ENGINEERING APPLICATION OF GEOSYNTHETICS IN CHINA

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ABSTRACT

This paper is to make a review on the state of practice for geosynthetics in recent 20 years of China, including their manufacture, relevant technical standards and engineering practice. The state of engineering practice is illustrated by a series of representative engineering projects in the three main fields of geosynthetics application, including highway and railway engineering, hydraulic and coastal engineering and solid waste landfill engineering.

Keywords: Geosynthetics, highway, railway, hydraulic engineering, landfill

INTRODUCTION

China has five to six thousand years' history that using natural plant fibers or combining with soil, rock as civil engineering materials. In the Neolithic Age, Chinese ancestors used the thatch as the reinforcement material of cob wall. In the Western Han Dynasty (about B.C. 200), there was a record of using natural plant fiber like willow and reed to build the Great Wall. During the Guangyuan year of Emperor Wu of Han (B.C.130), there was a record of combining bamboo and reed with soil and rock to plug a large breach of the Yellow River.

The use of modern geosynthetics in China started from the medium-term of 1960s. During the period there were many plastic and chemical fiber products. Few engineers tried to use the plastic membrane for barrier and leakage-proof of canals, reservoirs and dams. For example, asphalt-plastic memebrane was used to repair the Huanren hydropower station dam, and clay plastic membrane was used as the upstream apron of sluice in Hebei Province. All the applications were successful. At the later stage of the 1970s, as the development of reform and openness in China, the new type products like nonwoven fabric, plastic vertical drain and geotextile bags are imported to China in succession, which speeded up the application and dissemination of the geosynthetics in China. In 1976, the application of geotextile in revetment, flood fighting and embankment project started. For example, the soft mattress being made of the polyethylene woven cloth, polyethylene rope net and concrete blocks was applied for the shore protection of Yangtze River. The railway department used nonwoven geotextiles to tackle the mud-piping problem of railway foundation successfully. The highway department used nonwoven geotextiles to stabilize roadbed and side slope. Apart from the use of geotextile and geomembrane, other products like plastic vertical drain, plastic pipe, geocomposite, geogrid etc. have been used in engineering practice. The year of 1998 is the important kickpoint in China's development history of geosynthetics. In that year, serious flooding took place in Yangtze River, the Songhua River, and Nen River, the geosynthetics played a very important and unique role in the flood fighting and rescue, which drew great attention from the national leadership and public. The Prime Minister of the State Council had made four times written instructions. The nine ministries of Chinese government collaborated to set up a special leader team to plan and arrange the application and dissemination of geosynthetics. In a short time, they organized great manpower and financial resource to formulate and promulgate a series of product standards, testing procedures of geosynthetics and technical regulations, guides and handbooks, so that the application of geosynthetic was more standardized and common. They also organized 10 nation-level and 50 Ministry-level water resource demonstration projects with the application of geosynthetics. Afterwards, the manufacture and application of geosynthetics developed very fast in China, the type of products was expanded, the scale and quantity increased substantially every year, and the engineering application almost covered all areas of civil engineering.

Along with the application and dissemination of geosynthetics, related scientific research, training, and technical committee has developed. In 1984, the national "Scientific and Technical Information and Collaboration Net for Geotextile" was established in China, and later renamed as "Technology and Collaboration Net for Geosynthetics" in 1986, and in the same year, the "National Conference on

Geotextile" was held in Tianjin. Afterwards, "National Conference on Geosynthetics" is held at an interval of 3-4 years. On August of this year, "the eighth national Conference on geosynthetics" was held in Tianjin. "Chinese Charpter of International Geotextile society" was established in 1989, and changed to "Chinese Charpter of International Geosynthetics society" afterwards. In 1995, under the support of several departments of the Chinese government, one independent technical organization had been established, that was "Chinese Geosynthetics Engineering Association". Those technical organization and activities promote the development for geosynthetic production and its application technology effectively.

This paper is to make a review on the state of practice for geosynthetics, including their manufacture, relevant technical standards and engineering practice in recent 20 years of China. A series of representative engineering projects are presented to illustrate the application of geosynthetics in highway and railway engineering, soild waste landfill and hydraulic and coastal engineering. The existing problem and further development direction are pointed out at the end.

PRODUCTION OF GEOSYNTHETICS IN CHINA

(1) Geotextiles include woven geotextiles, knitted geotextiles and nonwoven geotextiles. Chinese manufacturers started producing geotextiles in late 1970s (Yan 2000). The early products were woven either by shuttle loom machine or by hand, and their width was not more than 2m. In 1980s, China imported a batch of facilities for the production of geotextiles from Europe and America, which promoted the production of geotextiles. At present, all kinds of geotextiles can be produced in China, including the new products such as 7m wide staple needle-punched nonwoven geotextiles. The most common geotextile products in China are the polyester staple needle fabric. From 2006 to 2011, the volume of geotextile production in China keeps increasing by an average of 35.3% per year, and up till 2011, the total volume of production for the geotextiles in China has been over 500,000 t.

(2) Geomembranes include PE, HDPE, and PVC geomembranes in term of material. The geomembrane surface can be smooth and textured. The development process of geomembranes in China was different from that of geotextile. At the beginning, being lack of hot bonding machine, PVC was mainly used as the raw material, so that the width of geomembrane products was only 1 to 2 m, and its thickness was more than 5 mm. The use of PVC geomembrane was not convenient. Later on, with the appearance of domestic hot bonding machines, the PE geomembranes were put into production in China. At present, Yixing Teda Geotextile Co., Ltd. has imported a set of HDPE geomembrane production line, which can produce 10m wide geomembrane (Fig. 1). The production line adopts the extrusion method to produce smooth, one-side textured and both-side textured geomembrane with a thickness ranging from 0.5mm to 3.0mm. The annual output of 10 m wide HDPE geomembrane is to 6500,000 m^2. The most common product of geomembranes in China is that geotextile-geomembrane composite or geotextile-geomembrane-geotextile composite (Fig. 2). The composites combine the sealing layer and protection layer, and hence the application is very convenient. Presently, the market scale of geomembranes in China reaches as much as 750 million m^2. It is anticipated that the market scale will keep increasing by 20% per year in the following 3 years.

Fig. 1 10m wide HDPE geomembrane manufactured by Yixing Teda Geotextile Co., Ltd

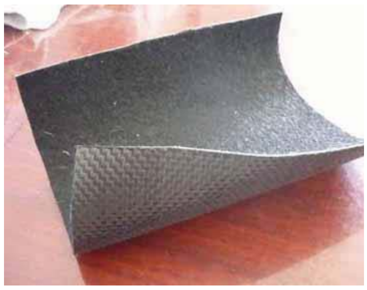


Fig. 2 Geotextile-geomembrane composite

(3) Geosynthetic clay liners (GCLs) include adhesive GCL, needle-punched GCL, stitch-bonded GCL. In 1991, GCL was first imported to China by CETCO, and used in the basement of Jinmao Tower of Shanghai. In 2002, a few domestic geosynthetics companies started to develop the production facility, and after continual improvement in the processing method the nationalization of GCL finally become true. Afterwards it is developed rapidly. At present, the GCL produced in China is 6 m wide by 40 m long. Dezhou Orient Geosynthetics Enterprise Limited is one of the representatives for such enterprises.

(4) Geogrids include plastic geogrids, steel-plastic, plastic welded geogrids, glass fiber geogrids and knitted geogrids. Since the first domestic

production line for plastic geogrid was introduced by Taian HaoHua Plastics Factory in 1998, over 20 enterprises had invested the production line of geogrids in the following 4 years. About 10 enterprises can produce both uniaxial and biaxial geogrids. Thanks to the heavy investment required for the production line, the manufacturers in China made efforts on the improvement of the geogrid product quality. In 2003, the quality of knitted geogrid products has reached the level of developed countries. Especially the innovative product of knitted geogrids combined with singeing asphalt geotextiles provides a wonderful material for the control of reflection cracking in highway pavement.

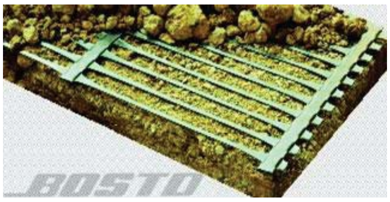


Fig. 3 Uniaxial geogrid manufactured by BOSTD geosynthetics

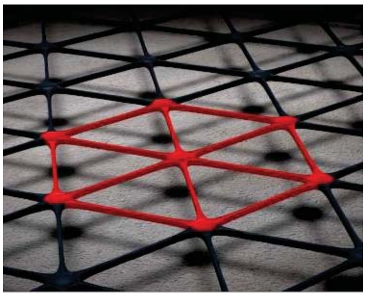


Fig. 4 TriAx manufactured by Tensar in Wuhan

At present, the leading manufactures of geogrids are as following: (1) BOSTD Geosynthetics in Qingdao, the representative products are uniaxial HDPE or polypropylene geogrids (Fig. 3) and biaxial polypropylene geogrids. Because of its strict quality control, the company won the "quality management award" at the 8th conference on geosynthetics in China; (2) Tensar Geosynthetics（Wuhan）enterprise, the representative product is TriAx geogrid (Fig. 4), which won the "production innovation award" at the 8th conference on geosynthetics in China. (3) Yixing Xintai Geosynthetics Enterprise Limited, the representative products include triaxial geogrids (Fig. 5) and reinforced geogrids with locks (Fig. 6). The triaxial geogrid functions more like a geocell. Compared to the uniaxial or biaxial geogrids, the triaxial geogrid can provide significantly stronger interlocking and reinforcement. The ribs of the reinforced geogrids are made of steel wire string encapsulated by polyethylene or polypropylene band. The longitude and latitude ribs are woven to form a continuous grid, and the locks at the junctions are made by using a special injection molding. The reinforced geogrids with locks are very high in strength and provide strong reinforcement. At present, the market scale of geogrids in China reaches as much as 300 million m^2. It is anticipated that the market scale will keep increasing by 18% per year in the following 3 years.

