# Role of Geosynthetics in Re-galvanizing Design and Restoration Strategies for Dams

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## ABSTRACT

Dam engineering is an ancient science. Construction and restoration of dams have been age old activities. Contribution of dams in civilizational development is immense. Without water management, no civilization can sustain and prosper. With the advent of newer materials in course of time, design philosophies and restoration strategies for dams have undergone remarkable changes. In some cases, better serviceability and longevity has been the net gain with advancement in materials. Construction methods have also undergone large changes in parallel. This complex process is marked with evolution of newer perceptions and principles. Engineers have been utilizing enhanced properties of the advanced materials in re–galvanizing the solution system, whether it is construction of a new dam or restoration of an existing one. Thus, paradigm shift in devising solution for a particular problem has been a process and product of advancements in materials. It is interesting that the other way round is also true. This bilateral adaption has been an interesting phenomenon to be studied by way of browsing the journey of evolution of concepts in dam engineering. The net results are in the form of saving of cost in addition to longevity. These are all inevitable characteristics of sustainability. The paper discusses the role of geosynthetics in re-galvanizing the design and restoration strategies for dams along with sustainability aspects emerging out of bilateral adaption by referencing case studies.

Key Words: Dam Engineering, Design, Geosynthetics, Restoration, Sustainability

## 1.0 EARLY DAMS

Water has been the basis of civilizational development and therefore construction of dams is known since prehistoric time. Dams had been practiced in Mehrgarh and Mesopotamia since the Neolithic times (ca. 7,000 – 3,200 BC). Thereafter, during the Bronze Age (ca. 3,200 – 1100 BC). Dams were built in south-eastern Greece and Indus valley by the necessities to make efficient use of natural resources, to make civilizations more resistant to natural hazards, and to improve the standards of life. The Sumerians constructed a network of irrigation canals along the lower reaches of river Tigris and Euphrates around 6500 BP. Remains of the earliest water storage dams built in 3000 BC are evident in Jordon, Egypt and other parts of the Middle East. The earliest dam in the Indian sub-continent is believed to have been built of stone rubbles by Zoroastrians in Baluchistan. Dams built of stone rubbles called Gabarbands are seen in Kutch and Brick bunds have been found in Karachi. Ancient dams were built with natural materials like soil, rubble, lime, etc.

## 2.0 CONCERNS FOR DAM SAFETY

Dams are found susceptible to local damages like upstream slope erosion due to wave action, downstream slope erosion due to heavy rains, slope failures due to pore pressure, overtopping during flood, failure due to earthquake, etc. various protection measures using different natural materials are practiced. With passage of time, advancements in materials for construction, protection and restoration of dams earmarked higher safety standards and better performance of dams. Because larger dams came in to existence during the last century, greater concern for safety became required and therefore advancements in design philosophy and restoration strategies also became necessary. Larger the dam, more the benefits but greater the risk if not maintained properly is known to all.

## 3.0 UPSTREAM FACING FOR EARTHEN AND ROCKFILL DAMS

The trapezoidal earth and rock mass of a dam is in far better conditions to resist the hydrostatic load of the reservoir when the waterproofing element coincides with its upstream face. The entire mass of the dam resists the water thrust. Only the horizontal component of the hydrostatic thrust must be resisted by friction along the entire base and sides of the dam, the vertical component, applies a compression on the fill and foundation and therefore increases confinement, shear resistance and moduli of both - fill and foundation. The grout curtain of an upstream facing dam, forcibly located at the face-to-abutments contact, lowers the piezometric surface throughout the abutment and under the whole embankment.

At equal foundation or embankment permeability and curtain efficiency, the pore pressure field is more favorable than in any other scheme. A uniform rockfill prism has greater tolerance to seepage. However, this type of state of pore pressure field is difficult to maintain for long years.

The upstream facing scheme allows accessibility to the curtain for inspections, repairs and strengthening. When acted upon by a train of seismic waves, the body of the dam responds as a single mass of fairly uniform dynamic characteristics. A core represents a discontinuity in response and the upstream and downstream shells may move in counter-phase, at certain moments of the shaking.

From a construction view point, the situation of a uniform embankment lends itself to maximum rate of progress. The grouting of the foundation can proceed as a separate and parallel operation while most of the dam's embankment is being placed. This offers the possibility of saving in completion time. On the other hand, a reinforced concrete plinth is always necessary, while most central core scheme do not require it.

