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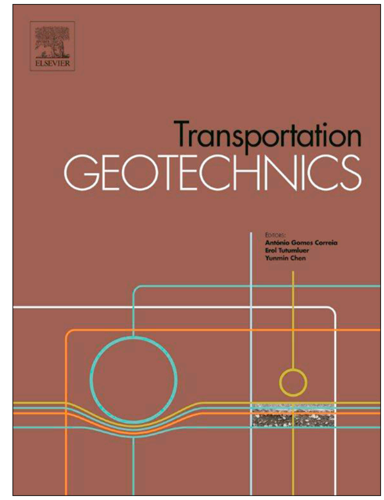

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Geosynthetics with Enhanced Lateral Drainage Capabilities in Roadway Systems

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Abstract

While moisture-induced distress is one of the major causes of premature pavement failure, geosynthetics are only seldom used to provide internal drainage within the structure of roadway systems. This is likely because conventional geosynthetic drains are only suitable to manage flow under saturated soil conditions, whereas unsaturated conditions prevail in pavement systems. Recent insight into the interaction between geosynthetics and unsaturated soils has led to new advances in geosynthetic manufacturing, including the development of geotextiles with enhanced lateral drainage (ELD), which allow drainage even under unsaturated conditions. This paper highlights the benefits of ELD in a number of roadway situations, including: (1) enhanced lateral drainage of moisture migrating upward from a high water table, (2) enhanced lateral drainage of moisture infiltrating downward from the surface, (3) control of frost heave-induced pavement damage, (4) control of pavement damage caused by expansive clay subgrades, and (5) enhanced lateral drainage in projects involving soil improvement. The mechanisms of moisture migration, as well as the impact of ELD are evaluated in each of these situations. Additionally, case histories involving recently constructed pavements involving the use of ELD geosynthetics are presented for each specific drainage application. The selected case histories involve post-construction evaluation of the ELD geosynthetic's performance either through assessment of lateral drainage, condition surveys of pavement sections with and without ELD geosynthetics, or in-situ monitoring of moisture content. Assessment of the data collected illustrates the beneficial impact of ELD used in the various pavement scenarios. Overall, this paper illustrates that incorporation of enhanced lateral drainage in roadway systems results in a range of improvements for pavement performance.

Key words: *Geotextile, Lateral Drainage, Pavement, Case Histories, Geosynthetics*

1 INTRODUCTION

Geosynthetics have been used to improve the performance of roadway systems by performing multiple functions including separation, filtration, stiffening, reinforcement, and drainage. In particular, geosynthetics have been in use since the 1970s to improve the performance of unpaved roads on soft subgrade soils. Beginning in the 1980s, geosynthetics were utilized to minimize reflective cracking in asphalt overlays as well as to improve the performance of base aggregate layers. Although one of the major causes of premature pavement failure is moisture-induced distress, implementation of geosynthetics as internal drainage for roadway systems has been comparatively limited. This is likely because conventional geosynthetic drains are only suitable to manage flow under saturated soil conditions, whereas unsaturated soil conditions prevail within pavement systems. Greater understanding of the interaction between geosynthetics and unsaturated soils has led to new advances in geosynthetic manufacturing, including the development of geotextiles with enhanced lateral drainage (ELD), which promote drainage under unsaturated conditions.

The advent of geosynthetics with ELD capabilities is particularly promising for roadway applications, as these products allow lateral drainage under unsaturated soil conditions and can facilitate drainage even under conditions of reverse gradient (e.g. caused by differential settlements). The presence of moisture within a roadway system is a major source of distress that eventually requires costly pavement maintenance. As an example, U.S. state highway agencies reported spending approximately $27 billion on pavement maintenance in 2013 alone (FHWA 2013).

Figure 1 illustrates the various sources of moisture in the relevant layers of a paved road. The specific conditions and sources of moisture for a given roadway project may result in a number of situations that would benefit from enhanced lateral drainage in particular. One such situation involves upward moisture migration into the subgrade and other roadway layers, due to capillary action, in locations where the phreatic surface is relatively high. While minimizing downward water infiltration is an important objective of paved roadways, a second situation pertains to cases in which water still reaches the relevant roadway layers through cracks in the asphaltic layer, infiltration through the pavement shoulders, or water losses in surface water drainage systems. A third situation, also involving upward moisture migration, occurs in cold regions subject to soil freeze, where the presence of moisture may result in particularly detrimental frost heave. A fourth situation, also related to downward or lateral moisture migration, occurs in roadways founded on expansive subgrade soils, where water migration from roadway shoulders results in major longitudinal cracks. Finally, a last situation corresponds to projects involving soil improvement techniques that would benefit from the enhanced de-watering capabilities provided by geosynthetics.

While water does not necessarily trigger all pavement-related distresses, once a crack or distress has developed, the presence of moisture will almost always exacerbate the problem (Rokade et al. 2012). Even though drainage layers have been considered for use as a sub-base layer across the entire pavement section, such alternatives are only rarely implemented due to concerns of high cost, constructability, and potential aggregate loss with time. Although uncommon, geocomposite drainage layers consisting of conventional geotextiles and a core geonet have been adopted within roadway systems. However, both granular and geocomposite drainage layers provide only lateral drainage under saturated conditions and do not provide such drainage under the most typical unsaturated conditions. Presented in this paper is an alternative approach involving the use of geosynthetics that provide enhanced lateral drainage, and more specifically, drainage generated not only by gravity, but also by suction gradients. Following a review of the functions and applications of geosynthetics in roadway systems, this paper provides an overview of the development of geosynthetics with enhanced lateral drainage. Multiple case histories of recently constructed pavements constructed using with ELD geosynthetics are then presented. These case histories highlight different applications in which an enhanced drainage material may be especially beneficial in mitigating moisture-related pavement distresses due to a high water table, surface infiltration, frost heave, expansive clays as well as supporting projects involving ground improvement technologies. Each case history includes field observations and/or monitoring after construction, and offers relevant insight into each project's performance.

2 FUNCTIONS AND APPLICATIONS OF GEOSYNTHETICS IN ROADWAY SYSTEMS

Geosynthetics can be defined as planar products manufactured from polymeric material, used together with soil, rock or other geotechnical engineering-related material as an integral part of a man-made project, structure or system (ASTM 1995). The geosynthetic products most commonly used in roadway systems include geotextiles (woven and non-woven) and geogrids (biaxial and multiaxial), although erosion-control products, geocells, geonets (or geocomposite drainage products), and geomembranes have also been used in some applications. These various types of geosynthetics can be used to fulfill one or more specific functions in a variety of roadway applications.

The terminology used in the technical literature to describe the various applications of geosynthetics in roadway systems and the functions of geosynthetics incorporated into roadways has not been consistent. This is understandable, as the mechanisms that lead to roadway improvement in each application are complex and often intertwined. Consequently, the framework considered in this paper aims at minimizing inconsistencies regarding the terminology used when using geosynthetics in roadways. While strongly based on current frameworks used to describe geosynthetic functions (e.g. Koerner 2012), the refined framework adopted herein follows two key premises: (1) different geosynthetic functions should be defined if they correspond to unequivocally different geosynthetic properties, and (2) geosynthetic applications, which should not be confused with geosynthetic functions, establish the different type of projects (in roadway applications) where geosynthetics are used.

Figure 2 shows a paved road section with the location of possible geosynthetic layers and the various functions that these geosynthetics can fulfill. These functions include:

1) Separation: The geosynthetic, placed between two dissimilar materials, maintains the integrity and functionality of the two materials. Key design properties to perform this function include those used to characterize the survivability of the geosynthetic during installation.
2) Filtration: The geosynthetic allows liquid flow across its plane, while retaining fine particles on its upstream side. Key design properties to fulfill this function include the geosynthetic permittivity (cross-plane hydraulic conductivity per unit thickness) and measures of the geosynthetic pore-size distribution (e.g. apparent opening size).
3) Reinforcement: The geosynthetic develops tensile forces intended to maintain or improve the stability of the soil-geosynthetic composite. A key design property to carry out this function is the geosynthetic tensile strength.
4) Stiffening: The geosynthetic develops tensile forces intended to control the deformations in the soil-geosynthetic composite. Key design properties to accomplish this function include those used to quantify the stiffness of the soil-geosynthetic composite.
5) Drainage: The geosynthetic allows liquid (or gas) flow within the plane of its structure. A key design property to quantify this function is the geosynthetic transmissivity (in-plane hydraulic conductivity integrated over thickness).

While comparatively uncommon in roadway applications, additional geosynthetic functions include:

6) Hydraulic/Gas Barrier: The geosynthetic minimizes the cross-plane flow, providing containment of liquids or gasses. Key design properties to fulfill this function include those used to characterize the long-term durability of the geosynthetic material.

7) Protection: The geosynthetic provides a cushion above or below another material (e.g. a geomembrane) in order to minimize damage during placement of overlying materials. Key design properties to quantify this function include those used to characterize the puncture resistance of the geosynthetic material.

One or more of the seven aforementioned geosynthetic functions have been used for one or more of the following five roadway applications: (1) mitigation of reflective cracking in asphalt overlays; (2) separation; (3) stabilization of road subgrade; (4) stabilization of road base; and (5) lateral drainage. This list is limited to applications of geosynthetics within a roadway section, and thus does not include other applications that may also involve the use of geosynthetics. Such applications, including trench drains, erosion control elements, and surface water management features, are discussed by Holtz et al. (1997, 1998) and Zornberg and Thompson (2010).

The relevance of the application discussed in this paper (i.e. lateral drainage) is significant because the presence of moisture in both the base and subgrade layers of a pavement is particularly detrimental, compromising the mechanical properties of these soils. Figure 3(a) shows the impact on road performance of a moisture-induced decrease in modulus in both the base and subgrade layers. One way to quantify the impact of increased moisture is to evaluate its effect on the structural number (*SN*) in the design method proposed by the American Association of State Highway and Transportation Officials (AASHTO 1993). This method considers the pavement as a multi-layer elastic system, with the overall structural number reflecting the total pavement thickness and its resiliency to repeated traffic loading. The required *SN* for a project is selected so that the pavement will support anticipated traffic loads and experience a loss in serviceability no greater than that established by project requirements. The *SN* is reduced by a modifier, *m*, which accounts for the moisture characteristics of each pavement layer. This modification factor can be sizable, with values for *m* ranging from as high as 1.4 for excellent drainage conditions to as low as 0.4 for poor drainage conditions. Or, stated more precisely, the structural capacity of a roadway with poor drainage conditions is as low as 29% (0.4 to 1.4 modifiers) of that of a roadway with excellent drainage conditions. Designers often overlook the importance of lateral (internal) drainage in a roadway, focusing instead on building thick, high quality material layers, while omitting good drainage features. Unfortunately, moisture trapped under a pavement will exacerbate pavement distresses by increasing pore pressures and softening the subgrade soil.

Figure 3(b) illustrates the use of a geosynthetic with in-plane drainage capabilities. In this illustration, a horizontal geosynthetic drain was placed directly beneath the pavement, laterally diverting moisture that may have reached the base layer through downward infiltration, which may result from the presence of cracks in the pavement surface. The geosynthetic can also minimize moisture in the underlying subgrade soils, which may have reached a high degree of saturation, for example, through capillary rise from a comparatively high water table.