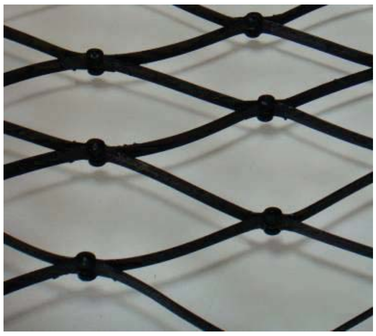


Fig. 5 Triaxial grid

Fig. 6 Reinforced geogrid with locks

(5) PVD includes separated type and integrated type (Fig. 7). The PVD consumption in China follows that of geotextiles. The annual consumption is over 70 million meters, which is the most in the world. PVD consists of a core and a filter sleeve. The core is normally placed loosely inside the filter for the separated type. There are two major shortcomings with this design. Firstly, the tensile strength of the core is not compatible with that of the filter, and sometimes differs a lot. Secondly, as the filter is fitted loosely to the core, the filter will indent into the drainage channels of the core under earth pressure. The integrated type of PVDs overcomes the above shortcoming. The representative manufactures for integrated type include Tianjing Hangaoderui Enterprise, Zhejiang Binwang Enterprise and Yixing Xintai Geosynthetics Enterprise Limited. For the integrated type, the filter and the core are adhered together by heat melting to form an inseparable body. The core is usually made of 100% transparent polypropylene plastic, and the filter is usually made of DuPont grey colour, pure long-fibre hot-bonded non-woven filter fabric. The integrated type possesses the following advantages (Liu 2009): (1) The tensile strength of the integrated PVD will be higher than that of the separated type; (2) The discharge capacity of the

integrated PVD will be significant greater than the foreign product. This is mainly because the indentation of filter into the drainage channels is considerably reduced for the integrated PVD, and the vertical wings of the core are also difficult to be bent under pressure as the overall stiffness of the PVD has increased; (3) The integrated PVD becomes more resistant to clogging because the drainage channels in the integrated type of PVD are not connected. Now the integrated type of PVDs has been widely used in Tianjin Port for soft ground improvement, and a good result has been achieved.

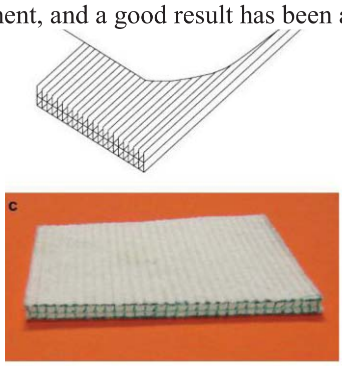


Fig. 7 Integrated PVD

At present, there are many geosynthetics enterprises in China, and the Chinese Geosynthetics Engineering Association has over 200 enterprise members, which are mainly located in two Provinces, i.e., Jiangsu and Shandong. 52 members of them have been approved by the government as national key enterprises. Ling town, so-called as “the famous geosynthetics city”, is the biggest production base in China. At present there are 156 geosynthetics enterprises and 320 production lines for all kinds of geogrids, and their products cover 90% of geosynthetics type. In 2011, Ling town produced 550,000 t geosynthetics in all, which accounts for 45 percent market share in China. Dezhou Orient Geosynthetics Enterprise Limited in the geosynthetics industrial park is the biggest geosynthetics enterprise in China till now.

Along with the improvement of production quality, the geosynthetics produced in China have stepped into the international market, and are exported to America, Japan, German, Australia, India and England etc. According to Chinese customs statistics, the total geosynthetics export in the first half of 2009 reached US $ 1.773 billion (Fig. 8), of which the geotextile export was US $ 22.66 million, the geomembrane export was US $ 166 million, and the geogrid export was US $ 1.584 billion.

Fig. 8 The total volume of trade of geosynthetics export

TECHNICAL STANDARDS AND GUIDES RELATED TO GEOSYNTHETICS IN CHINA

In order to standardize the production and application of geosynthetics, many technical standards related to geosynthetics have established. They generally include three categories:

(1) The first is the technical standard for engineering application. This kind of standards mainly involve the design and construction issues for the application of geosynthetics in various engineering projects, such as “Technical Standard for Application of Geosynthetics”(GB 50290-98), “Technical Code for Liner Systems of Municipal Solid Waste Landfill” (CJJ 113-2007), “Technical Code for Geosynthetic Application on Subgrade of Railway” (TB 10118-2006), “Standard for Application of Geosynthetics in Hydraulic and Hydro-power Engineering” (L/T225-1998), “Technical Specifications for Application of Geosynthetics in Highway” (JTJ/T019-1998), and “Technical Code for Application of Geosynthetics for Port and Waterway Engineering” (JTJ 239-2005).

(2) The second category of standards are the product standards. These standards mainly provide the classifications, specification, codes, technical requirements, quality testing methods etc., such as “Geosynthetics - Synthetic Filament Spun-bond and Needle-punched Nonwoven Geotextiles” (GB/T 17639-2008) and “Geosynthetics-Polyethylene Geomembrane” (GB/T 17643-2011).

(3) The third category of standards are the testing standards. At present, the testing standards we use are compiled mainly referring to the ISO and ASTM standards, such as “Testing Standard of Geosynthetics” (GB/T 17643-2012). In addition to technical standards, there are some guides and handbooks published in China, such as “Engineering Application Handbook of Geosynthetics” published by China Building Industry Press (2000), “The Principle and Application of Geosynthetics in Engineering” edited by Professor Bao Chenggang (2008) and so on. All the technical standards and publications have greatly promote the development of geosynthetic production and application in China.

APPLICATION OF GEOSYNTHETICS IN HIGHWAY AND RAILWAY ENGINEERING

Overview

Highway and railway engineering is one of main application fields of geosynthetics in China. The application involves not only a large amount of geosynthetics, but also various types of products. According to the incomplete statistics, each year over 600 million RMB market value of geosynthetics are used in highway engineering only. Geosynthetics have become the fourth one of the most used materials in highway engineering, following the cement, steel and asphalt. No highway is built without geosynthetics (Deng 2012).

The application of geosynthetics in highway and railway engineering solves numerous technical problems as following:

(1) Geosynthetic-reinforced retaining wall: reinforced retaining wall is the earliest scenario of geosynthetics application in roadway engineering Geogrid, polypropylene strip, geocell etc. are commonly used to construct the retaining wall at the steep slope of roadside;

(2) Control of bearing failure and differential settlement of road base: For this purpose, the geosynthetics such as geogrid, high-strength geotextile, geocell, and/or EPS block etc. are used on soft subgrade, at the connections between the filling and excavated sections, with different ground improvement methods, or between the old and expanded roads.

(3) Drainage for roadbed and sealing for tunnel: Geotextiles and geocomposites are usually placed on the subgrade to provide lateral drainage to edge drains. The commonly used sealing materials for tunnels include geomembrane, geotextile-geomembrane composite, asphalt-geomembrane and so on.

(4) Protection and revegetation of road side slope: geocell and three-dimensional geo-mat are commonly used to control erosion of side-slope and facilitate revegetation.

(5) Treatment for problematic soils such as expansive soils and saline soils: the common-used geosynthetics for this purpose includes geogrid, geotextile and geomembrane composite;

(6) Protection of permafrost roadbed: Thermal insulation materials such as polyurethane (PU) composite board and extruded polystyrene (XPS) board are commonly used for this purpose.

(7) Mitigation of cracking for pavement: For this purpose, the geosynthetics such as glass fiber grid, polyester glass fiber geotextile and nonwoven geotextile are placed at the bottom of asphalt or concrete pavement.

Four representative engineering projects are presented in the following sections to provide a further illustration of geosynthetic application in highway and railway engineering.

High Reinforced Retaining Wall in the Three Gorges Reservoir Area

The terrain and geological conditions of the Three Gorges reservoir area are very special with the high mountain and the steep slope. It is very difficult find enough flat land for building, so that the new town development for the relocation of immigrants from the Three Gorges reservoir area confronts great difficulties. In order to solve the problem, a great amount of high reinforced retaining walls were built at the resident land and along the roadside. The highest reinforced wall reaches a height of 60m (Lin and Weng 1999). Figure 9 shows a 57 m high reinforced retaining wall built along the mainroad to the new town of Wushan. The retaining wall has three levels, which are stagger. The wall height of the three levels is 27m, 18 m and 12cm, respectively.

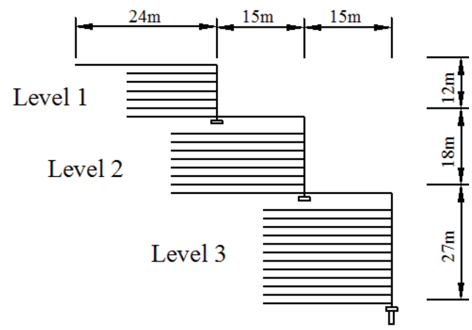


Fig. 9 57m-high reinforced wall

The high reinforced retaining wall was designed according to “Specifications for design of highway reinforced earth engineering” (JTJ015-91). The design work includes selection of reinforcement material, calculation of reinforcement spacing and length and analyses for the internal and external stability of the retaining wall, The compound geo-belt (CAT50022), being made of a monolayer steel wire string encapsulated by polypropylene band, was selected as the reinforcement material. The ultimate tensile strength of the geo-belt is 22kN, and the ultimate elongation is not more than 4.0%. The vertical spacing for the reinforcement is 0.5m. The backfill for the retaining wall is mainly from the material cut from the slope, and it is required the gravel content is 30% to 40%. The facing panel is constructed by cast-in-place concrete. 1m thick gravel liner was filled in between the facing panel and the backfill to provide drainage.