The waterproofing of the upstream face can be installed in stages, this allowing early impoundments or a safer diversion of large floods. Facing installation can be done during construction or during the serviceability life of the dam.

From the investment view point, placement of a single material for the whole embankment is faster and entails lower costs. The plinth and the associated longer grout curtain add to the cost. Considering the service life of the dam, the waterproofing element of an upstream facing is more vulnerable to damages than a central core. Upstream facings though, can be inspected and repaired, in some cases, even underwater. The upstream facing is better adapted to future increases in height of the dam.

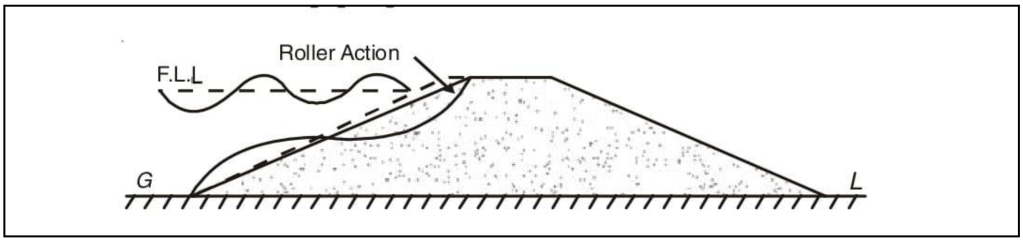

**Figure 1.** Behavior of Unprotected Upstream Face of Earthen Dam

### 3.1 Various Materials Practiced for Upstream Facing of Earthen and Rockfill Dams

3.1.1 Wood or Shotcrete

Wood facings on dumped rockfill mark the start of this solution. They were adopted initially in mining districts. Cogswell dam, 85 m high impounded in 1938 is possibly the best example. The embankment was rock, dumped in high lifts.

3.1.2 Metal

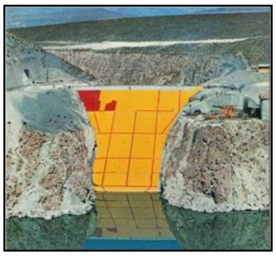

**Figure 2.** Aguada Blanca Ingot Iron Faced Rockfill at 3640 m Altitude in the Andes

Iron facings were used in a few instances. Oxidation and corrosion discouraged their use although Skagway Dam (Colorado) has been in service more than 60 years. The last such dam, Aguada Blanca (Peru) 45 m high, was commissioned in 1970.

### 3.1.3 Bituminous Concrete

Bituminous facings were largely adopted in the past decades and are less frequent today. Since the early examples like Mulungushi (South Africa) facing cross sections and bituminous mixes underwent a large evolution: double deck including a drain layer, and bituminous concrete mixes using standard asphalt cement were simplified to single deck schemes with modified bitumen. In parallel, deck laying pavers, rolling equipments and joints treatment methods were greatly improved. An evolved example was the single deck Montgomery dam (Colorado) 35 m high, commissioned in 1956.

### 3.1.4 Reinforced Concrete

Concrete facings date back to the beginning of last century. A remarkable example was San Gabriel 2 (California) 115 m high started in 1932 [4]. Later this solution underwent substantial improvements and became widely applied, boosted by an apparently simple design and by an increased confidence of engineers in reinforced concrete. In recent decades, at a time when concrete gravity and arch dams application decreased this got to be the preferred solution. Many of the recent and highest dams like Karahnjukar (Iceland) 190 m and Campos Novos (Brazil) 202 m are of this type. The solution is conventionally referred to as 'Concrete Faced Rockfill dam' (CFRD).

### 3.1.5 Geosynthetics

Geosynthetics (membranes) became available to civil engineering since the late 1950s. Their early applications to earth and rock dams date from 1959. A substantial evolution of polymers, the variety offered by the chemical industry and the introduction of 'composites' (a combination of different synthetic materials like geomembranes with geotextiles), promoted their application especially as refurbishment measure on existing dams. Synthetic facing offers remarkably low permeability and high deformability and were used as the sole waterproofing element in new dams of increasing height: Pitshanulok (Thailand) 20 m high 1978, Jibyia (Nigeria) 26 m high 1991, Bovilla (Albania) 58 m high 1992, Nam Ou 6 (Laos) 88 m high 2014. Several applications dealt with waterproofing tailings dams. This design, with service life records exceeding 40 years, is conventionally referred to as 'Geomembrane Faced Rockfill dam' (GFRD).