Conventional geosynthetic drains include geocomposite drainage products (a combination of geonets and geotextile filters) and geotextiles with comparatively high transmissivity. However, these conventional geosynthetic products can only provide gravity-induced lateral drainage, which is important when the soil adjacent to the geosynthetic has reached saturated conditions. Through advances in geosynthetic manufacturing, such as the development of geotextiles with enhanced lateral drainage (ELD), drainage under unsaturated conditions has also been made possible.

3 ADVANCES IN THE DEVELOPMENT OF GEOTEXTILES WITH ENHANCED LATERAL DRAINAGE

In-plane drainage has conventionally been achieved in transportation and geotechnical applications using geonets, geocomposite drainage products, or geotextiles (e.g. Zornberg and Christopher 2007, Koerner 2012). Typical drainage geocomposites involve a geonet sandwiched between two layers of non-woven geotextiles (Shukla 2012). While not used as frequently as drainage geocomposites, geotextiles can also provide in-plane drainage. This is the case of geotextiles with high transmissivity, in particular needle-punched non-woven geotextiles which, due to its manufacturing approach, results in comparatively large void spaces. Woven geotextiles may provide a pathway for moisture migration. However, conventional geosynthetic drainage products can only transmit flow once the surrounding soil becomes saturated. This is because a capillary barrier will develop if the soil in contact with a conventional geotextile is unsaturated (Zornberg et al. 2010).

A capillary barrier develops when an unsaturated fine-grained soil layer is underlain by another unsaturated porous material with relatively large-sized pores, such as a coarse-grained soil layer (e.g. sand, gravel), or a porous geosynthetic (e.g. a non-woven geotextile). Key to the understanding of capillary barriers is the assessment of water flow and storage in porous geomaterials (e.g. soils, geosynthetics) under unsaturated conditions. Though it seems counterintuitive, hydraulic conductivity of unsaturated gravel or geotextiles can be significantly smaller than that of fine-grained soils.

A good example of the capillary break effect in daily life is a baby bottle. When the bottle is inverted, milk will not pour freely out of the nipple's small hole to the rather large opening of air on the other side. Additional suction must be applied on the air side of the nipple to induce flow. The capillary break effect occurs at the interface between fine-grained materials with relatively small pores and coarse-grained materials with relatively large pores, as shown schematically in Figure 4 (Zornberg et al. 2010). As shown schematically in the figure, the diameter of pores changes from a comparatively small representative value ϕ_1 in the soil to a relatively large representative value ϕ_2 in the geotextile. The matric suction in the water is inversely proportional to the diameter of the air/water meniscus which, in turn, is related to the diameter of the tortuous "tubes" defined in the voids of the soil and of the geotextile. Consequently, small soil pores of diameter ϕ_1 yield comparatively large suction, and water can move to the larger geotextile pores only when a significantly smaller suction (corresponding to the larger diameter ϕ_2 of the geotextile) develops in the system. Macroscopically, the capillary break effect prevents a measurable amount of water flow from the soil into the non-woven geotextile until a critical suction close to zero (saturation) is reached. At this point, water is capable of 'breaking' into the large pore from the small pore.

An enhanced lateral drainage (ELD) geotextile is able to conduct flow through small capillary tubes, which develop matric suction that facilitates the drainage of water stored within an adjacent unsaturated soil mass. While the concepts associated with wetting in the textile industry has led to the development of wicking textiles, the general focus has been in maximizing moisture storage (Kissa 1996, Fangueiro et al. 2010, Parada et al. 2016). On the other hand, the main objective of ELD geotextiles is to mobilize flow under unsaturated conditions. Accordingly, while conventional geotextiles can only provide in-plane flow under saturated conditions, ELD geotextiles can also provide in-plane flow under unsaturated conditions. This is possible because of the effect of the surface tension acting on particularly small grooves, as described below. Figure 5(a) shows a magnified view of a typical monofilament non-woven geotextile along with a cross-section detail of this fiber. This geotextile structure will allow gravity-driven drainage through pore spaces created by the intersecting yarns, but only after the adjacent soil reaches saturation. In Figure 5(b), an ELD geotextile is shown, along with a cross-section detail of this fiber. As seen in the figure, the unique cross-section of this fiber contains deep groves, approximately 8 μm in diameter. The grooves act as capillary tubes, transmitting liquid along the longitudinal axis of the fiber through narrow channels. These particular fibers are manufactured using nylon, which is both hydrophilic and hygroscopic. More precisely, the nylon will pull water from the surrounding soil, as well as provide a conduit for moisture along its channels.

The grooved fibers shown in Figure 5(b) can replace a fraction of the conventional fibers in a standard woven geotextile. This replacement increases drainage capability of the woven geotextile by facilitating moisture transmission along the voids, as well as through the grooved yarns. Moreover, if the woven geotextile is rated for reinforcement, then the in-plane drainage layer simultaneously serves as a geotextile reinforcement.

Five specific cases involving applications of lateral drainage in pavement projects have been identified. In these cases, the overall use of lateral drainage, and of ELD in particular, are deemed particularly relevant. They include: (1) enhanced lateral drainage of moisture migrating upward from a high water table; (2) enhanced lateral drainage of moisture migrating downward from the surface; (3) control of pavement damage caused by frost heave; (4) control of pavement damage caused by expansive clays; and (5) enhanced lateral drainage in soil improvement projects. For each case, an overview of the specific application is provided, along with a case history of a recently constructed project using ELD geosynthetics. Each case history presents evidence obtained through field observations or field monitoring data of post-construction performance, providing valuable insight into the benefits of using lateral drainage in each of the specific applications.

4 ENHANCED LATERAL DRAINAGE OF MOISTURE MIGRATING UPWARD FROM A HIGH WATER TABLE

4.1 Overview of the specific application

Roadways in areas where the groundwater table is high are particularly prone to problems associated with high moisture content in the subgrade. Water migrates from the elevation of the water table to the roadway due to capillary action, which is the ability of water to flow in narrow soil pore spaces against the pull of gravity. Capillary rise develops within the comparatively small diameter of soil pores (equivalent to tortuous capillary tubes) under the action of water surface tension, and is responsible for moving water from the groundwater table (where water pressure is zero) to the overlying unsaturated soils (where water pressure is negative). The height of capillary rise in soil can be considerable, sometimes reaching heights of 9 to 27 m (Blades & Kearney, 2004). Fine-grained soils, which are common subgrade materials, result in a higher capillary rise than coarse-grained soils. Possible seasonal changes in the elevation of the water table are relevant as well. In particular, roadways near a body of water may be subject to significant fluctuations in the water table elevation, which follow water level fluctuations in the body of water.

The use of enhanced lateral drainage may be particularly effective at minimizing the detrimental effect of water on the mechanical properties of the subgrade. Figure 6 shows a schematic pavement section that incorporates an ELD geotextile in a high water table scenario. As illustrated in the figure, incorporating lateral drainage into the pavement section helps carry excess water outside the structural pavement layers. Specifically, upwardly migrating moisture that has reached the ELD geotextile can be laterally diverted to the pavement shoulders, where it can leave the system as evapotranspiration. Ultimately, incorporation of lateral drainage into the roadway section minimizes the problems associated with moisture-related weakening of the pavement subgrade.

4.2 Daniel Boone Bridge, Missouri, USA

In 2013, the Daniel Boone Bridge was newly constructed near St. Louis, MO. The main objective of this $125 million project was the expansion of an existing bridge, built in the 1930s along I-64 and crossing the Missouri River, which did not meet current interstate traffic requirements and required frequent preventive maintenance. Additionally, part of the newly-constructed bridge project involved a new pavement section for the bridge approach. Because of the location directly alongside the Missouri River, the groundwater level was high and the subgrade was nearly saturated. To remove water that may reach the pavement through upward migration from the high water table, the original layout called for a 4 in. (100 mm) thick layer of drainable aggregate to be placed below the 4 in. (100 mm) thick aggregate base layer. However, drainable base costs an average of $40/ton compared to about $12/ton for regular base aggregate (costs are estimated using average aggregate costs and the method outlined in USDA, 2011). To reduce costs while maintaining the same drainage capabilities, an ELD geotextile was incorporated into the pavement layout, replacing 2 in. (50 mm) of the originally proposed drainable aggregate. In addition to its drainage capabilities, the ELD geotextile was selected to provide separation and subgrade reinforcement as well. The layout of the new pavement is consistent with that illustrated in Figure 6. For moisture release, the discharge termination segment of the ELD geotextile entailed extending the geotextile beyond the shoulder, into an aggregate-covered edge, where moisture could then be released through either evaporation or into a trench drain.

The first pavement sections to include the ELD geotextiles were constructed in October 2013. Figure 7(a) shows the placement of aggregate over the ELD geotextile. Just a few days after installation, heavy rains allowed for assessment of the drainage system. As shown in Figure 7(b), effective release of the excess moisture can be clearly observed draining beyond the moisture discharge termination segment of the geotextile. The new eastbound and westbound bridges opened to traffic in June and November 2015, respectively. Good performance has been observed in the pavement sections since construction, showing no signs of distresses after opening to traffic. In summary, the Daniel Boone Bridge project illustrates a case involving a high water table, where an ELD geosynthetic was successfully used both to laterally divert upward migrating water and to replace 2 in. of expensive drainable base.

5 ENHANCED LATERAL DRAINAGE OF MOISTURE MIGRATING DOWNWARD FROM THE SURFACE

5.1 Overview of the specific application

As Figure 1 illustrates, multiple mechanisms may develop over time leading to downward migration of moisture. Moisture migration through cracks in a damaged surface asphaltic layer may be particularly problematic. Once moisture has reached the pavement base or subbase, it may be stored within the pavement layer for an extended period of time because mechanisms such as evaporation are not available to release the additional water back to the atmosphere. Even conventional drains (e.g. geocomposite drainage layers) placed, for example, directly over the subgrade may be ineffective. As previously discussed, the development of a capillary barrier between the unsaturated soil and the geotextile-backing of the geocomposite drain prevents water from getting into the drain and then migrating out of the system. Instead, moisture will accumulate at the interface of the soil and the drain until the soil reaches nearly saturated conditions. Similar problems may result when moisture infiltrating laterally from the pavement shoulders penetrates the base and subbase layers.

As previously stated, an ELD geotextile can provide drainage under unsaturated conditions and significantly minimize or eliminate the development of a capillary break (Azevedo and Zornberg 2013). It should be emphasized that, unlike other flow problems in geotechnical and transportation engineering (e.g. drainage of surface water), while the volume of liquid stored within pavement layers may not be particularly significant, it may be particularly difficult to eliminate. Consequently, the flow capacity of the ELD geosynthetic does not need to be significant, but it should be able to capture water stored within unsaturated soils. For pavement applications, this means that the comparatively small flow capacity provided by an ELD geotextile under unsaturated flow conditions can achieve the moisture reduction that a comparatively higher capacity geocomposite drainage layer cannot, as the latter will work only under saturated soil conditions. Figure 8 shows the use of an ELD geotextile to reduce excess water that may have penetrated into the base and subbase materials through downward infiltration, as well as through accumulation due to a capillary barrier.