After 5 months from construction completion, local collapse was observed on the retaining wall located at the road section from 0K+380 to 0K+398. The collapse of road surface was about 6m deep, and the facing panel moved inward for about 1.5m. Investigation on the failure mechanism was carried out by excavation and visual inspection. It was found that rupture happened to most of the shallow geo-belts, and all the rupture points were close to the facing panel. The reinforced backfill did not lose its stability.

The main reason for the local collapse was the significant differential settlement between the facing panel and the relatively loose backfill. Field measurements showed that the different settlement was about 280 mm. As a result, the tensile stress of the geo-belts closing to the panel may exceed the ultimate tensile strength and the rupture took place.

In order to avoid the differential settlement between the panel and backfill, enough compaction should be done on the backfill, particularly for the section closing to the panel. A small-size vibrating roller is useful for the compaction of backfill closing to the panel. In addition, the filling of the 1 m thick gravel liner in between the panel and backfill should be done layer by layer. After each layer of gravel (40 cm thick) is filled, coarse sand layer is placed on the gravel layer. Then watering is carried out to make the coarse sand seep into the gravel layer to obtain a more dense state. These measures have been taken when building many high reinforced retaining walls in Yunnan province. There is no more failure happened.

Treatment of Expansive Soil Slope and Subgrade along the Nanning-Youyi Guan Highway

Nanning-Youyi Guan highway (NNYGH) is located in the autonomous region of Guangxi Zhuangzu, in south China. The NNYGH connects China with other countries of southern Asia (e.g., Vietnam) and is considered one of the continent's most important roadways. The highway is put into use on Dec. 28th, 2005. NNYGH is the successful case of using geosynthetics to treat troublesome expansive soils.

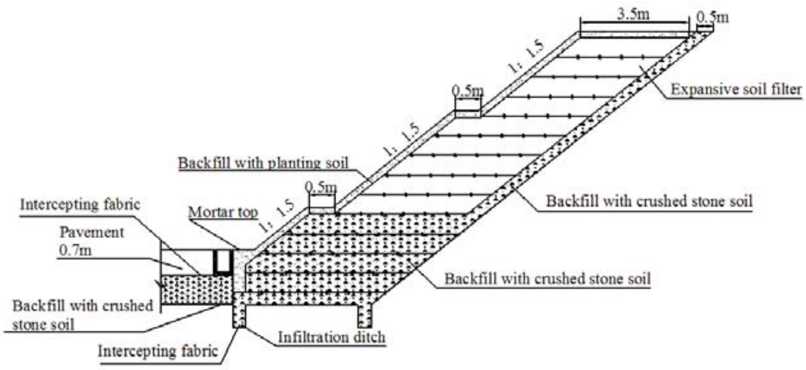


Fig. 10 Flexible supporting structure for cut slope in expansive soils (Yang et al. 2009)

It is well known that expansive soils undergo significant swelling and softening upon wetting, and appreciable shrinkage and cracking upon drying. The process repeats when the soils are subjected to seasonal wetting-drying cycles. The abundant cracks in the soils provide a path for rainwater infiltration. The properties result in a great difficulty of building infrastructures in expansive soils (Zhen and Yang 2004). 14 km long highway of the NNYGH is located within the Ningming basin, where expansive soil is continuously distributed. As part of the NNYGH's construction, roughly 2 million m^3 of expansive soil was to be excavated. The construction was started in March 2003. After a rainy season, excavated slopes in the expansive soils experienced landslides to different degrees. Some slopes remained unstable even after their grades had been flattened from a slope (H:V) of 1:1.5 to 1:3. As a result of the landslides, as much as 5 million m^3 of earth had to be excavated, greatly impeding the road's construction (Tan et al. 2006). Researchers at Changsha University of Science and Technology investigated 23 slopes that had experienced landslides, systematically analyzing the causes. After carrying out their studies and a series of tests, the research group developed and implemented new techniques for treating expansive soils. The primary approach of the new treatment techniques is to use geo-reinforcement to build a flexible retaining structure against the cut slope or fill embankment. The retaining structure not only provides a flexible support for the slope, but also prevents external moisture from entering the expansive soils. These methods addressed the technical difficulties associated with the slopes.

Table 1 Type and parameters of geogrid used in NNYGH (Yang et al. 2009)

Type	Ultimate tensile strength	Ultimate elongation /%	Tensile strength of 2% elongation	Tensile strength of 5% elongation
TGD G35	≥35kN	≤ 10%	≥10kN	≥20 kN

Figure 10 shows a typical layout of the flexible retaining structure against the cut slope in the expansive soils. It consists of four parts: reinforced retaining wall with backfill of expansive soil, internal drainage liner, and waterproof geomembrane at the top of slope and revegetation layer on the slope surface. The basic construction process involves excavating beyond the width of the designed slope, treating the foundation, setting up the drainage blanket and pipe, placing intercepting geogrids horizontally, backfilling and compacting layer by layer, covering the backfill with additional geogrids, and linking geogrids in the upper and lower layers with a connecting rod to form the slope face, and setting up the gravel drainage liner between the wall and cut slope, laying the geotextile-geomembrane composite on the top of slope, and setting up a revegetation layer on the slope surface with a help of the three-dimensional geonet. The type of geogrid used and its parameters are shown in Table 1.

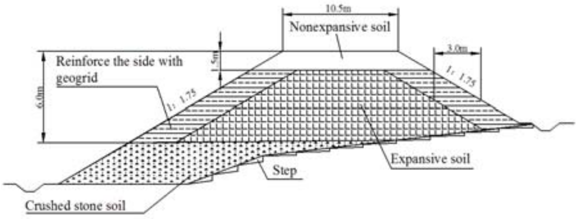


Fig. 11 Expansive soil filled embankment with side slopes reinforced by geogrid (Yang et al. 2009)

The flexible retaining structure was generally designed with a slope of 1:1.5 and a horizontal width of 3.5m. The height of the structure was over 2/3 of that of the cut slope. In this way, the reinforced structure enables the slope as a whole to resist the influence of soil pressure and deformation. The 3.5 m thick reinforced backfill together with the top cover of geomembrane prevents external moisture from entering the expansive soils, and have a resist to the weathering (Yang et al. 2007).

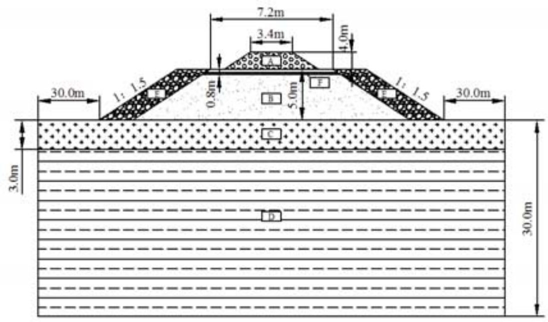
Similar technique and method was used to treat the embankment filled with expansive soils (see Fig. 11) along the NNYGH. The design height of embankment filled with expansive soils was less 6 m to limit the post-construction consolidation. 3m thickness of reinforced retaining structure was laid on the side slope of the embankment to prevent the expansive soil fill from weathering. 1.5 m thick fill of non-expansive soils was placed beneath the pavement. Waterproof geomembrane was laid on the expansive soil fill to prevent water infiltration.

At the time of Sep. 2006, there were totally 14 cut slopes and 4.28 km long embankment treated by the new technique. After several years of wetting and drying cycles, all the slopes and embankments keep stable for the time being. Compared with the rigid retaining wall, the flexible retaining structure with geogrid reinforcement is easier and less expensive to construct. For example, a 7 m high reinforced structure was constructed to stabilize a 10 m high, 300 m long cut slope along the NNYGH. Construction was completed in just 20 days at a cost of less than U.S.$120,000. However, had a rigid retaining wall been constructed and the slope covered with masonry pitching, the project would probably have cost more than U.S.$147,000 and taken more than a month. The new treatment technique provides a cost-effective approach for the treatment of expansive soil slope and subgrade along highways (Zheng 2010).

Protection of Permafrost Subgrade for Qinghai-Tibet Railway

Qinghai-Tibet Railway is the highest and longest plateau railway in the world. It starts from Xining, Qinghai and ends in Lhasa with a total length of 1965 km. The part from Xining to Golmud (845km) was put into use in 1984, and the construction of the other part from Golmud to Lhasa (1118km) began in 2001 and was completed in 2006.

965 km of the railway from Golmud to Lhasa is located on the Qinghai-Tibet Plateau with an altitude over 4000m high. It is permafrost area with a extreme climate and hydrogeololgy environment. The annual average temperature is -2 to -6°C, the extreme maximum air temperature is 25°C, and the extreme minimum air temperature is -36 to -45°C. Comparing with the common railway project, the construction of Qinghai-Tibet Railway confronts many technical difficulties associated with the permafrost deposit (Ge et al. 2004).



