-reinforced gunite, and so on.

Geomembranes have also been used to rehabilitate embankment dams, particularly in order to minimize seepage through the upstream face: different cases of geomembrane

applications to repair both bituminous concrete upstream facings and concrete-faced rockfill dams have been reported (Giroud and Bonaparte, 1993).

Concrete and masonry dams

In the last 25 years, geomembranes were used to rehabilitate approximately 40 large concrete and masonry dams, in order to reduce leakage phenomena that typically appear on these structures after 30 ÷ 40 years of operation, depending on the accuracy of construction and on conditions of the damsite.

The first dam in which a geomembrane was used for waterproofing rehabilitation was Lago Baitone masonry dam in Italy, 37 m high, constructed from 1927 to 1930 and rehabilitated from 1969 to 1971 using a polyisobutylene geomembrane, 2.0 mm thick (Cazzuffi, 1987).

The most popular rehabilitation technique, developed in Italy and used up to now in about 25 applications around the world, consists of fastening a PVC (polyvinyl chloride) geomembrane to metallic ribs anchored in the upstream face: usually the PVC geomembrane is thermocoupled in factory to a PET (polyester) nonwoven geotextile (thus forming a geocomposite membrane liner - GCM) and, after application, the GCM is not externally protected from atmospheric agents.

07 The first large dam rehabilitated with this technique was Lago Nero concrete dam in Italy, 40 m high, constructed from 1924 to 1929 and rehabilitated from 1980 to 1981 (Monari, 1984): in this dam a GCM formed by a PVC geomembrane ($t_{GM} = 2.0$ mm) thermocoupled in factory to a PET nonwoven geotextile ($\mu = 350$ g/m²), was used.

08 After about twenty years since application, the general behaviour of the GCM is satisfactory: regular inspections have ensured that no yielding of the GCM nor any

09 other detectable alteration has taken place (Cazzuffi et al., 1993).

Roller compacted concrete (RCC) dams

While it would be of course unnecessary to add a geomembrane to waterproof a new concrete dam built by conventional methods, the emerging roller compacted concrete (RCC) technology has favourite to make use of geomembranes for new constructions (ICOLD, 1991).

In fact, using this technology, where the main mass of RCC is insufficiently impervious, extra cement is usually added to the mix towards the upstream face of the dam or, in alternative, conventional or prefabricated concrete is used in this area: to reach the same result, geomembranes were also adopted, both protected and exposed. Among the first applications of exposed geomembranes on RCC dam upstream facings, are Riou dam in France, 22 m high, and Concepcion dam in Honduras, 70 m high, both completed in 1990.

10 In particular, at Concepcion dam a geocomposite membrane liner (GCM) formed by a PVC geomembrane ($t_{GM} = 2.5$ mm) thermocoupled in factory to a PET geotextile, was placed by mechanical fastening over the upstream face, using essentially the same technology commonly adopted in Italy for rehabilitation of concrete and masonry dams. The GCM was manufactured and shipped in rolls 2 m wide and was pre-assembled on the ground into sheets 4 m wide, which were positioned using a platform supported by a small portal crane moving over the crest of the dam (Giovagnoli et al., 1991).

DRAINAGE

The function of drainage represents the ability to collect and carry off fluids within a geosynthetic.

Embankment dams

For new constructions, the first application of a geosynthetic as chimney drain was at Brugnens earth dam, in France, 11 m high, constructed in 1973: the drainage geosynthetic used in that dam was a thick PET needle-punched nonwoven geotextile (Giroud, 1992).

11 Other more recent French applications of drainage geosynthetics have been reported by Navassartian et al. (1993); since 1987, a geocomposite shaft drain (including a PP-polypropylene)nonwoven geotextile draining core between two PP nonwovens geotextile filters) has been used instead of granular drain for the construction of a number of homogeneous earthfill dams about 10 m high: the geocomposite drains have been set down gradually with the alternative earth layers.

The chimney drain concept could be used also for rehabilitation purposes: in the case of embankment dams that exhibit seepage through their downstream slope, the construction of a drainage system in the downstream zone is required. A solution consists of using a geocomposite drain (GCD) placed on the entire downstream slope or only on the lower portion of it and covered with backfill: the GCD must be connected with the new toe of the dam with outlet pipes or with a drainage blanket. This technique has been used, for example, at Reeves Lake dam in United States, 13 m high, which was repaired in 1990 by placing a GCD (including a PE-polyethylene geonet core between two PP thermobonded nonwoven geotextile filters) on the downstream slope relatively steep, of the order of 1V:2H (Wilson, 1992).