5.2 Garwood Railroad Siding, Idaho, USA

This project involved a 2.1-mile long new railroad siding for the Union Pacific Railroad near Garwood, ID. It involved adding a turnout connecting the existing Union Pacific Railroad track to the new siding track and a turnout reconnecting the siding track to the existing main track. Figure 9 shows a typical cross-section for the new siding, located adjacent to the existing main track and an access road. The tracks are supported by a minimum of 12 in. (0.30 m) ballast overlying 6 in. (0.15 m) of subballast material. A geotechnical site investigation involving 12 borings to depths of 10 to 15 ft (3.05 to 4.57 m) identified an onsite soil mixture of silty gravel and sand.

While the groundwater table was determined to be deep, minimizing storage of water that may infiltrate into the ballast and subballast was critical to maintaining the required structural capacity and to minimizing potential problems with frost heave. To address concerns of frost heave, the top 6 in. (0.15 m) of soil were excavated and replaced with sub-ballast material. However, unless an effective drainage system was implemented, downward-migrating moisture would still infiltrate the foundation structure, with no easy route for subsequent removal.

Accordingly, an ELD geotextile was placed at a 2% grade below the sub-ballast to remove moisture infiltrating from the ground surface, as shown in Figure 9. Incorporation of an ELD geotextile into the final layout facilitated compliance with railway regulations by maintaining positive drainage away from the railway embankment both during and after construction. The discharge termination segment included the length of the adjacent access road and final discharge into a drainage ditch, wherein surface water was discharged as well. Construction of the Garwood Railroad Siding began in September 2015 and was completed in early 2016. Post-construction evaluation shows very good early performance, as indicated by evidence of drainage through the geotextile, illustrated in Figure 10. This image, dated March 2016, shows a clear delineation between wet and dry portions of the subballast material at the location of the ELD geotextile.

6 CONTROL OF FROST HEAVE-INDUCED PAVEMENT DAMAGE

6.1 Overview of the specific application

Frost action is a significant source of pavement degradation in cold regions. Specifically, as water expands 6% when becoming ice, the volumetric changes due to the development of crystal ice lenses within soil voids will manifest as "frost heave" in the ground surface (Hiroshi & Kiyoshi, 1993). For frost heave to occur, three conditions must be met: freezing temperatures, frost-susceptible soils, and the presence of a continuous source of water (e.g. a comparatively high water table). Low plasticity clays and silts are particularly susceptible to frost heave, as their particles are fine enough to promote capillary rise, but they do not have an extremely low hydraulic conductivity, so migration of water can occur in comparatively short periods of time. As illustrated in Figure 11(a), ice lenses develop when water migrating from the water table due to capillary rise reaches the elevation corresponding to frost depth. Ice lenses will continue growing until either the source of moisture is disrupted or temperatures rise above freezing values. Eventually, growing ice lenses will manifest as heave on the pavement surface, which can be significant.

While frost heave leads to considerable roughness and creates safety concerns during the winter, even greater problems occur during the spring thaw. Specifically, as ice lenses melt, the heaved areas in the pavement surface collapse, causing substantial surface cracking. In addition, the excess liquid water in the pavement's structural layers causes significantly diminished stiffness and strength. It is therefore not unusual for typical traffic loads, which would cause no damage to the roadway under regular circumstances, to cause severe pavement distress during the spring due to the substantial decrease in the road's structural capacity.

The distress caused by frost heave can be significantly mitigated by incorporating a drainage layer in the pavement section (Henry 1996). In particular, use of an ELD geotextile has been found to be very effective at mitigating pavement problems associated with frost heave and thaw soil weakening (Zhang et al. 2014). In this application, the mechanisms for moisture migration are similar to those described in the case of moisture migrating upward from a high water table. As illustrated in Figure 11(b), the ELD geotextile will promote two favorable conditions: (1) minimizing upward migration across the geotextile by developing a capillary barrier, and (2) providing lateral drainage of excess moisture to the edge of the pavement. Both actions will reduce the availability of water that may reach the frost depth and, consequently, will minimize pavement damage associated with frost heave and thaw soil weakening.

6.2 Pioneer Mountains Scenic Byway, Montana, USA

The Pioneer Mountains Scenic Byway, located in Beaverhead County, Montana, has experienced seasonal frost heave-related problems over a 20 mile (32 km) stretch of road. Because heavy snow accumulates on the pavement during the winter, the road is closed to traffic and reopens in the spring. Once cleared of snow, all 20 miles are routinely found to have developed new longitudinal, full pavement section-deep cracks as a result of freeze-thaw cycles. A section of pavement that has experienced particularly severe distresses due to frost heave is located near Moose Park. Some of the cracks are wider than a motorcycle tire, requiring immediate maintenance for safety. Figure 12(a) depicts the average conditions of the road before 2004, illustrating typical frost heave-induced cracks, while Figure 12(b) shows a major 755 ft. (230 m) long and 8 in. (200 mm) wide longitudinal crack in this area.

The pavement was repaired as recently as 2009, but distresses caused by freeze-thaw cycles led to recurring damage. A cross-section of pavement for the major repair efforts undertaken from 2004 to 2009 is shown in Figure 13(a). At the time, lateral drainage had already been identified as a relevant remediation feature, so a slit-film geotextile was incorporated, as well as a collector drainage pipe, in an attempt to remove moisture from the pavement and prevent frost heave. However, the drainage system incorporated at the time used conventional geotextiles capable of draining moisture only under saturated soil conditions. Consequently, despite numerous maintenance efforts, full section-deep cracks as wide as

6 in. (152 mm) reappeared in 2013 (Figure 13(b)). In fact, following the 2009 reconstruction, longitudinal cracks continued developing each season, from 2010 to 2013.

As a result, the Western Federal Lands Highway Division, in conjunction with Beaverhead County, proposed a new layout in 2013 to address frost heave-related problems at the byway's worst location, a 1,115 ft. (340 m) stretch of road in the Moose Park area. Pre-construction piezometer data revealed that the phreatic surface was comparatively high, with the water table located at an average depth of 6 ft. (1.8 m) below the ground surface, and only 1.5 ft. (0.5 m) below the surface in some locations. Site borings confirmed an on-site soil mixture of silty sand and gravels, with approximately 46% fines. Several options were considered, including: (1) over-excavation of frost susceptible soils; (2) geosynthetic-stabilized options; and (3) an option incorporating enhanced lateral drainage. The ELD geotextile option, combined with the use of a second, comparatively light geosynthetic for base stabilization, was ultimately selected. This alternative corresponded to the thinnest cross-section, thereby allowing the pavement layers to remain above the phreatic surface.

The cross-section of the recently-constructed roadway is shown in Figure 14(a). First, the ELD geotextile was placed directly over the prepared subgrade and covered with a 10 in. (0.25 m) sub-base aggregate. The second geotextile layer (solely for stabilization) was then placed to reduce the required thickness of the base aggregate. Next, an 8 in. (0.20 m) thick base layer was placed. Paving operations were subsequently completed, which included placement of a 4 in. (0.10 m) thick layer of asphalt cement. Finally, after paving and chip sealing, a 3 in. (762 mm) thick open-graded aggregate was placed at the pavement shoulders, over the discharge termination segment of the ELD geotextile. The open-graded aggregate allows for evaporation of moisture laterally diverted to the edge of the pavement, while also protecting the geotextile from ultraviolet degradation.

Pavement construction was completed in 2014, with early evidence of good performance. In fact, soon after placement of the ELD geotextile – even before construction was completed – water drainage to the road shoulder was clearly observed, as seen in Figure 14(b). After the first freeze-thaw cycle, no cracks were visible in the pavement section rehabilitated using ELD geotextiles. Indeed, good performance of the enhanced lateral drainage approach was clearly evidenced at the west end of the rehabilitation project. As shown in Figure 15, longitudinal cracks developed in a pavement section that did not incorporate enhanced lateral drainage, but these cracks abruptly ended at the pavement section that did incorporate enhanced lateral drainage. After two full post-construction seasons, the sections without ELD geotextiles have continued heaving and cracking. Yet, the rehabilitated portions of the roadway are performing extremely well, with no visible signs of cracking or heaving. Observations at the edge of the road reveal significant drainage at the discharge termination of the ELD geotextiles. In summary, by incorporating an ELD geosynthetic in the roadway rehabilitation at the Pioneer Mountains Scenic Byway, the pavement in the area of reconstruction did not sustain frost heave-related damage for the first time in years.

7 CONTROL OF PAVEMENT DAMAGE CAUSED BY EXPANSIVE CLAY SUBGRADES

7.1 Overview of the specific application

Another moisture-related pavement distress, particularly common in the central United States, is the development of longitudinal cracks associated with the presence of expansive clay subgrade soils. These environmentally-induced longitudinal cracks develop toward the pavement shoulders as a consequence of moisture content variations in the subgrade. Environmental moisture variations (e.g. rainy or dry periods) can reach the shoulder of a typical pavement comparatively easier than the center of a pavement. Consequently, the edges of the pavement will shrink during dry periods and will swell during rainy periods. However, because the center of the pavement does not experience such volumetric changes, differential settlements develop between the center and edge of the pavement. During particular dry seasons, the flexion of the pavement will result in tension toward the surface layer, leading to possibly significant longitudinal cracks (Roodi and Zornberg 2012).

Figure 16 illustrates the effect of placing an ELD geotextile at the interface of the base layer and an expansive clay subgrade. The geotextile is able to homogenize the distribution of water along its entire length. Accordingly, while moisture variations may still occur closer to the pavement edge, the ELD geotextile will facilitate migration of moisture under unsaturated conditions, resulting in a comparatively uniform moisture distribution across the width of the pavement structure. In the subgrade, this improved uniform moisture distribution will minimize differential vertical movements in the pavement and thus mitigate the development of longitudinal cracking. Unlike the applications of enhanced lateral drainage discussed in Sections 4, 5 and 6, when the objective is to control damage caused by expansive clays, the ELD geotextile should not have a discharge termination segment. When functioning to homogenize moisture content across the pavement width, rather than to strictly promote outward drainage, the ELD geotextile terminates without a daylighting segment to facilitate homogenization of moisture.

7.2 State Highway 21, Texas, USA

A 6 mile (10 km) stretch of Texas State Highway 21 (SH21), just north of Bastrop, TX, was founded on an expansive clay subgrade, rehabilitated by the Texas Department of Transportation (TxDOT) in 2013. Prior to rehabilitation in 2013, the road had been subject to continued maintenance operations. Yet, rating of this road's pavement performance conducted by TxDOT prior to the 2013 rehabilitation still revealed inadequate performance: while 26% of the road was performing comparatively well; 32% of the road showed edge cracking; 38% of the road had patches and level-ups; and 4% of the road had longitudinal cracks within the inner and outer lanes. The recurrence of the road's inadequate performance was extensively evaluated, and despite numerous maintenance operations, pavement degradation was not halted. The extent of the pavement degradation in 2012, which was characterized by longitudinal and edge cracks, can be seen in Figure 17. A comprehensive characterization of the subgrade revealed that the soil Plasticity Index ranged from 30 to 53 and that the percentage fines ranged from 75 to 100%. Consequently, the subgrade soils classifies as CH, per the Unified Soil Classification System. Mineralogical evaluation revealed the presence of Montmorillonite.