A: Embankment; B: Insulation Layer; C:Permafrost; D: Foundation

Fig. 12 Railway embankment treated by flaky stone layer and heat insulation method

One of the key technical difficulties for the Qinghai-Tibet Railway construction on the permafrost area is the thawing-induced settlement. The elevated railway embankment results in a change in heat exchanging condition between earth and atmosphere. The side slope of embankment becomes the main heat transfer. Field measurement indicates that there is heat accumulation in the embankment, and the temperature of the permafrost foundation beneath the embankment tends to increase after the completion of construction. The increase in temperature results in the thawing-induced settlement of subgrade. The construction of railway embankment will also change the surface runoff and groundwater movement. If there is not effective drainage system, the accumulation of surface and underground water will result in temperature increase and thawing in the permafrost foundation. In addition, the global warming seems to be inevitable, and the Qinghai-Tibet Plateau is the foreboding area of global warming. The global warming will aggravate the thawing-induced settlement problem of the Qinghai-Tibet Railway (Wu and Tong 1995, Yu et al. 2002).

Heat insulation method is commonly used to protect the frost-susceptible ground beneath the embankment (Sun 2003). The method is implemented by laying a layer of low thermal conductivity materials in the roadbed. Geofoam boards (PU and XPS) were used as heat insulation layer for the Qinghai-Tibet Railway construction. Field tests demonstrated that the insulation effect of 6cm thick PU geofoam board was equivalent with 0.8m thick granular material filling (Nie 2003).

Recent field evidences show the heat insulation method is not enough solve the permafrost problem associated with the Qinghai-Tibet Railway construction. The heat insulation layer is designed to isolate the permafrost foundation from external heat sources, but it also slows down the dissipation of the accumulated heat in the permafrost foundation. The thawing-induced settlement was still observed for the early-built Qinghai-Tibet railway (from Xining to Golmud) even for the section treated by the heat insulation methods (Li 2003). In order to overcome the technical difficulties, active cooling techniques were developed and implemented for the protection of the permafrost foundation along the newly-built Qinghai-Tibet railway. The active cooling techniques used include: (1) air cooling system by placing a layer of rubble fill at the bottom of embankment or on the side slope; (2) ventilation tubes installed near the bottom of embankment; (3) thermosyphons erecting in the embankment. Figure 12 shows an implementation of the air cooling technique combined with the heat insulation method in an embankment of the newly-built Qinghai-Tibet railway. The rubble fill placed on the side slope of embankment has an air cooling effect. During cold seasons when the wind is usually strong on the Qinghai-Tibet Plateau, the inclined rubble fill with a large void space can promote air circulation and facilitate the dissipation of the accumulated heat. During the warm seasons with a weak wind, the rubble fill acts as a heat insulation layer to isolate the embankment from external heat sources. A layer of heat insulation is placed beneath the pavement. Field monitoring demonstrated that the active cooling technique combined with the heat insulation method is very effective because it takes the advantage of the climate characteristic on the Qinghai-Tibet Plateau (Sun 2005).

Table 2 Geosynthetics used in the project of Qinghai-Tibet Railway

Type	Material	Specification	Size/density	Amount	Application
Geogrid	Warp knitted polyester fibre	PGA30	25×25×5.3mm	347×10^4 m^2	Reinforcement in embankment and cut slop
	Warp knitted high tenacity polyester fibre	PGA50	25×25×5.3mm	340×10^4 m^2	Reinforcement in retaining wall
geotextile-geomembrane composite	HDPE	Two layers of geotextiles with one geomembrane layer	750g/m^2	180×10^4 m^2	Prevent water infiltration and capillary rise in the frozen roadbed
Geofoam board		PU、XPS		25.6×10^4 m^2	Heat insulation in low embankment and tunnel
Water proof coiled Plate		SPRE、SBS		129×10^4 m^2	Bottom of over-fall, lining of tunnel
Geocell			400×100×1.1mm	1300 m^2	Slope protection
Geotextile					Erosion control

In addition to geofoam board, there are some other types of geosynthetics used in the Qinghai-Tibet Railway. They include geotextiles, geogrids, geomembranes, geocells etc. Their specification, usage volume and functions are showed in Table 2.

Geosynthetic - Reinforced Pile - Supported embankments used in Wuhan-Guangzhou High-Sspeed Railway

Wuhan-Guangzhou high-speed railway is the first longest and highest standard traffic line for passengers. Its total length is 1068.8 km, passing through Hubei, Hunan and Guangdong provinces. The design speed is 350km/h.

The railway goes through the tropical and subtropics pluvial region mainly with a low-hill terrain. Along the railway there are deep soft ground, loose soil and clayey soil deposit. For example, the 21.3km line from Shaoguan to Huadu is widely distributed with soft and loose soil deposit (Cui et al. 2008). According to "Contempory Regulation for the Design of Beijing-Shanghai High-speed Railway" (China Railway Publishing House 2003), the post-construction settlement of roadbed should be controlled to be less than 2cm for the railway line with a speed of 350km/h. For the railway line located on the soft soil deposit, the using of traditional ground improvement method such as the preloading with PVDs can not meet the requirement. Therefore, geosynthetic-reinforced pile-supported embankments were used to control the post-construction settlement.

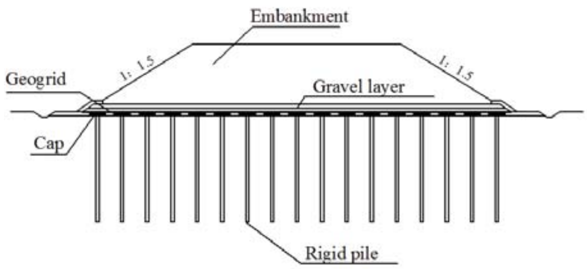


Fig. 13 Pile-supported embankment with basal reinforcement

Figure 13 shows a set-up of the pile-supported embankment with basal reinforcement. It consists of three parts: i) a certain thick of embankment; ii) geogrid reinforced mattress near the bottom of embankment; iii) piles with cap or columns with head in the soft ground. The commonly used piles and columns are driven piles and cement-fly ash-gravel columns, respectively. The total length of this kind of piles or columns used for the Wuhan-Guangzhou high-speed railway is 71.38×10^4 meters (Liu and Zhan 2011). The geosynthetic-reinforced pile-supported structure has the advantage of short construction period, cost-effective, easy control of construction quality (Bao 2008).

The key mechanisms associated with the pile-supported structure include soil arching due to different settlement between pile cap and soft soil, stress redistribution due to modulus difference between pile and soil, and tensioned membrane effect by geosynthetic reinforcement. The experimental study performed by Chen et al. (2008a) demonstrated that the embankment on the pile caps should be thick enough to form a complete soil arching. Otherwise, the incomplete soil arching will result in uneven road surface. Chen et al. (2008b) suggested that the thickness of embankment should be greater that half of the spacing to guarantee the formation of a complete soil arching.

In addition to the geogrid used in the pile-supported embankment, there are some other types of geosynthetics used in the Wuhan-Guangzhou high-speed railway. They include geotextile filters, geotextile-geomembrane composites, three-dimensional geonets etc.

APPLICATION OF GEOSYNTHETICS IN HYDRAULIC AND COASTAL ENGINEERING

Overview

In China, the application of geosynthetics in hydraulic and coastal engineering began in 1974 and has been steadily developing for almost 40 years. Nowadays, geosynthetics have been widely used in wharfs, waterways, inland rivers, dams, land reclamation and other projects, and have played important roles. The geosynthetics commonly used in hydraulic and coastal engineering include geotextile filters, reinforced cushions, reinforced banks, fill-containing geosystems, mortar-filled mattresses, geotextile revetment for erosion protection, plastic vertical drains, geomembrane barriers, etc. They are mainly used in the following aspects:

(1) The geotextile filters are most commonly applied in hydraulic and coastal engineering for wharfs, revetments, waterway repairs, dams, and land reclamation. The materials of filters should have the three functions of soil protection, drainage and anti-clogging, and the materials include knitted fabric, woven fabric and non-woven geotextiles.

(2) The reinforced cushion and the reinforced bank: The reinforced cushion is mainly composed of geotextiles and a coarse aggregate cushion layer. It is often laid between the dam and the soft base to increase the integrity and stability of the dam. The reinforced bank is a retaining structure mainly composed of panels, reinforced materials, backfill and other components, and is frequently used for erosion control of inland waterways and small wharfs. The reinforced materials used include geotextiles, geogrids, reinforced belts, etc.

(3) The fill-containing geosystem and mortar-filled mattress: In both cases, the geotextile fabrics are sewn into bags and filled with materials. The fill-containing geosystem is generally filled with sand, sand mixture, etc. In recent years, they are also filled with muddy soils solidified by cement and other materials (Tian et al. 2002), which are commonly used as dike materials. The mortar-filled mattress are filled with concrete and commonly used for erosion control of dam and dike surfaces.

(4) The geotexitle revetment: It is usually made by sewing the geotextile fabrics into a certain size of mats and fixing on the mats with heavy objects such

as sand-filled tubes, interlocked concrete blocks, etc. They have good flexibility, continuity and integrity, are adaptable to the terrian of riverbeds, and are commonly used to protect the bottoms from erosion and to stabilize beaches. The soft mat materials can be made of knitted fabric, woven faric, nonwoven geotextiles or geotextile composites. When used they should satisfy the requirements of soil keeping, high permeability and strength.

(5) The plastic vertical drains: These are mainly used for the reinforcement of the soft soil foundation under hydraulic and coastal infrastructures. They shorten the drainage paths and accelerate the consolidation of soft foundations. In general, they are used in combination with surcharg loading, vacuum preloading, etc.

(6) The geomembranes: These mainly have a sealing effect. They are used in engineering independently, or after being combined with geotextiles, into a geotextile-geomembrane composite. The application of geotextile-geomembrane composites in hydraulic and coastal engineering in China is relatively common. They are commonly used for leakage prevention around cannels, reservoirs, pools, water gates etc. The single layer of geomembrane is more frequently used as vacuum preloading sealing membrane.