Concrete and masonry dams - RCC dams

In the most of the cases of concrete and masonry dams upstream facings rehabilitation and also of RCC dams construction, a thick nonwoven geotextile has been used between the geomembrane and the dam, to perform the double function of drainage and of mechanical protection of the geomembrane itself. Usually, the geotextile is thermocoupled in factory to the geomembrane, thus forming a

geocomposite membrane liner (GCM), and, in some rehabilitation cases, where important quantity of water is expected to be drained from the body of the dam, an extra geosynthetic (like a geotextile or a geonet) is added between the geocomposite membrane liner and the dam itself. As far as construction details are concerned, it is important that the geosynthetic is connected to a related collector pipe at the toe of the dam. Particularly, in the case of rehabilitation of concrete dams, the concrete of the dam body, which has been saturated with water over the years, is allowed to drain, because of the presence of the drainage geosynthetic itself, thus contributing to slow down the mechanism of concrete deterioration, due also to the presence of water. A lot of concrete dams have in fact recently suffered the effects of AAR (Alkali Aggregate Reaction), which is influenced remarkably by the presence of water: some of these dams have been rehabilitated using the GCM technique.

PROTECTION (OF GEOMEMBRANES)

The function of protection (of geomembranes) represents the ability of a geosynthetic to prevent local damage to a geomembrane due to concentrated mechanical stresses.

Embankment dams

In many embankment dams where a geomembrane was used as barrier (to fluid), a thick geotextile was placed on one or, more often, on both sides of the geomembrane itself, to protect it from potential damage by adjacent materials, typically the granular layer underneath and the external cover layer.

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For example, at Codole dam in France, 28 m high, constructed in 1983 and also at Jibiya dam in Nigeria, 23.5 m high, constructed in 1987 (Sembenelli, 1990), two thick geotextiles were placed on both sides of the PVC geomembrane: in both dams, the lower geotextile was factory-bonded to the geomembrane, while the upper geotextile, independently placed, was positioned between the geomembrane and the external protection, made by cast-in-place concrete slabs.

The same technique could be exactly applied also for rehabilitation purposes. For example, at Goronyo secondary dam in Nigeria, 13 m high, constructed in 1982 and rehabilitated in 1987 with a geocomposite membrane liner (GCM) application, two different layers of geotextile were laid, both having a protection function: the lower geotextile, bonded in factory to the geomembrane, was glued to the original bituminous concrete facing, while the upper geotextile was independently placed between the PVC geomembrane and the cast-on-place concrete cover layer (Sembenelli, 1994).

Concrete and masonry dams

As already mentioned, thick nonwoven geotextiles, eventually associated with geonets, have been used not only for drainage function, but also for mechanical protection of geomembranes, in the frame of the techniques adopted for rehabilitation of concrete and masonry dam upstream facings. To this respect, the first case reported for a geotextile as protection of geomembrane was Lago Nero dam in Italy, where a GCM was applied: in some zones particularly deteriorated of the concrete upstream face, it was decided to add an additional geotextile layer as an extra protection between the GCM and the dam.

The first case reported for the application of an additional geonet performing the same function was Publino dam in Italy, 42 m high, constructed in 1951 and rehabilitated in 1989 (Zuccoli et al., 1989): for this work, a HDPE geonet was used as protection of the GCM, formed by a PVC geomembrane ($t_{GM} = 2.5 \text{ mm}$) and a PET geotextile ($\mu = 500 \text{ g/m}^2$).

Roller compacted concrete (RCC) dams

In RCC dams only nonwoven needle-punched geotextiles have been used to perform mechanical protection of the geomembrane, to which they are usually thermocoupled in factory. The mechanical characteristics of geotextiles adopted to perform this function are not so high as for rehabilitation of concrete dams, mainly because the application is made over a new structure and not over a deteriorated upstream face. For example, at Riou dam in France, the selected PET nonwoven geotextiles exhibited tensile strength ranging between 10.5 and 13.0 kN/m (Scuero, 1990).

FILTRATION

The function of filtration represents the ability of a geotextile to retain soil particles while being crossed by flowing water.

Embankment dams

- 13 The first application of a geotextile filter in an embankment dam was in 1970 at Valcros dam in France, 17 m high: according to Giroud and Gross (1993), PET nonwoven geotextile filters were used both around the downstream gravel drain ($\mu = 300 \text{ g/m}^2$) and also under the rip-rap protecting the upper portion of the upstream slope ($\mu = 400 \text{ g/m}^2$).
- 14 The performance of the dam and the extensive investigations on geotextile samples taken from the dam by several independent teams have clearly demonstrated the viability of geotextile filters in dams (Delmas et al., 1993).