The rehabilitation plan involved milling the top 3 in. (762 mm) of the pavement, followed by partial excavation of the outside line and additional expansion of the shoulder. Figure 18 shows a cross-section of the reconstructed pavement. In order to investigate the nature of moisture changes in the subgrade material and its direct impact on volumetric changes and pavement degradation, the University of Texas at Austin implemented a number of pavement test sections. Specifically, a total of eight 500 ft. (152 m) long test sections were constructed to evaluate the impact of various geotextiles on the performance of pavements founded over expansive clays. The following geotextiles were evaluated in the test sections: a standard non-woven geotextile used only for separation; two types of woven, high-strength geotextiles used for base stabilization and separation; and a woven geotextile used for lateral drainage, base stabilization and separation. As shown in Figure 18, each geotextile was 9 ft. (2.74 m) wide and placed only in the pavement shoulder area, in accordance with the planned rehabilitation project, where the subgrade was exposed in this portion of pavement only.

As part of the evaluation program, moisture sensors were installed in the subgrade, at the center of each 500 ft. (152 m) long test section, to monitor the performance of the geotextiles (see Figure 18). These moisture sensors allowed monitoring of changes in moisture content in the subgrade along the road shoulder, where moisture fluctuations are expected to be highest. Continued monitoring of moisture content throughout several seasons revealed a clear trend in moisture content distribution across the width of the instrumented sections. Similar trends were observed in the moisture content data obtained from the various sections in which conventional geotextiles (both woven and non-woven without ELD) were used. Typical moisture distributions obtained on different dates throughout the year are shown in Figure 19(a) for one of these conventional geotextile sections. As the results in this figure show, the moisture content in these sections was rather non-uniform, typically with the highest value toward the pavement edge and lowest value toward the center of the road. In fact, the difference in volumetric moisture content toward the edge and toward the center of the pavement reached values as high as 15%. Differences in moisture content across the width of the pavement may eventually result in differential settlements and, ultimately, in longitudinal cracks.

Figure 19(b) displays moisture distributions obtained on different dates throughout the year for a test section in which an ELD geotextile was used. In this case, moisture content remained relatively uniform over time and across the entire width of the shoulder. Even though changes in moisture content were expected over time because the monitoring period included reasonably wet and dry seasons, the changes were fairly similar across the various monitored locations. Consequently, moisture content distribution remained reasonably uniform at any given time. In this case, the difference in volumetric moisture content toward the edge and toward the center of the pavement remained at values below 3%. The comparable moisture content values across the width of the pavement indicate that the development of differential settlements was controlled in the pavement shoulder where ELD geotextiles were installed. Ultimately, the moisture monitoring data obtained at SH21 demonstrates the effectiveness of enhanced lateral drainage at homogenizing moisture content distribution across pavement sections in locations characterized by the presence of expansive clay subgrades.

8 ENHANCED LATERAL DRAINAGE IN PROJECTS INVOLVING SOIL IMPROVEMENT

8.1 Overview of the specific application

The enhanced lateral drainage that can be provided by geosynthetics may be central to soil improvement components often implemented as part of transportation projects. A good example is the use of ELD geotextiles to provide or complement the lateral drainage needed in soil improvement projects involving preloading and surcharge of soft soils, with or without accelerated consolidation using prefabricated vertical drains. The inclusion of geotextiles in these projects also capitalizes on their versatility, functioning not only to enhance lateral drainage, but to also achieve separation and subgrade reinforcement, all of which are particularly relevant functions when dealing with soft soil subgrades.

8.2 State Route (SR) 12, California, USA

The Bouldin Island rehabilitation project, in California's Sacramento-San Joaquin River Delta, involves the construction of a 4 mile (6.4 km) segment of SR 12. The project is characterized by the presence of highly compressible subgrade soils, with predicted ultimate settlements ranging from 6.6 to 11.5 ft. (2 to 3.5 m) for the various alternatives considered in the project. Consequently, approaches such as lightweight fill, soil mixing and use of prefabricated vertical drains (PVD) along with surcharge were considered to stabilize the foundation soils. Ultimately, PVD with surcharge, which required a drainage blanket to drain consolidation water, was adopted. While the original layout considered a drainage blanket involving a 1 ft. (30.5 cm) thick gravel layer, underlain by a separation geotextile and overlain by a reinforcement geotextile, this system was finally replaced by a single geotextile layer, which simultaneously provides enhanced lateral drainage, separation, and reinforcement.

The reconstruction of SR 12 involves the construction of a new highway section just south of the existing one. The new section will have standard 12 ft. (3.7 m) wide travel lanes, 8 ft. (2.4 m) wide shoulders and a concrete median barrier. Removal of the existing highway section is planned after construction of the new section is complete. The existing road was constructed on an approximately 10 ft. (3 m) high embankment and has undergone considerable settlement-related damage over its lifespan. This includes significant cracking, edge failures, major roughness along the length of the pavement, and longitudinal cracks along the centerline. Pavement maintenance began soon after the road's original construction, with the last major rehabilitation completed in 1996. This rehabilitation involved milling 3 in. (762 mm) of the asphalt layer, adding a leveling course with geosynthetic reinforcement, completely replacing some roadway sections, and expansion of the shoulders. Nonetheless, road conditions by 2002 were already as poor as those prior to rehabilitation.

In 2002, a thorough geotechnical investigation was conducted at the site to determine the most effective strategy of rehabilitation and long-term maintenance cost reduction for SR 12. The site investigation revealed that the road is underlain by a layer of soft to very soft clayey peat, ranging in thickness from 5 to 20 ft. (1.5 to 6.1 m). The peat layer is characterized by an extremely high natural water content and void ratio, and is composed primarily of decomposed organic material. The peat layer is underlain by a clay layer ranging in thickness from 10 to 35 ft. (3 to 10.7 m). The clay underlying the site was also found to have a relatively high in-situ moisture content, and was expected to control the consolidation time required to reach the target settlements under surcharge. The compressible layers at the site were underlain by a medium-dense to dense, coarse-grained, silty sand. Without employing techniques to accelerate consolidation, the primary consolidation settlements in the peat were expected to be completed in a matter of months, which was considered reasonable. However, the time reaching 90% of the primary consolidation settlements in the clay layer was expected to take up to 3.5 years.

Results from laboratory consolidation tests confirmed that significant consolidation settlements should be expected under the loads of new road embankments. Specifically, significant primary consolidation was anticipated in both the peat and clay layers, with a longer period predicted for the clay layer to reach the end of consolidation. In addition, the peat was also expected to undergo time-dependent secondary consolidation settlements, or creep, which could be just as significant as those due to primary consolidation. The groundwater table was measured at a depth of 3 ft. (0.9 m) below the ground surface. In addition, the low shear strength of the in-situ soils required a thorough slope stability evaluation, which revealed the need for staged construction in order to meet minimum factors of safety of 1.2 and 1.5 for temporary and permanent conditions, respectively.

A typical cross-section for the project in Figure 20 shows an initial cut into the existing embankment with a 1:1 slope. The PVDs were placed through the peat and clay soils in a triangular pattern, at 5 ft. (1.5 m) spacing, and installed to a depth of 60 ft. (18.3 m). After PVD installation, the ELD geotextile was placed to provide the required lateral drainage, separation, and subgrade stabilization. The temporary fill was added for surcharge, extending to an elevation of 10 ft. (3 m) above the proposed embankment finished grade. The temporary fill involved construction of a steep geosynthetic-reinforced slope with a facing inclination of 0.5:1 (H:V). The temporary surcharge continued at a height of 10 ft. (3 m) to the outer edge of the proposed structural section and then sloped down to the original ground level at a 1.5:1 (H:V) slope. The temporary geosynthetic-reinforced steep slope (and a portion of the embankment fill) will be removed after settlements ranging from 5 to 10 ft. (1.5 to 3 m) are reached, which corresponds to the predicted settlements for the new road's 30-year design-life. Upon removal of the temporary fill, the permanent embankment will remain to widen the existing road embankment, as indicated in the figure. The height of the permanent embankment will range from 3 to 10 ft. (0.9 to 3 m), with most of the widened embankment standing less than 5 ft. (1.5 m) high.

Figure 21(a) shows a view of PVD, right after installation in a triangular pattern along the length of the new road. The ELD geotextile was placed directly on top of the ground level and PVDs. Lateral drainage through the ELD geotextile could be observed soon after its placement, as shown in Figure 21(b). At the time of preparation of this paper, staged loading through construction of the temporary fill was being completed. Use of an ELD geotextile in this project provided the required lateral drainage, while simultaneously offering additional separation and reinforcement of the soft foundation soils.

9 CONCLUSIONS

Even though a prime cause for pavement distress is the presence of moisture in its structural layers, the use of internal drainage in pavement systems has not been typically adopted. While the volume of moisture within pavement sections may not be particularly significant, its removal cannot typically be accomplished with conventional drainage systems because soil moisture is stored under unsaturated conditions. Recent advances in the manufacturing of woven geotextiles have led to the incorporation of specially designed fibers with a unique cross-section characterized by the presence of deep grooves. The characteristics of this fiber cross-section promote capillary flow within the fiber itself, which provides enhanced lateral drainage by mobilizing moisture under unsaturated soil conditions.

This paper highlights a number of roadway situations that would benefit from the use of enhanced lateral drainage. Case histories in Missouri, Idaho, Montana, Texas, and California are presented to illustrate various scenarios where enhanced lateral drainage should be considered in the pavement cross-section. More importantly, the case histories also include post-construction evaluation of the ELD geosynthetic's performance, either through assessment of lateral drainage, condition survey of pavement sections with and without ELD geosynthetics, or in-situ monitoring of moisture content. The following conclusions can be drawn from the information presented in this paper:

- Conventional geosynthetic and granular drainage systems are unable to convey flow from base and subgrade materials under unsaturated conditions. Thus, the incorporation of wicking yarns into woven geotextiles has led to the development of ELD geosynthetics, which are capable of conveying moisture stored in these unsaturated pavement layers.
- Specific applications of ELD geosynthetics in roadway systems have been identified to be beneficial to pavement performance. They include: (1) enhanced lateral drainage of moisture migrating upward from a high water table; (2) enhanced lateral drainage of moisture infiltrating downward from the surface; (3) control of frost heave-induced pavement damage; (4) control of pavement damage caused by expansive clay subgrades; and (5) enhanced lateral drainage in projects involving soil improvement.
- The use of ELD geosynthetics has shown pavement benefits complementing those strictly related to enhanced lateral drainage. This includes multiple additional applications of geosynthetics in

pavements, including separation (see all five case histories), subgrade stabilization (see Missouri, Montana, Texas, and California case histories) and base stabilization (see Idaho case history).

- The use of ELD geosynthetics, often because of additional applications they offer, has shown cost savings associated with a decrease in thickness of the base layer (see Missouri, Idaho, and California case histories).
- Evaluation of post-construction performance indicates that use of ELD geosynthetics provides the intended enhanced drainage. This is based on an evaluation of field observations of effective lateral drainage (see Missouri, Idaho, Montana, and California case histories), condition surveys to compare performance of pavement sections with and without ELD geosynthetics (see Montana and Texas case histories) or in-situ monitoring of moisture content (see Texas case history).

Overall, data on roadway performance from a number of case histories reported in this paper indicates that enhanced lateral drainage in roadways can often offer significant opportunities to improve the performance of a wide range of transportation projects.