In order to regulate the application of geosynthetics in hydraulic and coastal engineering, the relevant departments formulated the Technical Specification for the "Application of Geotextiles in Water Transport Engineering" (JTJ/T 239-98) in 1998, which was revised in 2005 to the "Technical Specification for the Application of Geosynthetics in Water Transport Engineering" (JTJ 239-2005). Below, with illustrations from 3 representative engineering projects, this paper will further expound the main progress in the recent 20 years of the application of geosynthetics in hydraulic and coastal engineering in China.

Erosion Control for the First-Stage Project of the Deep Waterway Channel Harnessing of the Yangtze River Estuary

Introdution of project

The Yangtze River estuary is a large sandy river mouth. Every year, over 0.4 billion tons of upstream sourced sediments are deposited and migrated within the estuary area. After years of historical development, shallow sections of the waterway had a water depth of only 5.5 to 6.0m. This became a particular hindrance to various sections of the waterway to Shanghai Harbor. In 1975, the depth was dredged from 5.8m to 7.0m, enabling seagoing vessels of up to 20,000 ton class to ride the tide in and out of Shanghai Harbor. In 1995, Shanghai decided to carry out further harnessing and dredging of the waterway to the depth of 12.5m. This enabled 100,000 ton vessels to navigate in and out of the channel at the Yangtze River Estuary with the tide. The whole project was implemented in three phases. The first phase included the outlet, the 16.5km long north guide levee, the 20km long south guide levee, 6 spur dikes with a total length of 9km, and many aspects of dredging engineering. The goal of the first-phase project was to reach a water depth of 8.5m (Cai and Fan 2009). It was started in January 1998 and finished at the end of 2000.

At the Yangtze River Estuary the breeze is strong, the waves high, and the flow significant. Therefore, in the construction process of the south and north guide levees and spur dikes, erosion control of the river bed, the levee body and side slope remains one of the key technical problems. Geotextiles have played an important role in solving these technical problems (Zhu et al. 1999). This project has used a total of 14 million m^2 of geotextiles and, in combination with other types of geosynthetics, a variety of innovative protective structures have been developed. These include: (1) geotextile revetments; (2) fill-containing geosystems; and (3) mortar-filled mattresses. These innovative structures have many functions such as separation, filtration, drainage, protection and others, which can bear high velocity flow and violent typhoon conditions, and play an indispensible role in guaranteeing the success of the Yangtze River estuary harnessing project. The use of geotextile revetments and mortar-filled mattresses for erosion control in the construction of the south and north guide levees is expounded below. The use of fill-containing geosystems will be presented in the next section.

Geotextile revetment for bed protection

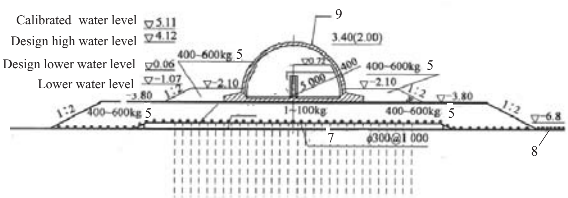
In the construction process of the south and north guide levees (totally 36.5km long), geotextile revetments are adopted for erosion control of river bed. The structures of the south and north guide levees are shown in Figs. 14a,b. The north guide levee is a breakwater whose core is constructed with sand-filled geo-tubes, a needle punched non-woven geotextile is used for a filter, and mortar-filled mattress is used as a coping structure. The south guide levee adopts a hemispherical-structure sitting on the rubble-mound foundation. Geotextile revetments are laid at the bottom of the south and north guide levees. The geotextile revetments for bed protection have three main types:

(1) Geotextile revetments with sand-filled ribs are used for the levee bottom (the sand-filled ribs are 300 mm in diameter and 1000 to 1500 mm in spacing) and the section extends beyond the levee (the ribs are 300 mm in diameter and 500mm in spacing). The revetment adopts a needle punched composite geotextile. This is made from the needle

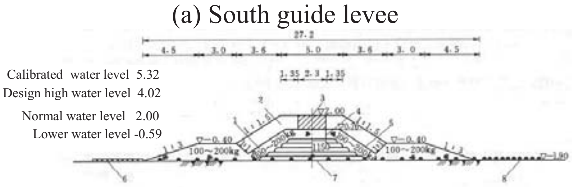
punched combined machining of high-strength polypropylene filament woven geotextile (230g/m^2) and polyethylene ferephthlate staple nonwoven geotextile (150g/m^2). The sand-filled ribs, being made of long geotextile tube (300mm in diameter), act as a loading for the revetment. The ribs are fixed on the revetments.

(2) Geotextile revetments with concrete interlocked blocks are used for protecting the extension beyond the levee bottom. These revetments use needle punched composite geotextiles together with the interlocked concrete blocks and reinforced belts which are jointed together to act as revetment loading. The size of a single interlocking block is 4.5m×9.5m, 4m×5m, etc. These blocks are a little more expensive than the sand-filled ribs, but more adaptable to multidirectional deformation of river bed. At the same time, they can also be applied to the places where the erosion is more serious and the river bed is deep.

(3) Hybrid geotextile revetment: Hybrid geotextile revetments have both of the above characteristics and are frequently used for the bed protection in the first phase of a project.



(a) South guide levee



(b) North guide levee

1: 450g/m^2 nonwoven geotextile filter; 2: 2t Locked concreter block; 3: C20 Mortar-filled mattress; 4:450g/m^2 nonwoven geotextiles; 5: Rubble cushion; 6: Geotextile revetment with interlocked concrete blocks; 7: Geotextile revetment with sand-filled rib (1000-1500 mm in spacing); 8: Geotextile revetment with sand-filled rib (500 mm in spacing); 9: Semicircle caissons of precast reinforced concrete

Fig. 14 Structure of the guide levee for the first-phase project of the deep waterway harnessing

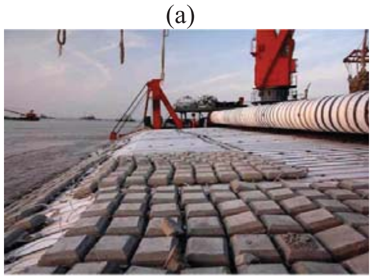
The length of the above geotextile revetment shall be determined according to levee width and the required extension beyong the levee. The maximum length is 140m. The width of the geotextile revetment shall be decided based on the platform of the revetment laying ship. The maximum width is 40m. Below is some experience in geotextile revetment design and construction:

1. Combining the advantage of high strength and small elongation of woven geotextile and the merit as a good filter of non-woven geotextile, the needle punched composite geotextile revetment functions well in erosion control. The pore diameter of the needle punched composite geotextile used is 0.07 to 0.1 mm (O95 is 0.07 mm), and it has an excellent filter function for the sandy soil sediment (d85 is 0.13 to 0.15mm, d15 is 0.05 to 0.08mm). The thickness of the composite geotextile is above 2mm, and its permeability is great than 10^{-2} cm/s.

2. Reinforced belts are installed in the revetment in the direction perpendicular to the axis of the dike in order to fix the sand-filled tube and concrete interlocked blocks in the geotextile revetment, and to uniformly distribute the stress at the levee bottom.

3. The laying of the revetment is a very difficult and important task. There are two kinds of purposely-designed laying ships, 600t and 3000t. The width of the working platform is 18 to 40m, on which conveyance devices and large-scale steel cylinders used for geotextile revetment rolling and laying. In addition, the ships are equipped with a GPS system to determine the exact laying position (Fig. 15).

(a)



(b)

Fig. 15 Laying ships working for geotextile revetment

The economic benefit brought by the application of the geotextile revetment for bed protection is considerable. As has been calculated, the unit price of geotextile revetment with sand-filled ribs is about 50% of that of the geotextile revetment covered with rubbles, and the unit price of the geotextile revetment with interlocked concrete blocks is about 80% of that of the geotextile revetment with rubbles. Compared with that of a wood revetment, the benefit is even more significant.

Mortar-filled mattresses for face protection

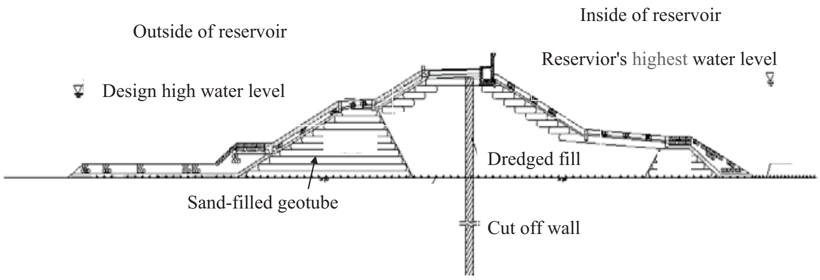
The initial segment of the north levee (3 km long) was a rubble dike with a hight of 3m. After the dike foundation had been settled stable, the 40 cm thick Mortar-filled mattresses were used for slope protection. The rest of the north levee used sand-filled geo-tubes to construct the dike core, rubbles to protect the slope, and mortar-filled mattresses for capping (as shown in Fig. 15). The single mortar-filled mattress was 64cm thick and 2.3m wide. The capping of the north levee was 1.28m thick, consisting of two layers of mortar-filled mattresses. The geotextile used in the mattresses was the double-layer PP woven cloth of 600g/m^2 to 700g/m^2, with a tensile strength of 2.5 kN/m and pore diameter of 0.084mm to 2.0mm. The grade for the concrete filling is C20.