**Figure 3.** Murdari GFRD Dam Waterproofed with Wide, Pre-welded, Bands of Polymer ‘Composite’: PVC Geomembrane + PP geotextile

Lago Nero Dam in Italy was constructed in Italy in 1935 with reservoir capacity of 3.35 MCM. Dam was made up of masonry and the spillover section of concrete gravity type. Its restoration was done in 1979. Geocomposite formed by a PVC geomembrane thermocouple to a polyester geotextile. The geotextile was prestressed and fastened to the main structure of the dam with specially designed steel ribs. This was much advanced an application of geosynthetics as facing.

## 3.2 Geosynthetics Practiced for Upstream Facing of Masonry and Concrete Dams

Masonry dams are susceptible to seepage through body due to delamination of cladding concrete or migration of mortar material or displacement of stone or brick owing to some gap, etc. Conventional practice is to grout the masonry using some cementitious materials. If pressure in grouting is lower than required, reaching of the grout material up to targeted locations is not possible. If pressure is greater, it becomes invasive and damages the existing masonry body itself. Application of just right pressure is not a simple exercise. Filling of gaps on the external surface using polymeric materials or polyurethane is also practiced in some cases. But it is not really a long lasting solution. Several advancements in materials for grouting and plugging got developed and milestone improvements have been recorded. But the solution till recent dates have not been really effective for a long time is a fact.

In concrete dams, honeycomb in the dam body is the major issue. Choking of perforated vertical drainages is an added issue. Grouting is generally done to address the honeycombing but the same limitations as they are with the masonry dam grouting pose a challenge.

Covering the masonry or concrete dams with bituminous sheets earmarked the historical paradigm shift in dam repairs. The modern use of bitumen as a geomembrane waterproofing layer for dam facings commenced in the early 1970's with the in-situ impregnation of a synthetic geotextile placed onto a prepared substrate, and impregnated with bitumen sprayed onto the material at a high temperature – typically in excess of 180ºC. The first application of this form of sprayed geomembrane was in lining ponds in 1973-74 and around the same time, on small dams such as the dam of "Les Bimes" (9 metres high) or the dam of "Pierrefeu" (8 metres high), both of them located in the south east of France. This, although an effective method of producing a waterproof and seamless geomembrane layer, had major inherent drawbacks both in terms of operator safety and quality control. The process was sensitive to moisture, and the bitumen usage was difficult to control leading to variations in thickness. The introduction of prefabricated geomembranes manufactured using bitumen impregnated geotextile under quality-controlled factory conditions removed these failings, leading to greater confidence in their use. There was a transition to the use of the prefabricated geomembranes in the mid 1970's. PVC composite geo-membrane and geo-textile was used for the waterproofing system in many concrete and masonry dams against the leakage of upstream reservoir water through the dam body. Cement Impregnated Polypropylene got developed and started practiced almost contemporarily.

There are various instances where the upstream faces of the dam were to be installed with a PVC composite geo-membrane or geotextiles as a rehabilitation measure against the seepage related issues in such dams all over the world. The Kadamparai dam in TamilNadu, installed with PVC geo-membrane system were reported to have reduced the seepage by a large measure. In Kadamparai dam waterproofing for an area of 17,300 m$^2$ was reported to have completed in 3 months and six weeks. Construction and restoration of dams now a days involve usage of advanced geosynthetic membranes in the form of composites.

### 3.3 Factors Propelling Enhancement of Design and Materials for Upstream Facing

Wood facing could last only for ten years or so as wood was a decaying material. Iron facing could last longer but being a rigid material could not follow the profile of the inner earth or rockfill which would undergo settlement due to internal readjustment of the mass. Cost factor would also be a discouraging factor in case of iron facing.

Early years with CFRD were of successful. Initially, facing thicknesses, reinforcement quantities and peripheral plinth sizes were recommended only as a fraction of the height of the future dam. Slopes were always step (1.3 H/ 1V). Design practice was influenced by this philosophy and essentially the same cross section was applied to increasingly high dams. Severe accidents however affected in recent years some of the highest CFRD, forcing to reconsider the relevance of stresses and deformations in high embankments. Key facts, other than height, are - valley width, abutment steepness, abutment profile and, last but not least, the engineering parameters of the rockfill, like strength and moduli, as well as construction specifications.