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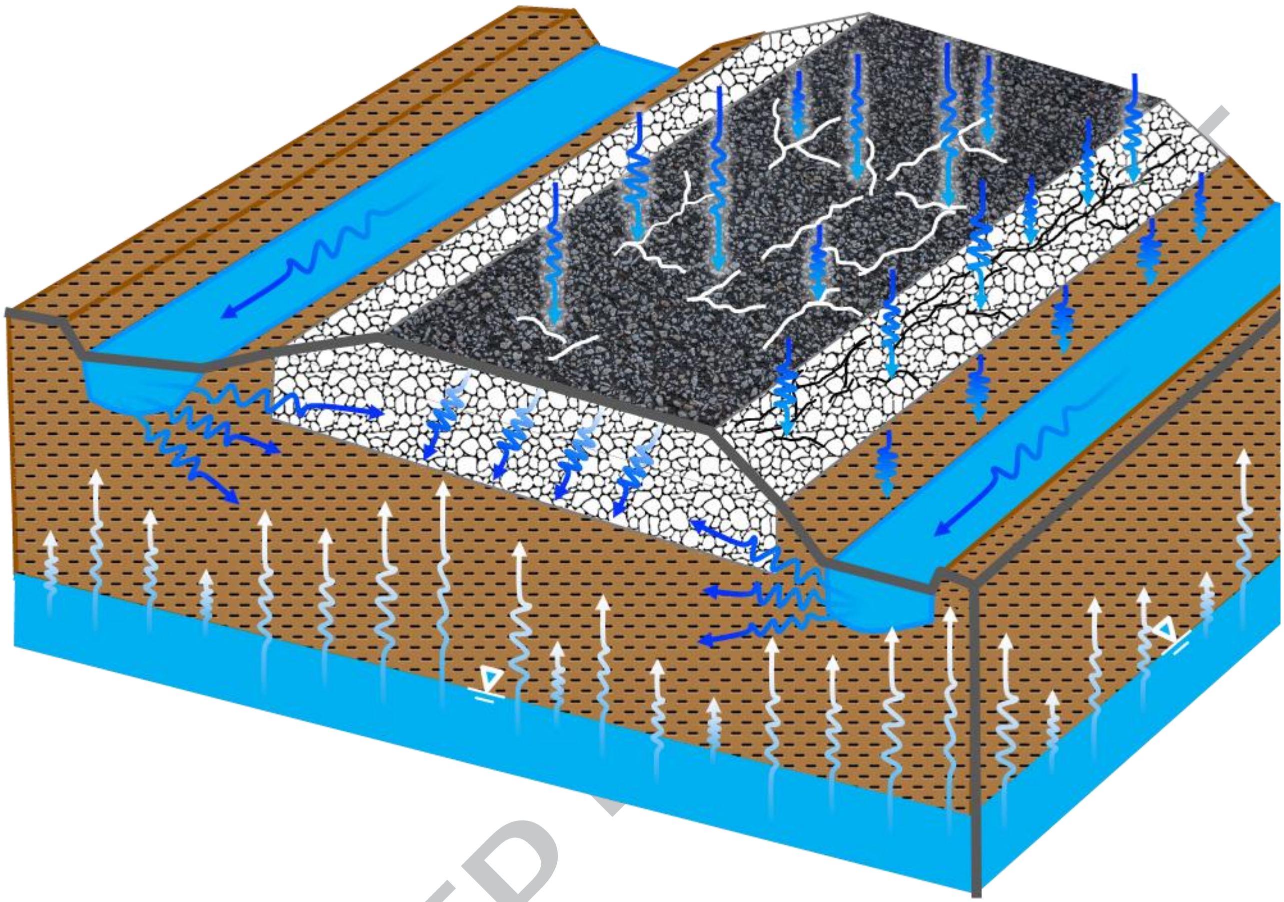


Figure 1: Multiple sources of moisture migration into a roadway

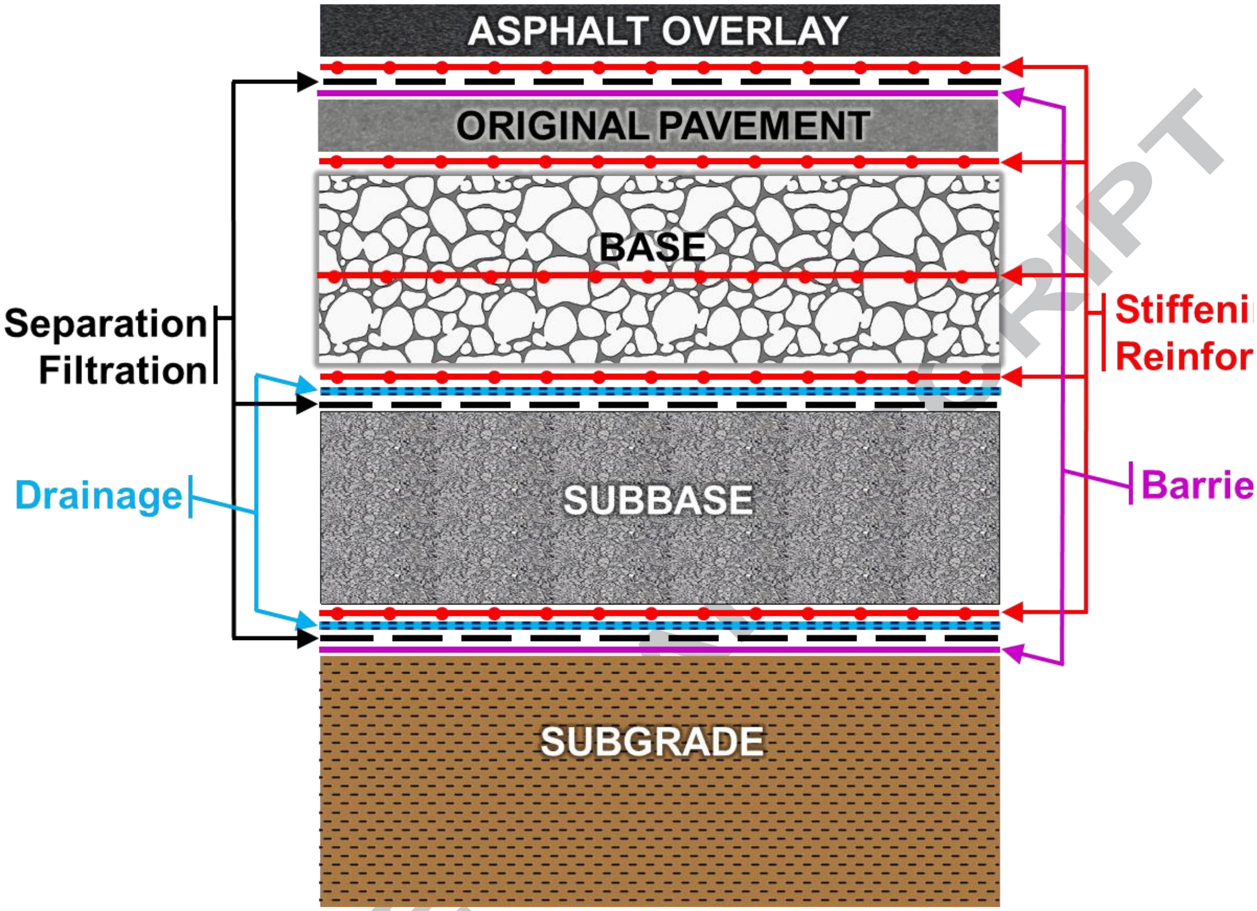


Figure 2: Multiple functions of geosynthetics in roadway applications

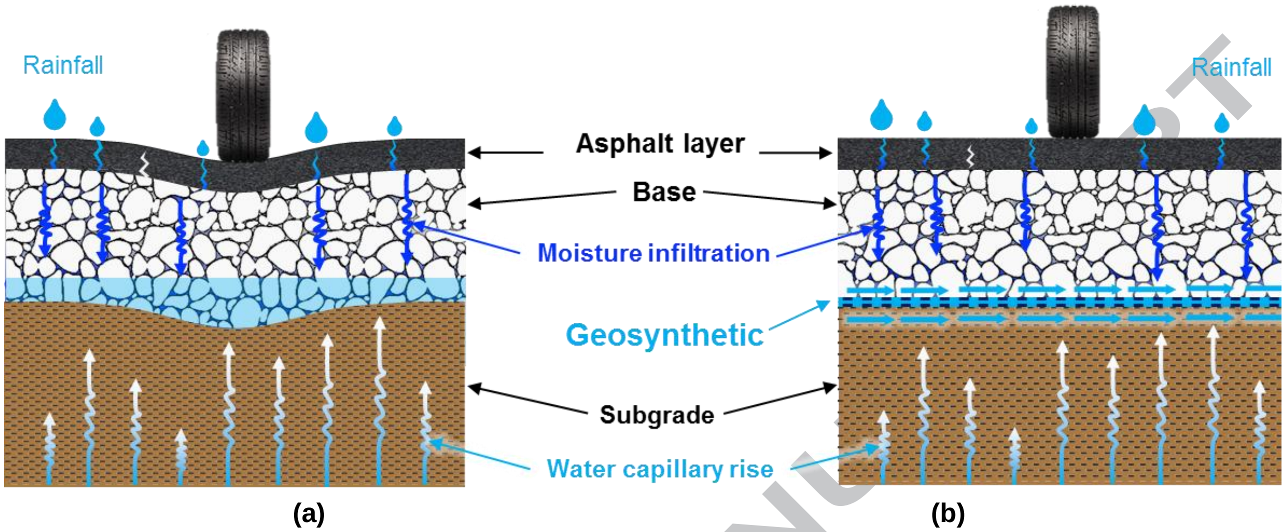


Figure 3: Road cross-section: (a) not including geosynthetics for lateral drainage; (b) including geosynthetics for lateral drainage.