Fill-Containing Geosystems used for the Construction the Qingcaosha Reservoir Dike at the Yangtze River Estuary

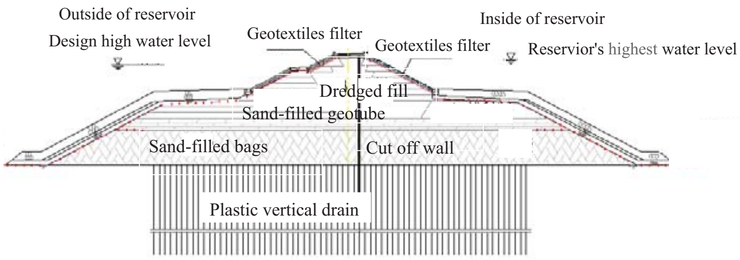
Located in the tidal zone of the Yangtze river estuary, Qingcaosha Reservoir is a fresh water storage and salt water free reservoir. With an effective storage capacity of 435 million m^3 and serving 10 million people, the reservoir is the largest water source project of Shanghai. Qingcaosha Reservoir, surrounded by newly-constructed dikes, covers a total area of 66 km^2, and its ideal design water level is 7.00m for water storage. The surrounding dike consists of the south dike, west dike, north dike, east dike and the Changxing Island seawall with a total length of 48.4km. Of these the north dike and the east dike are both newly constructed and 22km long in total. Other engineering work included the heightening and strengthening of the older dikes.

The project is located at the front zone of Yangtse River Estuary delta with a great thickness of loose sediment of the Holocene series of the Quaternary System. The deposit (from top to deep) mainly consists of sandy silt, silt, silty clay, muddy and silty clay. The designed water level inside the reservoir dike is 7.0m, and the designed highest tide level outside the dike is 6.0m. This scenario is significantly different from the conventional sea dike (seawall), and the reservoir dike is subjected to a bidirectional hydraulic head of 6.0m to 7.0m. The dike foundation and body are to be built by the shallow sediments (i.e., silts and silty sands) with a weak seepage stability, and hence seepage-induced failure is likely. Seepage control is the key technical problem in the construction of the surrounding dike of the reservoir.

In this project, the above technical problem was solved by adopting fill-contained geosystems for the construction of dikes (Zhang and Chen 2009). As for the shoal area, both sides of the dike were constructed by sand-filled geotubes. The middle and upper part of the dike body are formed by pump filling of the dradged materials (Fig. 16(a)). In the area of a water depth greater than 6m, the construction with sand-filled geotubes becomes more difficult. Therefore, the lower part of the dike body was filled by droping sand-filled bags. Then, sand-filled geotubes were used to fill and construct both sides of the dike. At last, pump filling of dredged materials was adopted to form the middle and upper part of the dike body (Fig.16 (b)) (Liu and Wu 2011). Geotubes were made of 150 to 175g/m^2 polypropylene woven fabric, 20-40m in length and 3 to 4m in width (Fig. 17). The sand-filled bags are made of polypropylene filament woven geotextile of 260g/m^2, and the common size is 4×6m (Fig. 18). It is required that the fill-contained geosystems should have good soil retention, drainage, and anti-aging abilities. In addition they should be able to withstand the filling pressure. The geotextile used for the fill-contained geosystems of the Qingcaosha Reservoir project amounts to be above 65 million m^2.



(a) Structure of dike on the the shoal area



(b) Structure of dike the area of a water depth greater than 6m

Fig. 16 Geotextile pump filling of the dike of Qingcaosha Reservoir Engineering at the Yangtze River Estuary

In the Qingcaosha Reservoir project, the technique of fill-contained geosystems was used for the construction of the surrounding dikes, which had achieved good economic and environmental benefits: (1) saving of resources through the use of the dradged materials from the river bed and reducing the consumption of granular material resources from the land; (2) avoiding a destruction of the ecological environment caused by the mining of granular materials; (3) the technique is suitable for the dike construction in the water without the requirement of a cofferdam; (4) the construction technique is not affected by tide, rainfall etc; (5) time saving as many tasks can be done simultaneously; (6) significant reduction of investment.

In a manner similar to that of the deep waterway harnessing project at the Yangtze Estuary, geotextile revetments were laid at the bottom of the dike surrounding the Qingchaosha reservoir. These were used for the erosion control of river bed during the construction and the protection of the river bed closing to the dike after completion of construction. As mentioned previously, the reservoir dike was subjected to the bidirectional hydraulic head of 6-7 m. To prevent soil piping and loss, geotextile filters were placed on both the inner and the outer side slopes of the dike. To control seepage, in the middle of the dike, cut-off wall was installed and extended to the low permeable stratum. For some local areas, geotextile-geomembrane composites were laid for seepage control. In addition, plastic vertical drains (PVDs) were used to accelerate the consolidation of the silty clay foundation under the dike. The type and amount of the geosynthetic materials used for the Qingcaosha Reservoir Project is shown in Table 3.

Fig. 17 Sand-filled geotube

Fig. 18 Sand-filled bag

Table 3 Type and amount of the geosynthetic materials used for the Qingcaosha Reservoir Project

Name of the geosynthetics	Unit	Usage
150-180 g/m^2 knitted fabric	10 thousand m^2	3202
200-1300 g/m^2 woven fabric	10 thousand m^2	2023
380 g/m^2 composite fabric	10 thousand m^2	934
150 g/m^2 non-woven fabric	10 thousand m^2	362
Geotextile-geomembrane composite	10 thousand m^2	3.4
125 g/m^2 knitted cloth bag	10 thousand	3520
Polypropylene nylon rope (16mm)	Ton	1665
Reinforced geogrid	10 thousand m^2	2.7
Plastic vertical drain	10 thousand m^2	400

Drainage Cushion in the Liner of the Yellow River-Crossing Tunnel for the Middle Route of the South-to-North Water Transfer Project

The South-to-North Water Transfer Project in China aims to transfer the water of the Yangtze river basin in the south to the north water-deficient areas. Currently, it is the world's largest water transfer project. It includes an eastern route, a middle route and a western route. In the middle route project, water is diverted from the Danjiangkou reservoir at the upper reach of Hanjiang river. A large water transfer canal is built by excavation or filling. The canal goes through the provinces of Hubei, Henan and Hebei, and reaches Beijing and Tianjing at the end. Near Zhengzhou of Henan province, the water crosses the Yellow River through two tunnels. The total length of the canal is 1,277 kilometer, the midline route will provide life and industrial water resource for over 20 cities in Henan and Hebei province, Beijing and Tianjin. The annual water conveyance volume is expected to reach 130 billion cubic meters per year.

In the middle route of the South-to-North Water Transfer Project, the section crossing the Yellow river uses 2 tunnels of 8.2m in diameter for water conveyance. The tunnels are deeply (40m) buried in the thick alluvium at the bottom of the Yellow River. The alluvium layer is mainly composed of sandy soil with a high permeability. The Yellow River-crossing tunnels use double lining systems, of which the outer layer involves the assembling of pre-cast concrete segments, and the inner layer is constructed by a cast-in-place reinforced concrete (Fig. 19). The inner and outer liners are separated by an interlayer cushion, so that they can work independently (Ding et al. 2009). The outer liner bears the surrounding soil pressure, outer water pressure and the additional load caused by the erosion of the river bed. The internal water pressure is mainly born by the inner liner. A geotextile-geomembrane composite is generally used for the interlayer cushion to meet the requirement of a limited thickness. The geotextile-geomembrane composite consists of three layers, including a geomembrane layer in the middle and a geotextile layer on both sides. The total thickness of the three layers is less than 10mm.

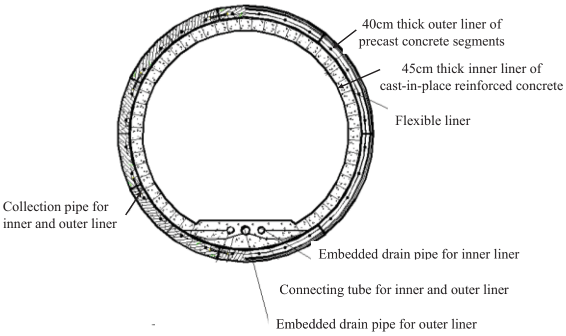


Fig. 19 Structure of yellow river-crossing tunnel liner

The middle geomembrane in the composite is an ideal sealing material and the geotextiles on both sides can provide functions of drainage and protection. Thus the geotextile-geomembrane composite has a wide range of application in the hydraulic engineering and tunnel engineering in China. However, the inner liner of the Yellow river crossing tunnels is constructed by the cast-in-place concrete. The cast construction may have significant influence on the drainage ability of the geotextiles in the cushion layer: (1) The geotextiles may be compressed by the tunnel stress, resulting in a decrease of their permeability; (2) Concrete grout may clog the geotextile due to the precipitation of hydrated calcium silicate gel; (3) Concrete casting and depression of the high pressure water may generate bubbles. The bubbles fill the pores of geotextiles and reduce the water permeability. The researchers have carried out a large number of permeability tests to investigate the three factors. The test results show that the first two factors above will cause the permeability of geotextile to decrease from the initial 10^{-1}cm/s to 10^{-2}cm/s. The influence of the third factor is much more significant. When the geotextile is filled a lot of bubbles, its water permeability can be decreased to the magnitude of 10^{-4}cm/s~10^{-5}cm/s, which will significantly affect the geotextile's drainage ability.