The drive toward developing flexible and deformable facing was largely promoted by repeated observations of deformations, joint ruptures and cracking of the slabs of CFRD and by high and increasing rates of water loss in high rockfills. The deformability of synthetic polymer sheets (geomembranes and 'composites'), plus the possibility of creating a continuous facing by welding, appeared a promising answer to the limited capability of a reinforced concrete facing to survive unharmed the unavoidable deformations of high embankments. It appears necessary to recall the key facts governing the deformations of a rockfill embankment during construction and under the hydrostatic load of the full reservoir.

**Figure 4 and 5.** Damage to a Concrete Facing due to Rockfill Deformations (left) and Large Water Loss Crossing the Embankment, Consequence of Invisible Damages to the Facing (right).

Geosynthetics being flexible and deformable exhibited several other advantages. Welding at joints helped attain waterproofness, composite manufacturing technology provided facilitation of drainage phenomenon on inner side which helped relive internal water pressure and their UV resistance and temperature tolerance made them suitable for extreme climates. Their design philosophy involved tensile strength, elongation, puncture property, etc. as the main parameters. Imperviousness of geomembranes can be appreciated from following.

| **PERMEABILITY OF INTACT MATERIALS COMPARED TO THE <10-14 m/s "PERMEABILITY" OF GEOMEMBRANES** | |
|---|---|
| Cement concrete, ideal | $10^{-12}$ m/s |
| Cement concrete in field | $10^{-10}$ m/s to 10-8 m/s |
| Roller compacted concrete | $10^{-8}$ m/s to 10-6 m/s |
| Bituminous concrete, ideal | $10^{-9}$ m/s |
| Bituminous concrete in field | $10^{-8}$ m/s |
| Clay layer, ideal | $10^{-9}$ m/s |
| Clay layer in field | $10^{-8}$ m/s |
| Bentonite | $10^{-11}$ m/s |

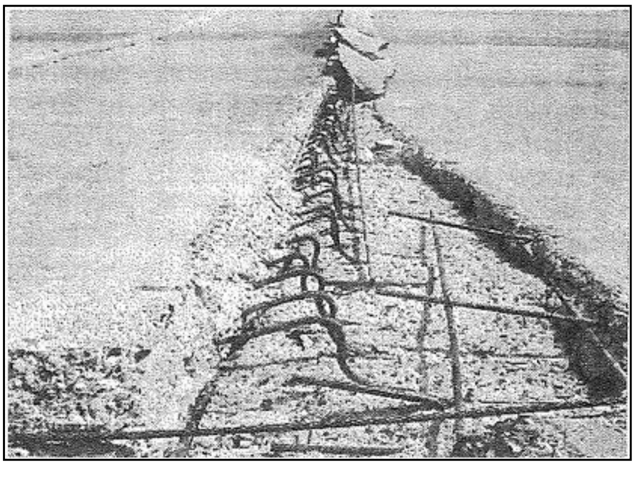

**Figure 6.** Concrete Facing Failed in Compression along a Vertical Joint

## 4.0 INTERNAL DRAINAGE SYSTEM

Phreatic line develops in the earth and rockfill dams and its shape keeps changing with reservoir water level variations. Line of seepage or phreatic line or saturation line is defined as the line within the dam section below which there are positive hydrostatic pressures in the dam. The hydrostatic pressure on the phreatic line is equal to the atmospheric pressure and hence, equal to zero. Above the phreatic line, there is a zone of capillary saturation called capillary fringe, in which the hydrostatic pressures are negative. The appreciable flow through the dam body below the phreatic line, reduces the effective weight of this soil and thus reduces the shear strength of the soil due to pore pressure. But on the other hand, the insignificant flow through the capillary fringe, leads to greater shear strength, because the capillary tension in water lead to increased inter-granular pressure. The effects of the capillary fringe are thus on a slightly safer side and hence neglected.