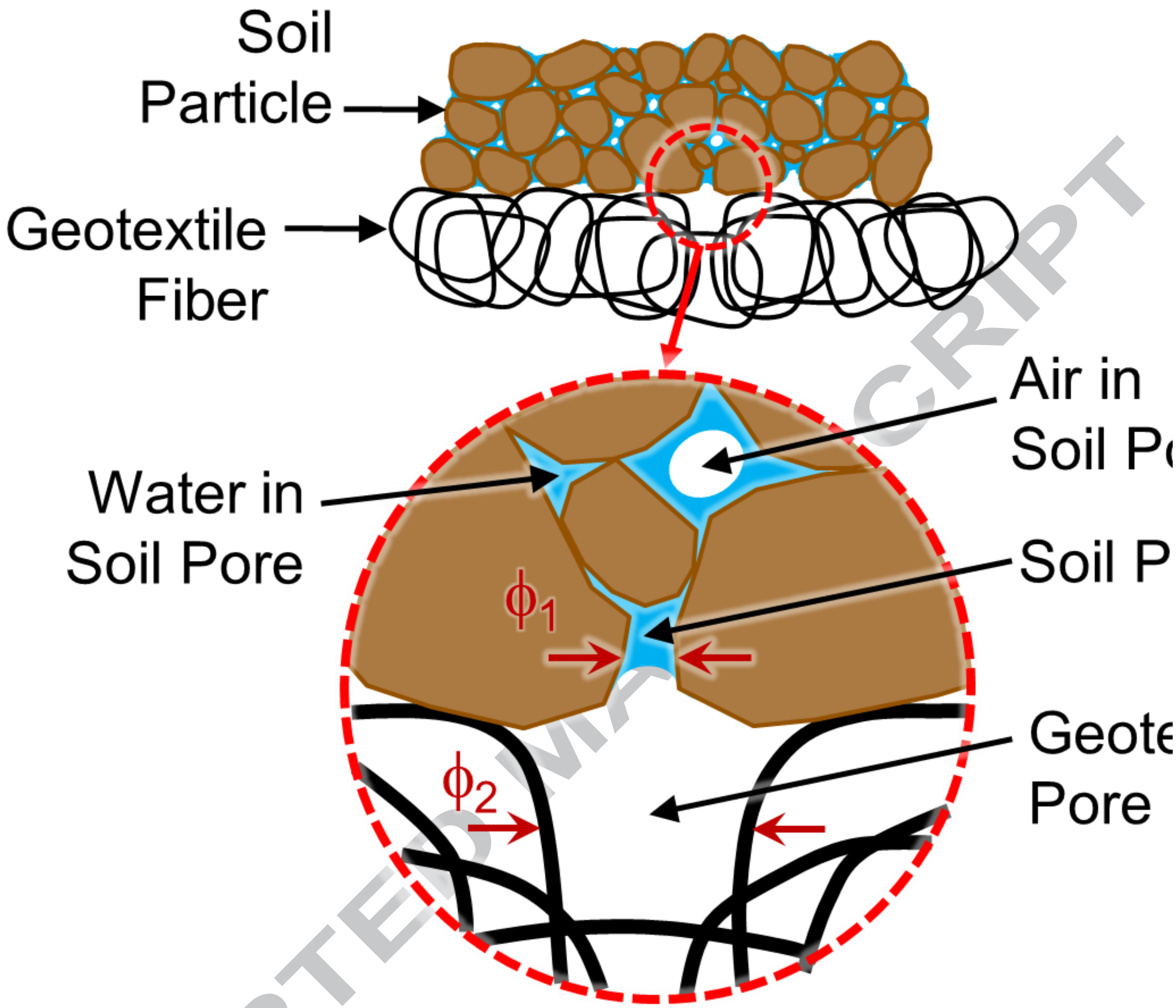
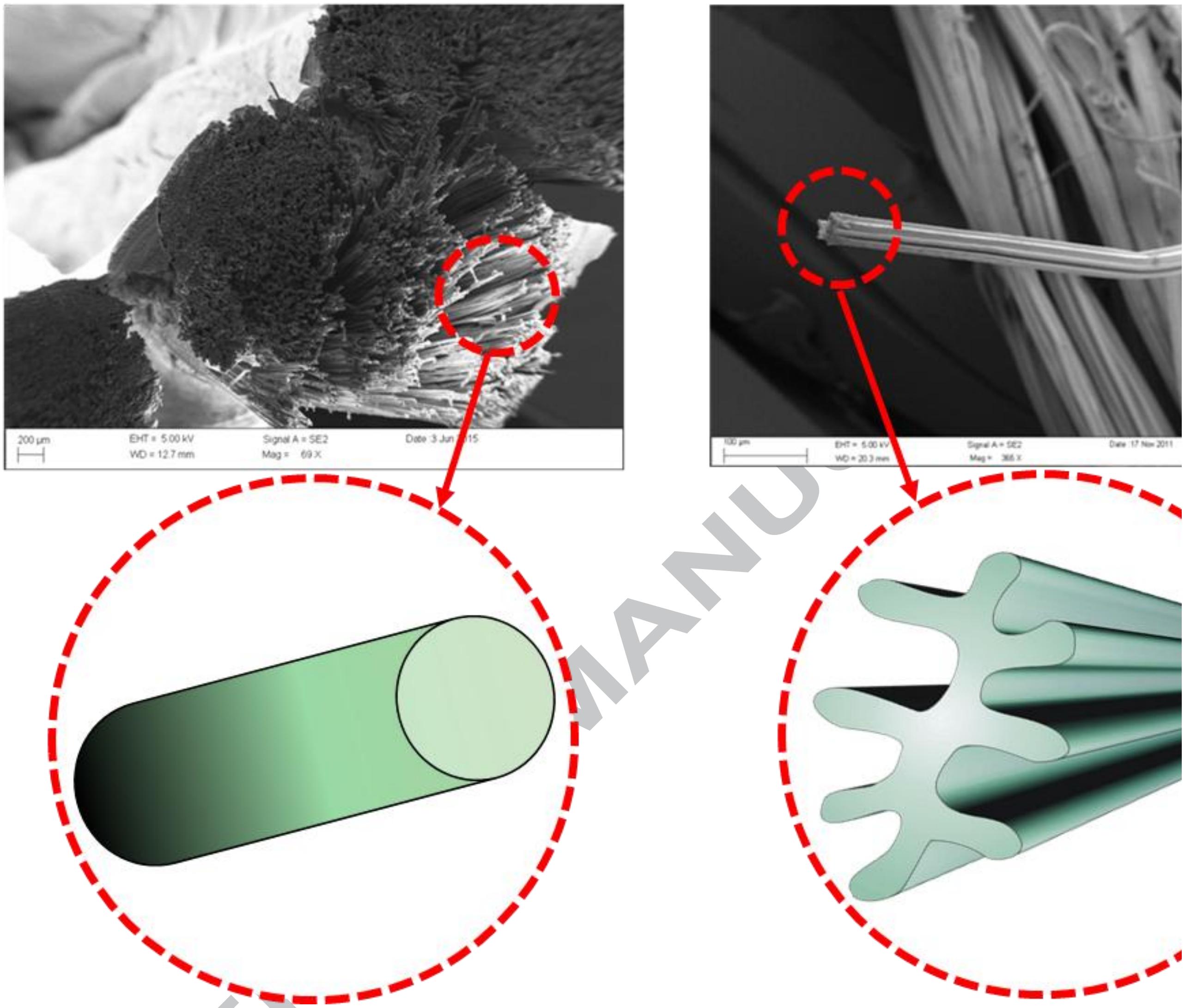


Figure 4: Schematic of capillary break effect at soil-geosynthetic interface



(a) (b)

Figure 5: Cross-sections of fibers in geotextiles, (a) typical monofilament fiber, (b) grooved fiber used in manufacturing of ELD geotextiles

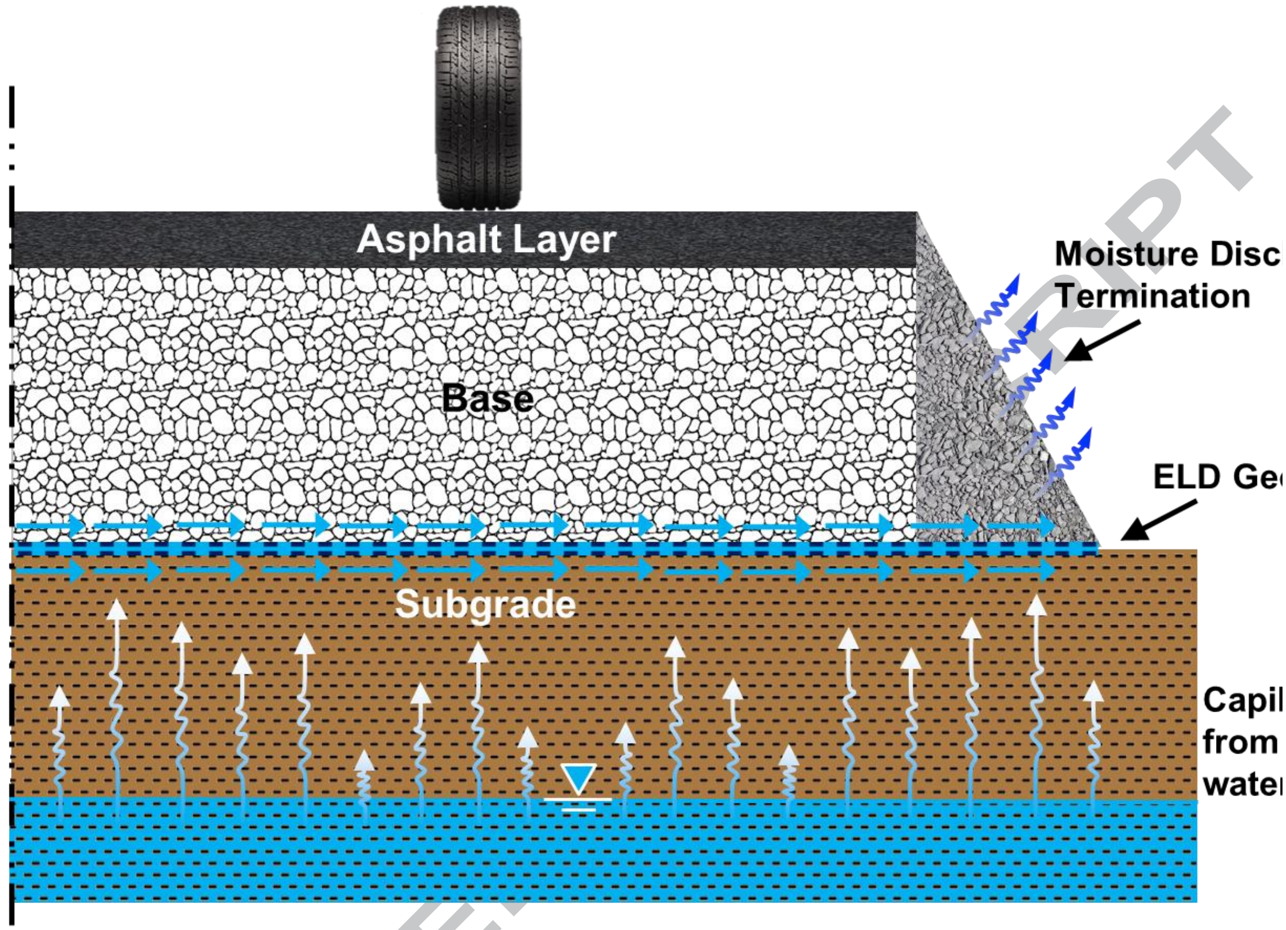


Figure 6: Enhanced lateral drainage of moisture migrating upward from a high water table

(a) (b)

Figure 7: Construction of bridge approaches to Daniel Boone Bridge: (a) placement of base aggregate over drainage geotextile, (b) visible drainage at edge of geotextile after placement
Note: Arrow points to indication of visible effective drainage