Fig. 20 New type anti-clogging geotextile-geonet Composite

Therefore, through selection tests, researchers now recommend a new type of anti-clogging geotextile-geomembrane composite material. The middle of the composite material is still a geomembrane, while the geotextiles at both sides are replaced by the geotextile-geonet composites, as shown in Fig. 20. The core of the geotextile-geonet composite is made of three-layer plastic grid. The pore size of the plastic grid is significantly greater than the bubble size, and the discharge area is large. This means that bubble clogging can be effectively prevented. The plastic grid is high in strength and stiffness, so the influence of the normal pressure from the tunnel liner on the permeability of the composite is small. In addition, the geotextiles on both sides of the plastic grid serves as a filter layer to prevent a clogging caused by the concrete grout. Lab and field model tests have shown that under the working conditions of the Yellow River-crossing tunnel, the permeability of the new geotextile-geomembrane composite material can be maintained at 100 to 10^{-1}cm/s. It is superior to the traditional geotextile-geomembrane composite. The new type of geotextile-geomembrane composite material has already been used in the whole line of the Yellow River-crossing tunnels.

APPLICATION OF GEOSYNTHETICS IN LANDFILL ENGINEERING

Overview

At present, the generation of municipal solid wastes (MSWs) in China is over 240 million tons per year, and keeps increasing by 8~15% per year. The landfill disposal takes 90.5% of the whole amount of MSW disposal. Landfill is the inevitable choice and the dominant way to dispose MSWs in China in the following decades. The first national-wide survey of pollution source in 2007 showed that there were 2,353 MSW disposal facilities, and half of them are landfills.

According to "Technical Code for Municipal Solid Waste Sanitary Landfill"(CJJ17-2004), it is required that the sanitary landfill should consist of barrier system, leachate drainage system, gas collection and control system and cover system etc. At present, various products of geosynthetics have been widely used in the above-mentioned systems of MSW landfills. Their main functions include sealing liner, filtering, separation, drainage, gas venting, reinforcement, protection, erosion control, revegetation and so on. Therein, the application of geosynthetics in liner system and cover system are most widely. There are five types of liner structures recommended in "Technical Code for Liner System of Municipal Solid Waste Landfill". Four types of them include geosynthetics as material. The covering systems recommended by "Technical Code for Municipal Solid Waste Sanitary Landfill Closure" also include geosynthetics. The main application of geosynthetics in MSW landfills can be summarized as the following three aspects (Qian et al. 2001):

(I) Barrier system: At present, the basal barrier systems commonly-used for MSW landfills in China are composite liners, which is made up of the geosynthetics such as HDPE geomembrane (GM), geosynthetic clay liner (GCL), geotextile (GT) and geogrid (GG). The geomembrane and GCL are low in hydraulic conductivity and act as a sealing layer. The geotextiles are placed on or beneath the geomembrane, acting as a protection layer. The geogrid, having a high tensile strength and stiffness, can be used as a reinforcing layer on the soft foundation or a protection layer on the inclined liner against the tension induced by the downslope movement of waste body. Prior to 1990s, many simple landfills did not have a basal barrier system. Vertical barrier is one of the most commonly-used measures of pollution control for the unsafe landfills. Vertical barrier with HDPE membrane has been used in China recently.

(II) Cover system. Geosynthetics used for cover system include LLDPE geomembrane, GCL, GT, and geotextile-geonet composite. The main effect of LLDPE geomembrane and GCL is to prevent rainfall infiltration into the landfill. GT can protect LLDPE geomembrane and also acts as a filter layer or a medium for gas venting. Once one filling unit is completed, temporary cover system made of LLDPE geomembrane or waterproof geotextile will be placed. This temporary cover system is convenient to operate, and can save the storage capacity of landfill compared with a soil cover. Geotextile-geonet composite is widely used as surface water collection and removal on the sealing layer of cover system.

(III) Drainage system for leachate and landfill gas. Geotextile is commonly used as filtration or separation layer in leachate drainage layer/trench and landfill gas collection wells. For the sloping foundation where it is hard to lay the gravel drainage layer, Geotextile-geonet composite can be used for the leachate drainage system. Besides the above-mentioned geosynthetics, HDPE pipes are also widely used in drainage system.

Composite Liner System of Xiaping Landfill in Shenzhen

The Xiaping landfill in Shenzhen is one of the first sanitary landfills with a basal liner in China. At present, it disposes 3,500 tons wastes per day, which accounts for 32% of the wastes in Shenzhen. Since its operation in 1997, it has accumulatively disposed 9.8 million tons of municipal solid wastes, 800,000 tons of municipal sludge. The disposed wastes in the landfill is 60m in thickness, and covers an area of 225,000 m^2

The Xiaping landfill in Shenzhen is China's first landfill designed according to the international standard of landfill barriers. Fig.21 shows the basal liner system at the bottom and along the sloping ground. It is composite liner involving various types of geosynthetics. The bottom liner system consists of the following parts (from bottom to top): 40cm sand layer with collection pipes installed at the groundwater drainage trench, nonwoven geotextile protection layer, imported HDPE geomembrane (partial area covered by both-side textured GM, and the rest covered by single-side textured membrane with the rough side laid downwards), nonwoven geotextile protection layer, 50cm compacted clay layer, nonwoven geotextile separation layer, and 40cm leachate drainage layer. On the sloping ground, the liner system consists of the following parts (from bottom to top): nonwoven geotextile protection layer, imported HDPE geomembrane (the same texture setting as above), and nonwoven geotextile protection layer.

As for environmental protection, the application of geosynthetics in the liner system solves the leachate pollution problem well. However, as the interface shear strength and tensile strength of geosynthetics are relatively small, two major geotechnical engineering problems may arise during the operation of landfill (Lin 2009): (1) landfill failure along the weak interface of composite liner system; (2) tensile failure of the liner system on the sloping ground due to gravity and waste settlement.

On the basis of experimental results and practical experience, the basal liner used at the Xiaping landfill has two weak interfaces, i.e., the HDPE membrane/geotextile interface and the compacted clay/geotextile interface. Landfill slip may happen along these two interfaces, especially for the Xiaping landfill with a high leachate mound. After continuous heavy rainfall in June, 2008, waste slip was observed on the landfill slope (see Fig. 22). Field

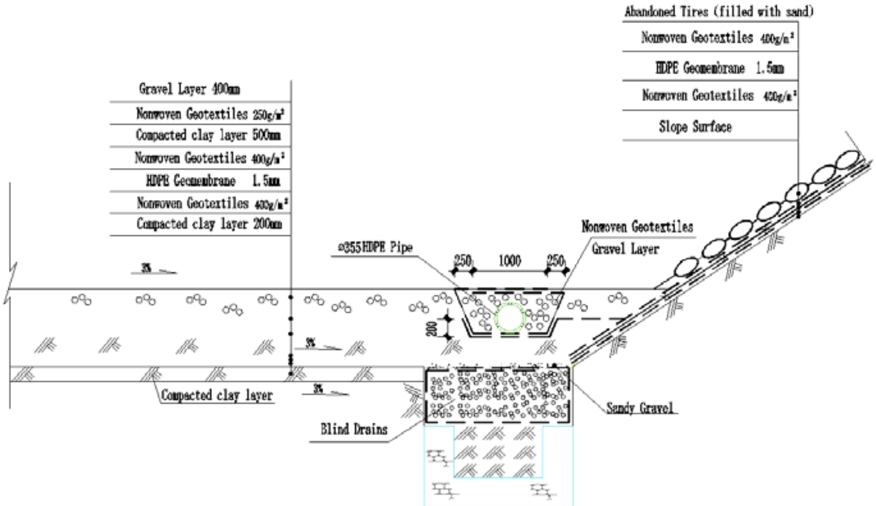


Fig. 21 The base liner system at the landfill bottom and slope of Shenzhen landfill

monitoring of waste movement indicated that deep slip along the weak interface of the basal liner was the failure mode (Fig. 23, Zhan et al. 2010). It was found that the slip area was corresponding to the sloping ground with a relatively large inclination (about 18°) at the bottom. The monitoring data also showed a correlation between the downslope displacement and the leachate level in the slope. Horizontal displacement significantly decreased after a drawdown of leachate level by pumping. Thus, the high leachate level in the slope is a key factor triggering the waste slide (Chen et al. 2010). According to "Technical Code for Geotechnical Engineering of Municipal Solid Waste Sanitary Landfills" (CJJ176-2012), reshaping the sloping ground and waste body, using liner structures with strong interfaces, and drawing down the leachate level will enhance the landfill stability.

Fig. 22 Local failure of landfill slope induced by a heavy rainfall

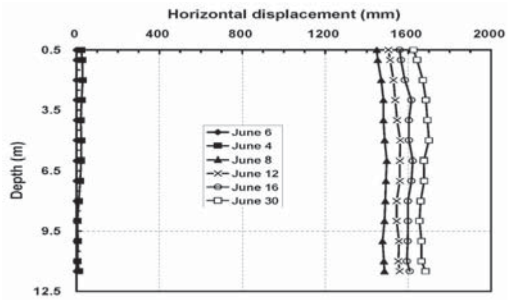


Fig. 23 Down-slope displacement measured by a inclinometer installed in the slope of Xiaping landfill

Fig. 24 Tension and failure of liner system induced by settlement and downslope movement of waste body

Xiaping Landfill in Shenzhen is a typical valley type landfill, and this is the case for most of the landfills in China. The sloping ground on both sides of the valley is very steep (mostly over 45°). Tensile failure will be caused in the liner system laid upon the sloping ground by the weight of waste body and waste settlement. At present, the relevant technical standards in China require the gradient of the sloping ground should be reshaped to an inclination less than 1:2. However, it is hard to meet this requirement for most of the landfills located in a valley. Landfill designers in China usually choose single-side textured geomembrane (with the rough side downward) on the sloping ground. In this way, the tension in geomembrane could be decreased. However, because the overlying geotextile protection layer will be tore off easily, and then geomembrane will lose protection. Even if both-side textured geomembrane is applied, the geomembrane can be strained to breaking point when laying on a steep ground. Fig. 24 shows a geomembrane tensile failure observed in Xiaping Landfill in 2009. With respect to the liner system laying on a steep slope, the research and experience are still not enough to solve the tensile failure problem. According to the preliminary study of Lin (2009), the following measures may be helpful: (i) Placing a smooth woven bag (filled with fine-grained soil) on the nonwoven geotextile protection layer of liner system for the landfill without a risk of waste slide. It is believed that the weak interface between smooth woven bag and nonwoven geotextile will protect the liner system beneath. (ii) Placing a layer of geogrid on the nonwoven geotextile protection layer of liner system. It is believed that the geogrid will share most of the down-slope force because of its high stiffness and strength, and hence protect the underlying nonwoven geotextile.