After this pioneering application, geotextiles have been worldwide used as filters in various locations within the embankment dams, both for new construction and rehabilitation purposes (Bertacchi and Cazzuffi, 1985).

The main use has been a replacement or a supplement for granular filters: geotextiles do not act in the same way as granular filters, as the stability of interfaces between

different soils under hydraulic flow involves complex mechanisms (Gourc and Faure, 1990).

Many of the uses of geotextiles as filters have been in non-critical locations within the dams, often where examination and repair is relatively easy (ICOLD, 1986): most applications have been in fact realized below the entire upstream slope protection (like rip-rap).

More attention has to be devoted to applications in critical locations, like filters in zoned embankment dams: for this critical location, the present practice is more oriented to use geotextiles in association with granular filters, than to completely substitute earth materials.

15 The first remarkable example of such tendency is represented by Hans Strijdom dam in South Africa, 57 m high, constructed from 1975 to 1980: for this zoned rockfill dam, problems were encountered in obtaining filter sand in sufficient quantities. Therefore, it was decided to use a PET nonwoven geotextile filter ($\mu = 340 \text{ g/m}^2$) between the core material and the sand filter, thus reducing to 1 m the thickness of the sand filter itself, both on the upstream and the downstream sides of the core zone (Hollingworth and Druyts, 1982).

In any case, geotextile filters in embankment dams have to be carefully selected: several design criteria have already been proposed (see, for example, the review of design criteria by Bertacchi and Cazzuffi, 1985 and by ICOLD, 1986), but a lot of work has to be done in this field, particularly for critical locations within the dam and large hydraulic heads. Surely, more substantial coordinated efforts by manufacturers, designers and installers are needed: manufacturers should develop and propose special products for such important application while dam designers have to be less conservative in relation to geotextile filters. In fact, according to Lawson (1982), it is important to remember that, unless some risks are accepted in the use of these relatively "new" materials, there can be no important progress in dam engineering technology.

REINFORCEMENT

The function of reinforcement is the result of stress transfer from soil to a geosynthetic.

Embankment dams

16 For new constructions, the first dam in which geosynthetics have been used with reinforcement function was Maraval dam in France, 8 m high, constructed in 1976. The dam has a sloping upstream face lined with a bituminous geomembrane ($t_{GM} = 4.8 \text{ mm}$) and a vertical downstream face obtained by constructing a multilayered geotextile-soil mass, reinforced with a high-strength PET woven geotextile ($\mu = 750 \text{ g/m}^2$ and $T = 210 \text{ kN/m}$). Due to the vertical downstream face, the spillway is short and therefore not particularly expensive, which is beneficial for such small dams, where spillways usually

represent a large fraction of the total construction cost. It is also interesting to note that the dam was overtopped three times during construction with virtually no damage (Kern, 1977).

Perhaps also due to the negative impact on the landscape (the geotextile remains exposed on the vertical downstream face), the geosynthetic-reinforced soil mass technique has not developed remarkably for construction of small dams. This consideration does not exclude further developments of this type of dam application in the future, particularly taking into consideration the recent constant effort to conceive geosynthetic-reinforced structures exhibiting also facing systems more consistent with the landscape. In fact, the use of metallic reinforcements, with more aesthetically attractive facing systems, was already reported for about ten dams around the world with a low or moderate height (maximum 22.5 m), as illustrated by ICOLD (1993a).

Some examples of uses of geosynthetics with reinforcement function have to be reported for dam heightening, both for rehabilitation and new construction purposes.

This technique has been used, for example, at Davis Creek dam in the United States (Engemoen and Hensley, 1989): the dam, constructed in 1990, is 33 m high; its upper part presents a steep geogrid-reinforced down-stream slope. Two types of geogrids were adopted: six layers (each 5 m long) of one type of HDPE (high density polyethylene) geogrid were used to provide adequate deep-seated stability, while 19 layers (each 2 m long) of a lighter HDPE geogrid type, were placed to give adequate near-surface stability. Of course, particular attention was dedicated to establishing vegetation on the downstream slope (1V:1H): to this goal, hydro-seed was covered by natural fibres (coconut) and then irrigated for longtime.