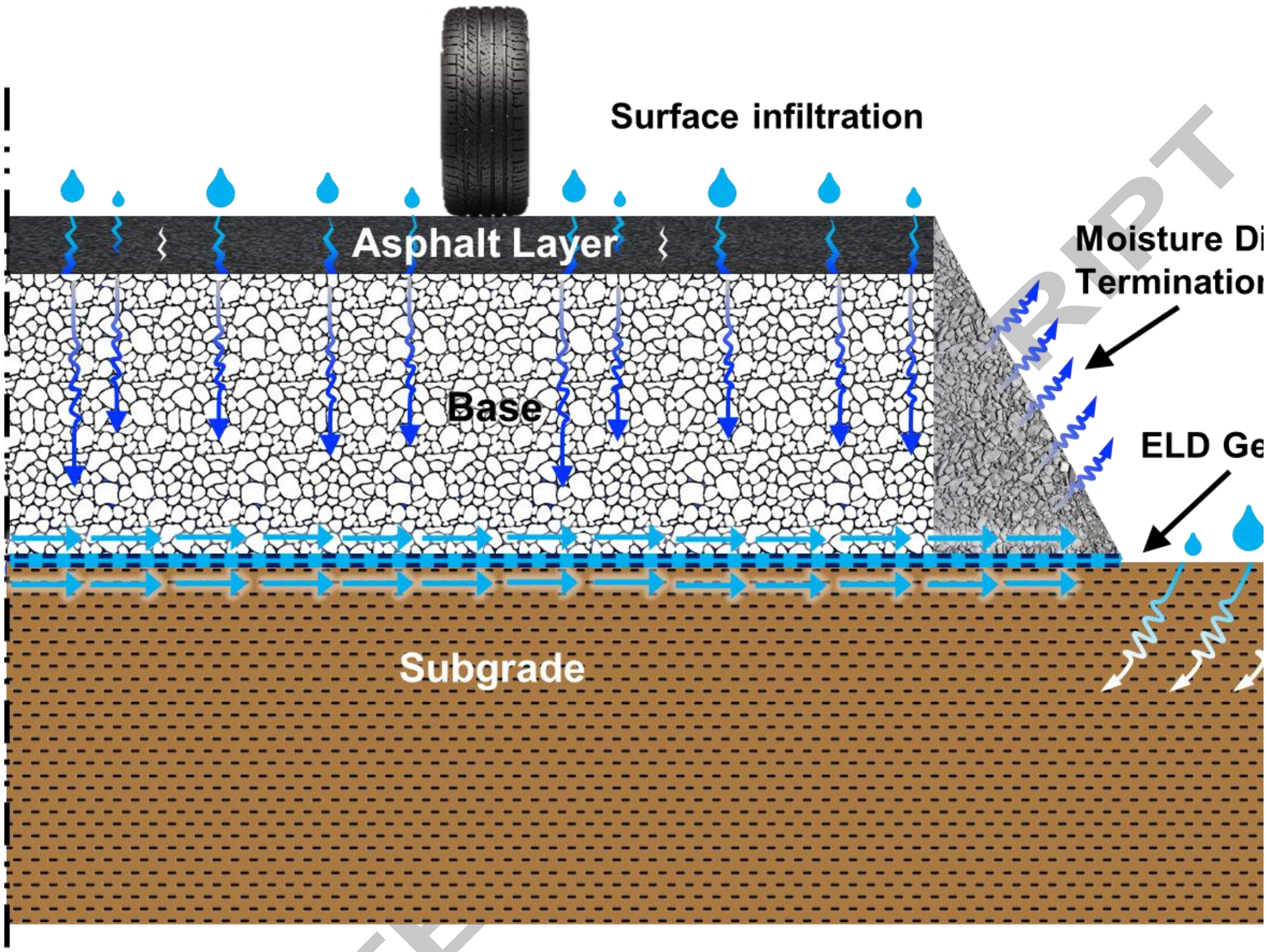


Figure 8: Enhanced lateral drainage of moisture infiltrating downward from the surface

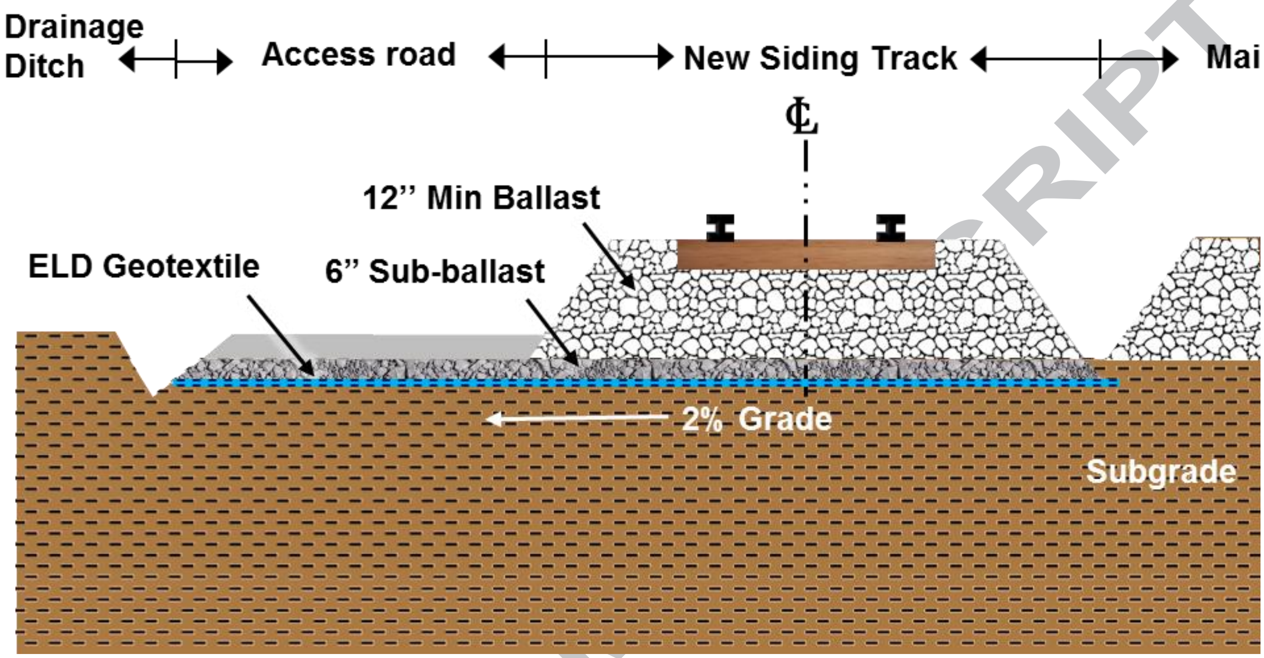


Figure 9: Cross-section of Garwood Railroad siding

Figure 10: Completed Garwood Railroad Siding project with visible moisture line at geotextile level

Note: Arrow points to indication of visible effective drainage

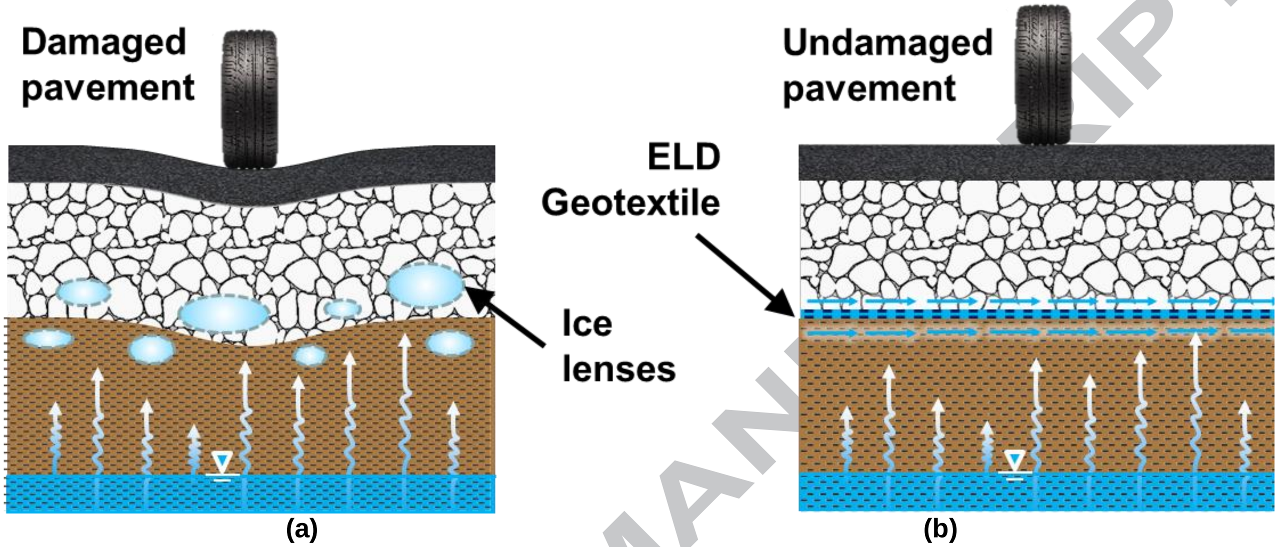


Figure 11: Control of frost heave-induced pavement damage: (a) Without use of ELD geosynthetic, (b) With use of ELD geosynthetic.

(a) (b)

Figure 12: Longitudinal cracks previous to 2004 repair: (a) Typical frost heave-induced crack; (b) View of major longitudinal crack repaired using cold mix

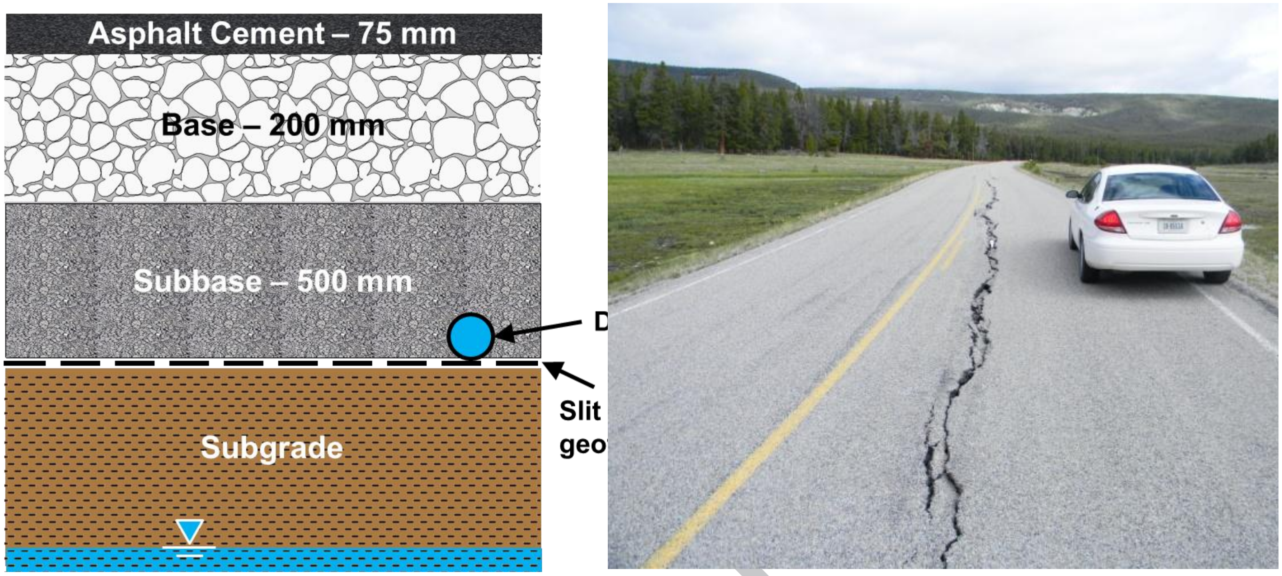


Figure 13: Pioneer Mountain Bayview, 2008 repair without ELD geosynthetic: (a) Typical cross-section; (b) Reappearance of longitudinal crack after repair