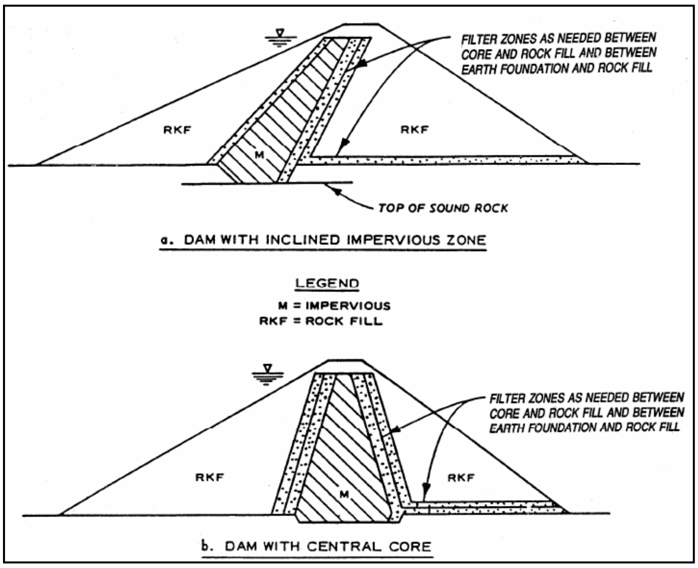

**Figure 7.** Internal Drainages in Earth and Rockfill Dams

Controlling phreatic line to be within base width and releasing pore pressure leads to requirement of impervious core and/ or inclined filters in central zone of earth or rockfill dam. Horizontal blanket filter to drain out seepage water collected in inclined filter is also required. In some cases, only horizontal filters or only rock toe is sufficient. Conventional filters are designed using gritty or coarse natural material. Design of drainage is based on coefficient of permeability and focal distance which is computed using parabola curve of phreatic line and accordingly the length and thickness of the filter is computed. Graphical methods can also be used which use the same parameters.

Drainages and filters using natural gritty materials have been in practice since long back though they have innate limitations like mixing of the casing material with filter material during construction reducing effective thickness of the drainage. During the life of the dam, travel of seepage water tends to dislodge the particles from casing material which are finer and hence gradually clogs the drainage and affects its effectiveness. Drainage can note be subsequently repaired or replaced in the dam body and therefore becomes a critical element for longevity of the dam. Subsequent restoration of dams become very difficult and expensive.

In 1954 polypropylene were invented and they came in to use for different purposes including manufacturing of engineering textiles. Filtration property of non-woven material came in to use and the geocomposites with core as a drainage and layer of filter material on each side came in to use as a drainage material in dam body mimicking the behavior of perforated pipe. Geocomposite as a drainage material received a fast response. La Parade Dam of France was constructed using a geocomposite shaft drain instead of a granular drainage.

Limitations of granular drainage – mixing of gritty material with the casing material during layer wise construction in the process of rolling and subsequent clogging due to particle migration from dam body are avoided at large. The pores made by needle punching in the filter later are so small that the gap between the neighboring soil particles and filter layer remains sufficient to allow water to pass through without any movement of the soil particles and therefore migration of soil particles within the dam body is well prevented. Not only the life of the drainage gets longer but also of the casing material. As an additional advantage, thick drainage is replaced by a thin geocomposite and construction pace is also enhanced. But this advancement has not taken place step by step; rather, it was a leap from granular natural material to geocomposite. Design philosophy remains almost the same in granular filter and geocomposite but parametric values are much different. Serviceability and longevity of the solution became very important as the life of the dam is much longer than the life of the conventional internal drainage.

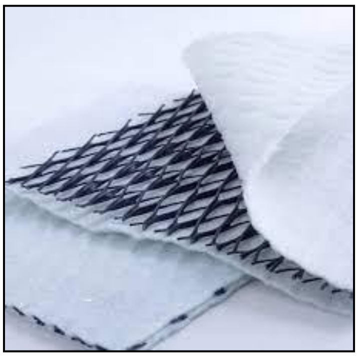

**Figure 8.** Geocomposite Drainage

There are some important criteria on different aspects of performance of filter for earthen or dams like retention, permeability, anti-clogging criteria, serviceability and durability. Performance in drainages in dams using natural materials is affected over a period of time and therefore geocomposite drains have been widely used. Kandaleru Earthen Bund Reservoir, Chennai Kandaleru reservoir earthen dam was eroded at chainage 7.50 KM to 8.12 KM due to high current forces from the reservoir. The Height of Earthen Dam was 45 m. Slope stabilization of existing Kandaleru Dam for a length of 500 m long was carried out. The internal drainage was executed using geocomposite.

**Figure 9.** Kandaleru Dam, Tamilnadu, India

## 5.0 SLOPE STABILITY UNDER STATIC AND DYNAMIC LOADS

Dams located over active fault zones are quite susceptible to earthquake induced damages. Dynamic analysis is recommended for important dams and embankments, failure of which may lead to high levels of risk. Under severe ground motions, major contributors to earth dam failure are overtopping, piping, and structural failure. Conventional approaches included provision of additional free board, flattening of slopes, rubble pitching, usage of selective soil with better compaction in casing zones, etc. But they proved costly and less effective. Their design philosophies were based on Rankine’s or Coulomb’s theory.