The geosynthetic-reinforced techniques for dam heightening will surely have an important development in the coming years. In fact, even for rehabilitation purposes, reinforced structures constructed on the narrow crest of existing embankment dams represent an ideal way to heighten the dam itself, in order to increase the storage capacity or, eventually, the freeboard, taking also into consideration the environmental aspects related to the soil/vegetative cover.

Always in the field of embankment dams, a number of applications of geosynthetics used to reinforce bituminous concrete or cement concrete cover layers have to be mentioned. In particular, some cases of light geogrids as reinforcement of gunite layers placed as external protection of geomembranes liners were reported. For example, at Pappadai secondary dams in Italy (height ranging from 6.5 to 8.5 m), constructed in 1992, the protection of the GCM liner (including a PVC geomembrane and a PET geotextile) was obtained by a PP nonwoven geotextile over which a layer of gunite, 60 mm thick, reinforced with a PP bioriented geogrid ($\mu = 70 \text{ g/m}^2$), was sprayed (Sarti, 1994). Finally, especially in seismic regions, it is good practice to adopt geosynthetics also in order to reinforce bituminous concrete layers incorporated in embankment dams revetments: usually PET woven geotextiles ($\mu = 250 \text{ g/m}^2$ and $T = 50 \text{ kN/m}$) able to

resist thermal shock due to the contact with bitumen at about 160°C, have been selected (Cazzuffi, 1988).

SURFICIAL EROSION CONTROL

Surficial erosion control represents the complex function carried out by a geosynthetic or by a bioproduct to prevent ground surface soil particles from detachment and transport.

Embankment dams

Geosynthetics have been used to control surficial erosion in a number of embankment dams, both for new construction and rehabilitation purposes.

Two main groups of applications could be mentioned, according to the origin of the erosion to be dealt with:

- erosion caused by atmospheric agents (mostly rainwater);
- erosion caused by overtopping of the dam.

In the first group, the applications have concerned mostly the entire downstream facing and the upper portion of the upstream facing; in fact, the portion of the upstream facing directly in contact with the stored water has been generally protected using the typical techniques adopted for river bank revetments, as rip-rap, in which geotextiles are performing a filter function or, in alternative, other solutions (see ICOLD 1993b), as soil-cement blankets, concrete slabs, bituminous concrete layers and so on, in which geosynthetics could be incorporated with a separation or even a reinforcement function.

The products commonly used to control surficial erosion due to atmospheric agents are mainly geomats and geocells, but also biotextiles, biomats and biocells are adopted, particularly when biodegradation is desirable in case of temporary role during the vegetation growth. This solution is not only typical of earth dam facings, but today has become common practice to solve problems induced by erosion due to rainfall and consequent runoff, also on natural slopes, embankment slopes, man made cut-slopes and so on.

The group of surficial erosion control applications really peculiar for dams is related to protection against overtopping. This type of application is surely one of the possible future remarkable expansion areas concerning the use of geosynthetics and bioproducts in dams: the protection against overtopping represents in fact a crucial aspect of dam engineering. Many failures of embankment dams have been induced in the past by overtopping, mainly because the downstream face was not protected. Documented case histories have shown that phenomena induced by overtopping have been influenced by several factors, as valley morphology, dam type and size, physical and mechanical characteristics of the construction soils, hydraulic regime of the reservoir and so on. In particular, the soil grain sizes have an important influence on the

failure mechanism induced by overtopping, as illustrated in the enclosed figure (after Croce, 1989).

All the observed failure mechanisms due to overtopping (both on site real cases and on physical model studies) have been originated in the downstream face and have then progressed towards the dam body. On the basis of this consideration, it is of course evident the need to protect the downstream face: different experiences could be mentioned on this subject, using different techniques, but only few incorporating geosynthetics.

Particularly interesting is the Australian experience, where about 40 rockfill dams since 1964 have been protected and reinforced on their downstream side using metallic grids and gabions: up to now reinforced rockfill has been used mostly in the construction phase. Such a technology allows for substantial saving in diversion works: therefore, it has mainly temporary character and it does not involve any corrosion consideration (ICOLD, 1993a). Different protection and reinforcing systems have been developed and used: some of them are patented and the commercial ownership of these patents has to be complied with for any application.

Among the different examples, the case of Mooloolah dam in Australia, 12 m high, constructed in 1971, could be mentioned. In fact, in this dam metallic grids and meshes were adopted to reinforce the downstream side and also to protect the downstream face for a longer term than the construction period (Johnson, 1973): the dam was already overtopped several times, without any substantial damage. Only some pieces of timber were found on the downstream face after each overflow. In any case, the Mooloolah dam was supposed to be enlarged ten years after completion of the first stage, and also to be provided with a separate spillway.