Cover system of Xiaping landfill in Shenzhen

As shown in Fig. 25, cover system was applied in the Xiaping landfill slope after the failed waste body was stabilized. The design was in accordance with "Technical Code for Municipal Solid Waste Sanitary Landfill Closure" CJJ112-2007 and experiences in similar landfill closure projects. From bottom to top, the cover system consists of foundation layer, 400g/m^2 filament nonwoven geotextile, 1.0mm LLDPE geomembrane, 8mm geotextile-geonet composite, 500mm soil protection layer, three-dimensional geomat and 100mm surface soil for vegetation (see Fig. 26).

Fig. 25 Scene after landfill closure

With the consideration of big surface runoff on the cover system during rainstorm, two main drainage trenches were set up on the landfill slope. As shown in Fig. 27, geocells filled with concrete were used to construct the drainage trench. The use of geocells is to reduce concrete cracking due to landfill settlement.

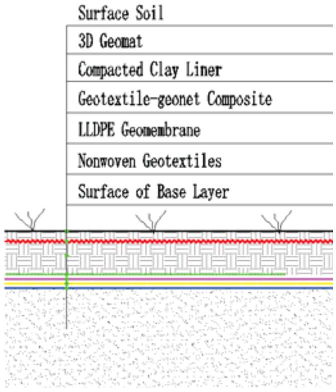


Fig. 26 Structure of cover system

Fig. 27 Surface water drainage trench

Intermediate Liner System used for the Vertical Expansion Project of Qizishan Landfill in Suzhou

The Qizishan landfill in Suzhou was put into operation in 1993. Its capacity and service life as design were 4.7 million m3 and 15 years, respectively. It is a valley type landfill, and a cut-off wall was installed at the downstream of valley to limit downstream migration of leachate. The landfill had to be expanded to dispose more MSWs generated after 2008. Lateral and vertical expansion was designed to increase the landfill capacity (see Fig. 28).

According to the new standard of landfill design in China, a liner system must be laid at the bottom of the expanding landfill. The liner system placed in between the old and expanded landfill is called intermediate liner system. Because of the highly degradable wastes such as vegetables and corrosive metal in the old landfill, local subsidence and even cavity may be formed below the liner system. It will make the liner system suspended above the subsidence and bear the upper surcharge loading, as showed in Fig. 29 (Chen et al. 2009). The local subsidence will cause tensile strain in geosynthetics

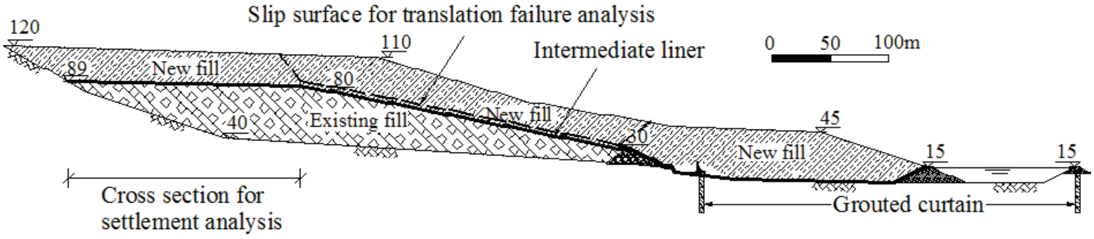


Fig. 28 Design of landfill expansion in Suzhou, China

(e.g. geomembrane, geotextile, GCL, composite geonet, geogrid etc.), Finally, tensile failure of liner system may occur, and result in a leakage of leachate.

Figure 29 shows a sketch of the liner system stress and deformation under the partial subsidence of subjacent soil (Chen et al. 2008b).

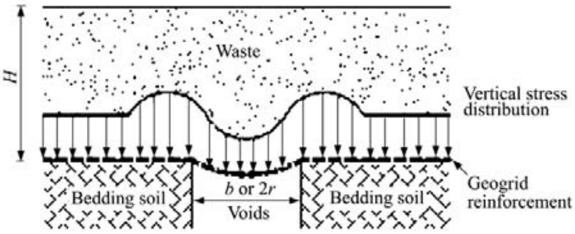


Fig. 29 Geosynthetic reinforcement above a local subsidence

In order to reduce the influence of local subsidence on the intermediate liner system, "*Technical Code for Geotechnical Engineering of Municipal Solid Waste Sanitary Landfills*" CJJ176-2012 recommends adding geogrid reinforced layer into the liner system. The number of layer needed can be calculated as follows: firstly, the allowed minimum tensile strain ε_a of all the geosynthetics used in the intermediate liner system is determined, secondly, the allowed short-term tension Ta corresponding to ε_a and the allowed long-term tension T_l are obtained through tensile test of the geogrid, then the design value of tension T for geogrid is got by assuming $\varepsilon=\varepsilon_a$, finally, the layers of the geogrid, n, is given by:

$$n \geq T / T_1 \tag{1}$$

The relationship between T and tensile strain ε under the effect of local subsidence can be defined as (Giroud, 1990):

$$T = 2\gamma_s r^2 (1 - e^{-0.5H/r})\Omega \tag{2}$$

where T (kN/m) is designed tension of geosynthetics; H (m) is the thickness of upper soil layer; γ_s (kN/m3) is the average unit weight of the upper soil layer; r (m) is radius of round local subsidence area; Ω is the dimensionless parameter corresponding to the tensile strain ε of geosynthetics.

According to experimental results of Gao (2009), adding a compacted soil buffer layer upon the geogrid reinforced layer can help to restrain the deformation of intermediate liner system. As shown in Fig. 30, the intermediate liner system used for the expansion of Qizishan landfill includes a thick buffer layer, two layers of geogrid, LLDPE, and GCL (Chen et al. 2011).

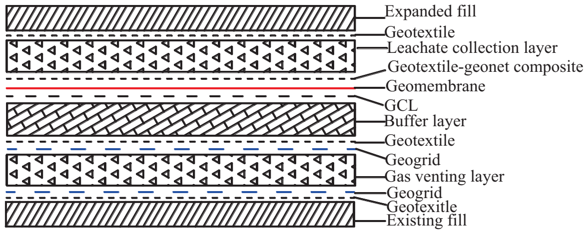


Fig. 30 Illustration of the intermediate liner system in the Suzhou landfill expansion

OTHER ENGINEERING APPLICATION

In addition to three aspects of engineering application above, the applications in the flood fighting and rescue, drought relief and water saving and water environment protection in China also should be noted:

(1) Flood fighting: It is mentioned previously that the geosynthetics played a very important and special role in flooding relief work in the vast flood of 1998. In that year, the amount of usage for geotextile reached 500 million m^2. Geotextiles were mainly made into soilbag to heighten and stabilize dike and dam, control soil piping, protect bank and river bed. Moreover, the pile-supported geomembrane cofferdam played a very important role in the plugging Jiujiang breach of Yangtze River in 1998.

(2) Drought relieving and water saving, China is poor in water resource. The per-capita water resource is the 1/4 of world average level, and the regional distribution is not uniform. Therefore, drought relieving and water saving work are very important in China. One of the applications for the geosynthetics in drought relieving and water saving is to use geomembrane to treat water storage and delivery facilities to reduce leakage, evaporation and pollution, such as the seepage-proofing treatment for the foundation of aquatic sport track in 2008 Beijing Olympic Games. In addition, the purposely-designed geo-pipe and geotextile are applied in water-saving

irrigation of agriculture. Afterwards, the development and application of geosynthetics on this aspect will have a good future.

(3) Water environment protection: at present, the inland rivers and lakes in China are seriously polluted. The polluted mud at the bottom of rivers and lakes is the main inner pollution source. In recent years, engineers apply the geosynthetics in pollution control of the river and lake bottom mud. For example, in the second-stage project of Shenzhen river restoration, the geotextile was used as separator and filter in between the polluted mud and the above water. In the restoration project of the Dian Lake in Kunming applies geotextile tubes to dewater the dredging mud and stabilize the contaminants in the mud.

FINAL REMARK

The application of geosynthetics in China starts late but develops rapid, and the category of product expands continuously, and the application nearly covers all respects of civil engineering, especially in the highway and railway engineering, hydraulic and coastal engineering, solid waste landfill engineering. The application scale and quantity are at the top of the world. In recent years, the application starts to extend to the new fields like water environment protection, drought relieving and water saving. However, during the fast development process, there exist some problems needing paying attention to (Bao 2008), including: (1) More efforts should put on the research and development of high quality, innovative, big size and/or special geosynthetics products; (2) The domestic and overseas technical exchange should be promoted and the training of relevant engineers should be enhanced to improve their theoretical level and flexible application ability; (3) More efforts should be put on the fundamental study on the mechanism and theory associated with geosynthetic application, the accumulation of scientific data and the innovation of application technology; (4) The technical standards and specification associated with geosynthetics application should be revised and updated accordingly. Solving these problems will promote the further development of the geosynthetics application work in China.

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