With invention of various types of geosynthetics, some of them found to be very useful in reinforcing soils in dam construction and restoration. Application of reinforced soil walls in roads became popular soon in 1950s but soon then the same design philosophy with some additionality started being applied to dam engineering. Reinforcing the soil with geosynthetics has proven to steepen the slopes, thereby considerably reducing the earthen material used for the dam construction. Reinforced earth dams also provide the advantages of structural flexibility, increase in factor of safety of the slopes, displacement and stress level reduction.

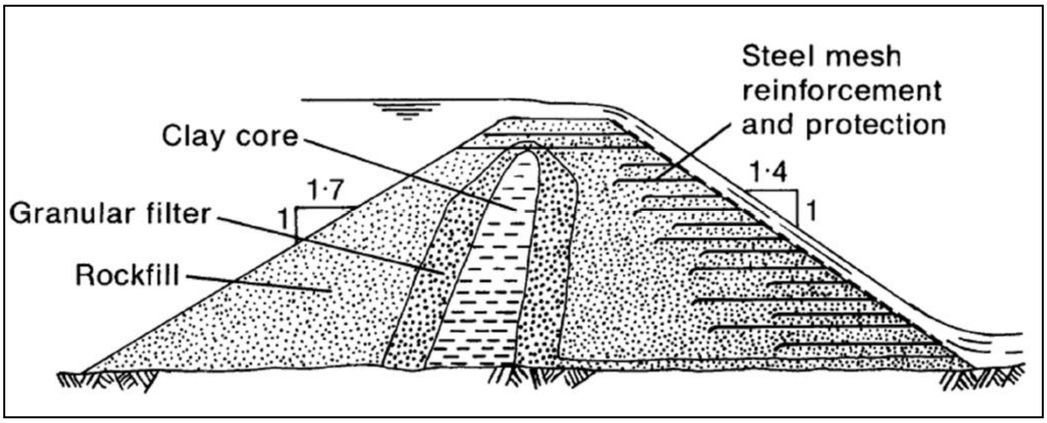

**Figure 9.** The Moochalabra Zoned Rockfill Dam, Australia

The successful integration of geosynthetic materials to the civil, geotechnical and earthquake engineering applications has become an advantageous and cost-effective way to achieve the required stability conditions of related structures. The use of geosynthetics is common on static load conditions but not limited to. Geosynthetics are capable of absorbing dynamic forces and transmitting less dynamic forces to engineering structures.

In the initial days, steel reinforcements were used in important structures as soil reinforcements. Subsequently geosynthetics came in to practice. Design phiposophy in both the types of materials remained the same. 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 with a bituminous geomembrane and a vertical downstream face obtained by constructing a multilayered geotextile-soil mass, reinforced with a high strength PET woven geotextile.

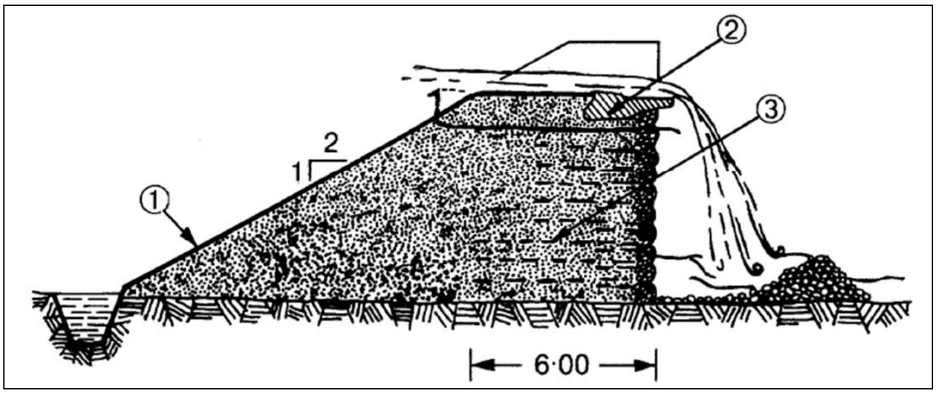

**Figure 10.** The Maraval Earth Dam, France

Performance of reinforced earth wall is better while it is subjected to dynamic loads as compared to conventional earthen embankment. During an earthquake, the retaining wall is subjected to inertial forces due to the backfill inertia. Reinforcements in the soil mass tend to make the soil mass act as a monolith and therefore shear failure of the soil mass becomes avoidable. So is the avoidance of dispersion type of failure. The design must consider displacement at the back of reinforced soil zone, displacement due to foundation yielding, compaction, slack in reinforcement connection, and dislocation of facing blocks, etc. Investigation of reinforced soil walls that built in water and power resources (e.g. dams and powerhouses) projects shows that there is a considerable improvement in response to earthquake if the earthen embankment is reinforced either on upstream or downstream side or both.