Some applications of geosynthetics and bioproducts have already been reported to solve the problem of overtopping protection, both for new construction and rehabilitation purposes. For example, Lake-in-the-Sky earth dam in United States, 10 m high, constructed in 1964, was rehabilitated in 1991 by placing a turf biomat (reinforced with a geosynthetic) over the entire downstream facing, in order to control the erosion phenomena in case of short-term overtopping: the reinforced biomat represented a technical solution significantly less expensive than conventional concrete spillway (Giroud and Bonaparte, 1993).

In the case of the construction of Maraval dam in France (see before) the PET woven geotextiles ($\mu = 750 \text{ g/m}^2$) were adopted also to improve the resistance to overtopping, but mainly to perform a reinforcement function.

In the case of rehabilitation of three small dams in United States (Bass Lake dam, 12 m high, constructed in 1990; Trout Lake dam, 8.5 m high, constructed in 1951; and Price Lake dam, 9 m high, constructed in 1958), articulate concrete blocks linked by cables and resting on a geotextile have been used in 1991 in order to protect the crest and the downstream slope against overtopping (Wooten et al., 1990). In those cases, woven

geotextiles were adopted mainly to perform a filter function; it is interesting to note that the geotextile opening size was selected not only to satisfy filter criteria, but also to allow penetration by grass roots: in fact, the articulate blocks were covered by grassed topsoil layer. This soil/vegetative cover has given the overtopping protection a natural appearance and also provided additional anchorage for the articulate concrete blocks.

It seems evident that the geosynthetic applications in the field of overtopping protection are still at an experimental stage: surely, considering their flexibility even in presence of important settlements of the downstream face and also their durability already exhibited in other relevant applications, a bright future could be envisaged for the use of geosynthetics in this specific area, but only provided that specific design procedures should be developed, with the aid of both physical and mathematical models, validated by means of full scale experiments.

In definitive, from a safety point of view, geosynthetics, eventually associated with a combination of bioproducts, earth materials and vegetation, could represent a stable solution to resist overtopping phenomena in embankment dams. From an environmental point of view, the same combination of materials, could represent the "natural" alternative (much more attractive also from the aesthetical aspect) to traditional protection systems on the downstream slope, like rigid concrete slabs.

Finally, a concluding remark concerns the applications of geosynthetics for performing the surficial erosion control function in embankment dams: not always the use of geosynthetics in this field is giving a positive impact of the entire structure on the landscape and, more generally, on the environment.

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For example, the use of geotextiles according to the fabric-forming technique should be generally adopted only for emergency applications. This technique consists of pouring a highly fluid sand-cement mortar between two geotextile layers kept parallel by separator yarns, thus generating a mattress-like slab. Also geotextile tubes filled with sand or clay granules do not represent an environmentally acceptable solution for erosion control systems.

Nevertheless, both types of revetments have been sometimes used to control erosion on the upstream face of small embankment dams: being vegetation growth practically impossible through these structures, the impact of these solutions on the landscape is surely negative. Therefore, for both solutions (mattresses and tubes) some further efforts by the geosynthetics manufacturers, designers and installers are needed to solve the problem related to the environmental impact on the landscape.

CONCLUSIONS

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As described previously, geosynthetics have been used in concrete and masonry dams mainly for rehabilitation works and in RCC dams for new constructions, while for embankment dams they have been employed for both purposes.

For embankment dams and also, in some way, for RCC dams, the use of geosynthetics is always associated to a reduction of the natural earth materials to be exploited and placed: therefore, this result represents surely one of the most important positive impact related to applications of geosynthetics on such structures.

Moreover, for all types of dams, geosynthetics, if properly designed and correctly installed, surely contribute to increase safety: this is particularly evident for rehabilitation works. The safety improvement necessarily means a reduction of the hazards, and this result corresponds to another important positive impact due to the use of geosynthetics on dam structures.

Other positive impacts are typical of the different dam structures and also of the specific performed functions. For example, geomembranes or eventually geocomposite membrane liners, adopted for rehabilitation of concrete and masonry dams upstream facings, could be easily transported by using helicopters, even to the remote locations typical of such applications (mountain areas, arid regions and so on). On the contrary, conventional techniques usually request the transport of higher quantities of different materials (like cement, selected aggregates and so on), therefore involving the need to build or, at least, to renovate adequate access roads.

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