Design philosophy of reinforced earthwall has undergone many changes. Reinforced earth can be considered as a cohesive material with anisotropic cohesion introduced due to reinforcement being a function of strength and density of reinforcement. However, the concept of anisotropic cohesion did not find direct application in design of retaining structures. The early design of wall was based on an anchorage concept with each reinforcing strip or tie locally balancing the Rankine active thrust on the area of skin supported by it. Subsequent work in France and elsewhere showed local equilibrium analysis to be conservative, especially for failure due to sljppage between soil and reinforcement. New models for strength properties of reinforced soil and new methods of analysis of reinforced earth walls were proposed in the latter half of the twentieth century. Overall equilibrium methods which considered a bi-planar or curved failure surface were advanced which were significant improvements over the earlier methods. Soil-reinforcement friction is fundamental to the concept of reinforced earth.

## 6.0 FOUNDATION SEEPAGE CONTROL

Upstream blanket and cutoff walls are usually provided for checking seepage through foundation. Conventional technique involves use of bentonite grouting, sheet pile, diaphragm wall, etc. Technological development permitted deep sheet piles in river bed and sea bed. Diaphragm walls also became popular with advancement in driving machinery. With the advent of geosynthetics, its usage came in to practice and cost effective and promising results came to the notice of the designers. As cutoffs are designed from scour depth principles, derivation of required depth has remained unchanged in olden days and the present time. What has undergone changes are the thickness and joineries. Permissible deformations in all the materials is the key for designing the strength. Geosynthetics provide larger benefits there and therefore have come in to practice on large scale. Moreover, they have better resistance against chemicals in the surrounding soil.

An example of a reclamation project in which a geomembrane was used for a seepage cutoff through the crest of a structure is Reach 11 Dikes which are zoned earthfill embankments and are part of the Hayden/ Rhodes aqueduct in Phoenix, Arizona. The facility was leaking excessively through the embankment and foundation, requiring a seepage cutoff that would intercept an underlying impervious foundation stratum.

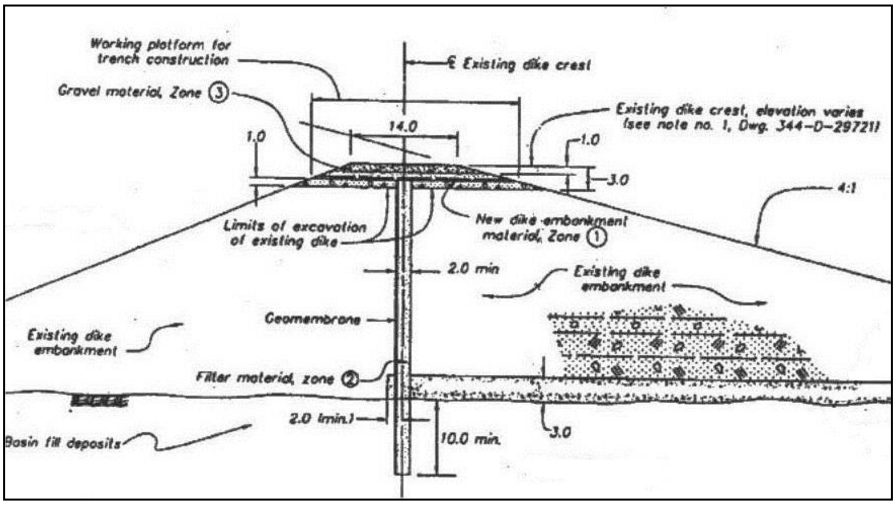

**Figure 11.** Reach 11 Dikes - geomembrane cutoff wall design, Phoenix, Arizona

## 7.0 ENERGY DISSIPATION

In any dam, energy dissipation may be required in the downstream either by providing a launching apron or a secondary apron to ensure a streamline flow in the river gorge. The same way, a divide bund between tail race channel of hydropower and spillover section of the dam has to take severe water currents and streamline the flow in the downstream. Earlier practice was to provide rigid components for all such purposes. Either the rigid component would bear the impact or would facilitate dispersal of energy owing to its shape like friction block, etc. With the advent of various types of geosynthetics, the entire design philosophy has undergone large changes. Multilayer load dispersal mechanism is designed using various geosynthetic materials. Divide bund of Ukai dam of Gujarat, India is an example of application of geosynthetics in energy dissipation. The divide bund between the tail race channel of the hydropower and the spillover section which was constructed over 50 years back was made up of earthen bund with stone pitching and was found distressed in the year 2017. It was restored using geosynthetics.

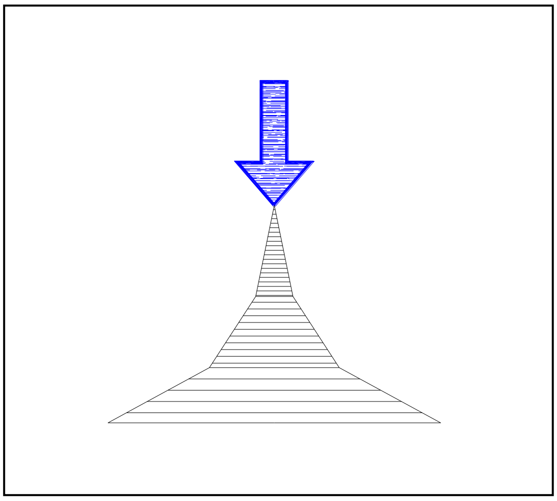

**Figure 12.** Multilayered Dispersion of force using various types of geosynthetics

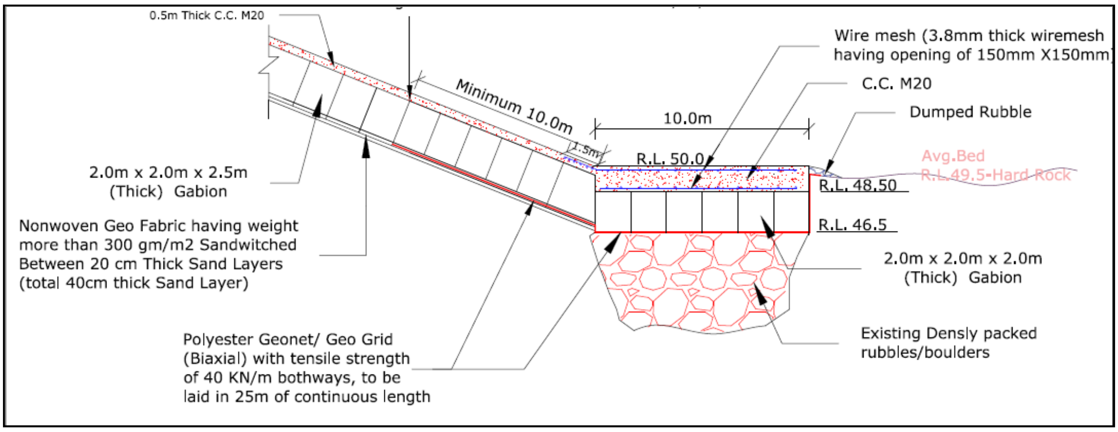

**Figure 13.** Design of restoration of divide bund (cross section)

**Figure 14.** Actual performance of divide bund during monsoon of 2019

Geocomposite drainage, non-woven polypropylene, biaxial geo-grid and gabions were used for designing the solution. The performance of the divide bund after restoration was tested with high discharges from the dam.

## CONCLUSION

Advancements in materials happen in the wake of necessities, challenges and field experiences. They invariably go hand in hand with design philosophies and working practices. Sustainability has become a major concern for everyone these days as none affords disruptions in services and cost to spend on frequent repairs. But at the same time sustainability demands longevity of every utility service from expense of materials point of view. Resource crunch is becoming more and more sever with passage of time and therefore this aspect has become very important. Geosynthetics have emerged as promising materials to address the present day problems related to dam engineering with longevous and sustainable solutions and with cost effectiveness as an added advantage in many cases. Varieties of geosythetics are manufactured with different purposes to be served and therefore they have changed the design philosophies and restoration methodologies along with performance criteria adopted in dam engineering.

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