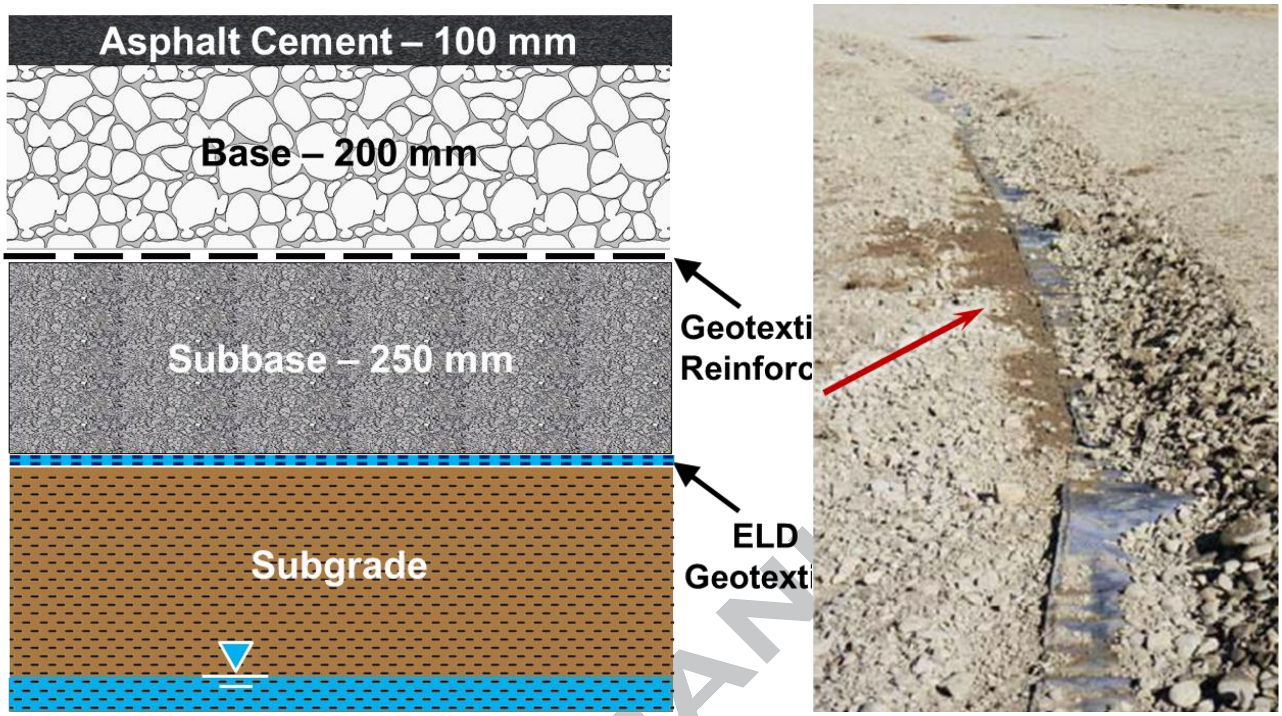


Figure 14: Pioneer Mountain Bayview, 2013 repair with ELD geosynthetic: (a) Typical cross-section; (b) View of effective drainage soon after geosynthetic installation

Note: Arrow points to indication of visible effective drainage

Figure 15: View of sections rehabilitated with ELD (top) and without ELD (bottom). Note longitudinal crack in section without ELD, which does not propagate into section with ELD

Note: Arrow shows where the old road meets the new road

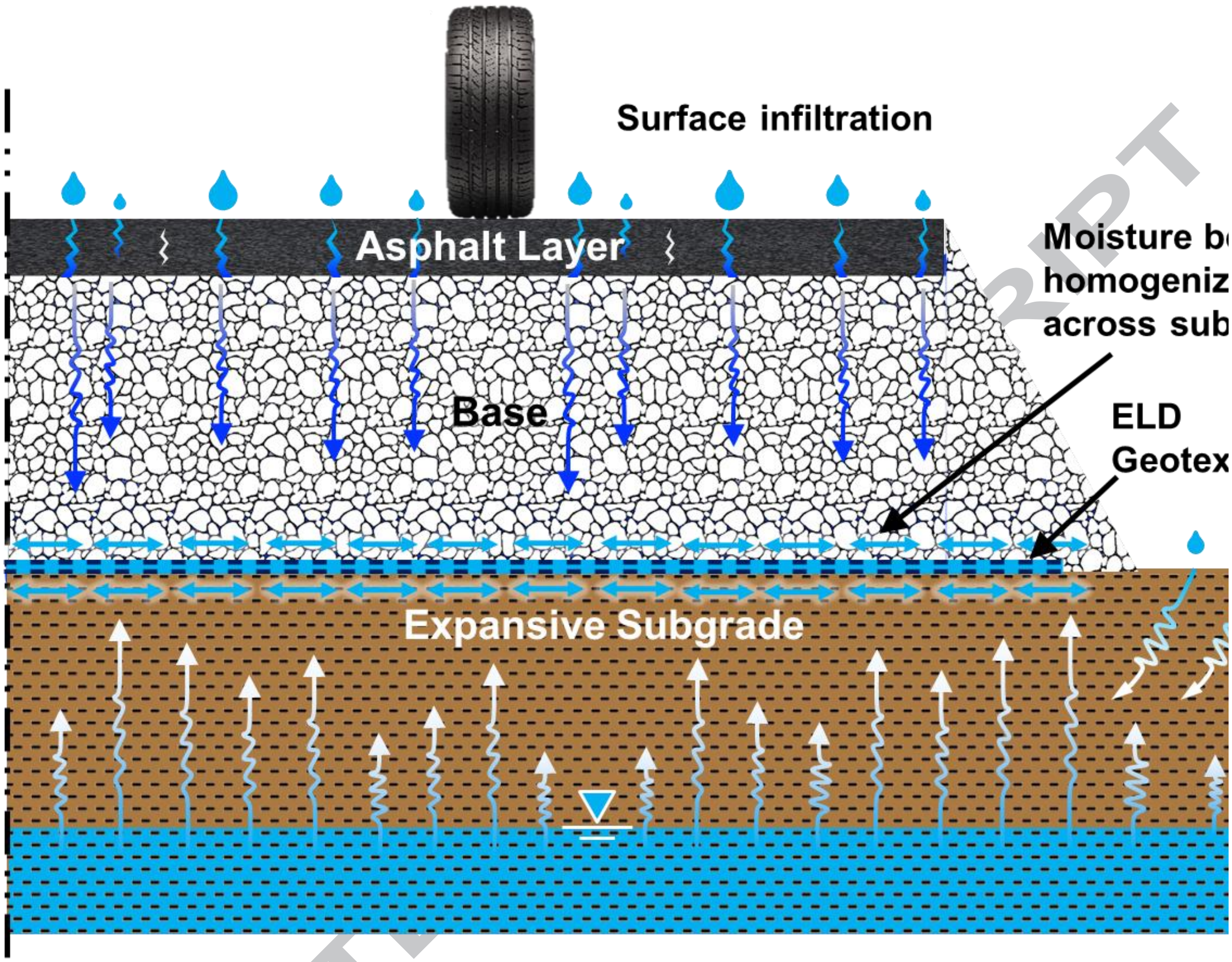


Figure 16: Control of pavement damage caused by expansive clay subgrades

Figure 17: Extensive cracking of SH21 in 2012, as observed before rehabilitation of the road

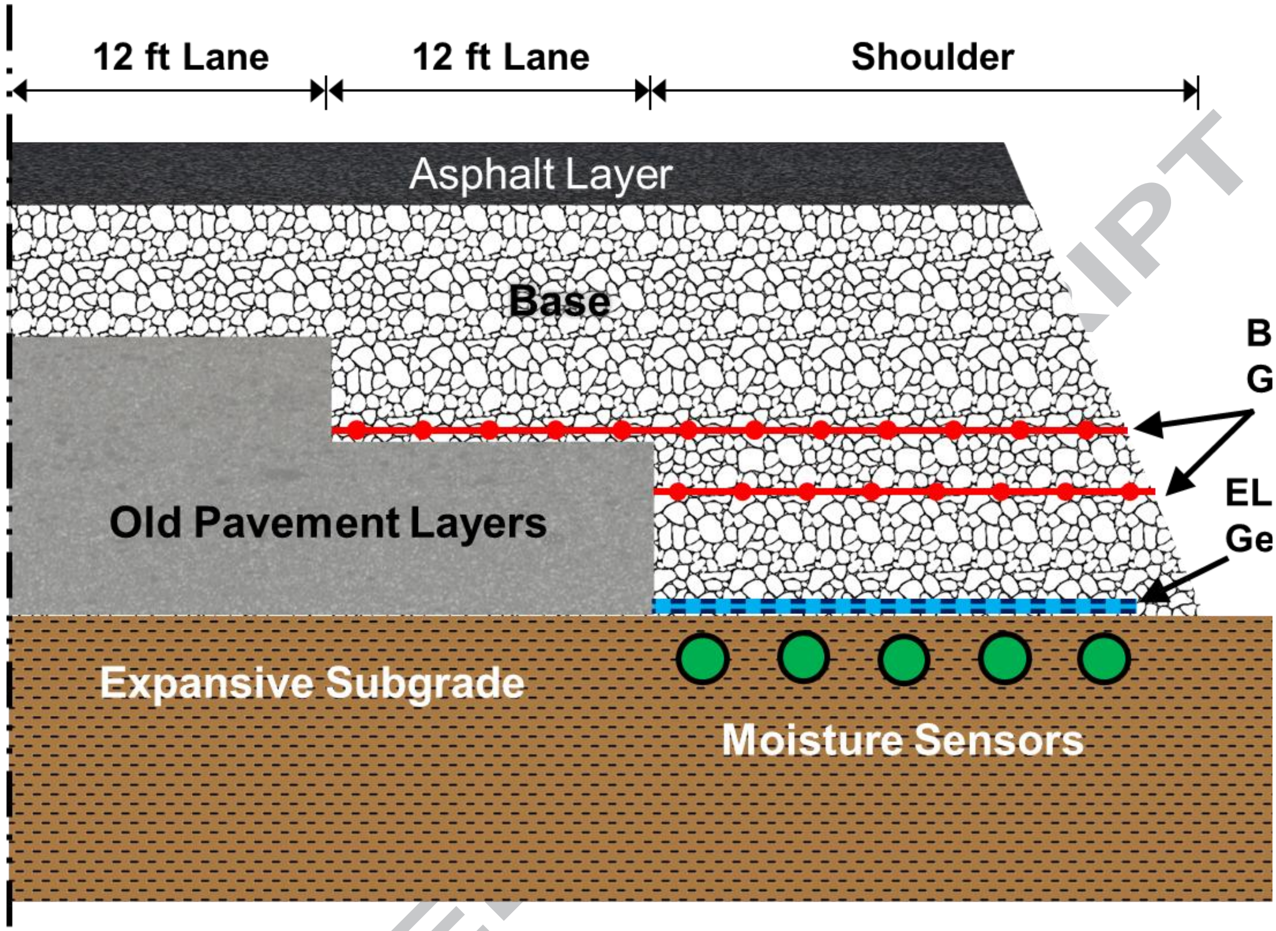


Figure 18: Cross-section of widening of SH21, including use of ELD geosynthetics and installation of moisture sensors

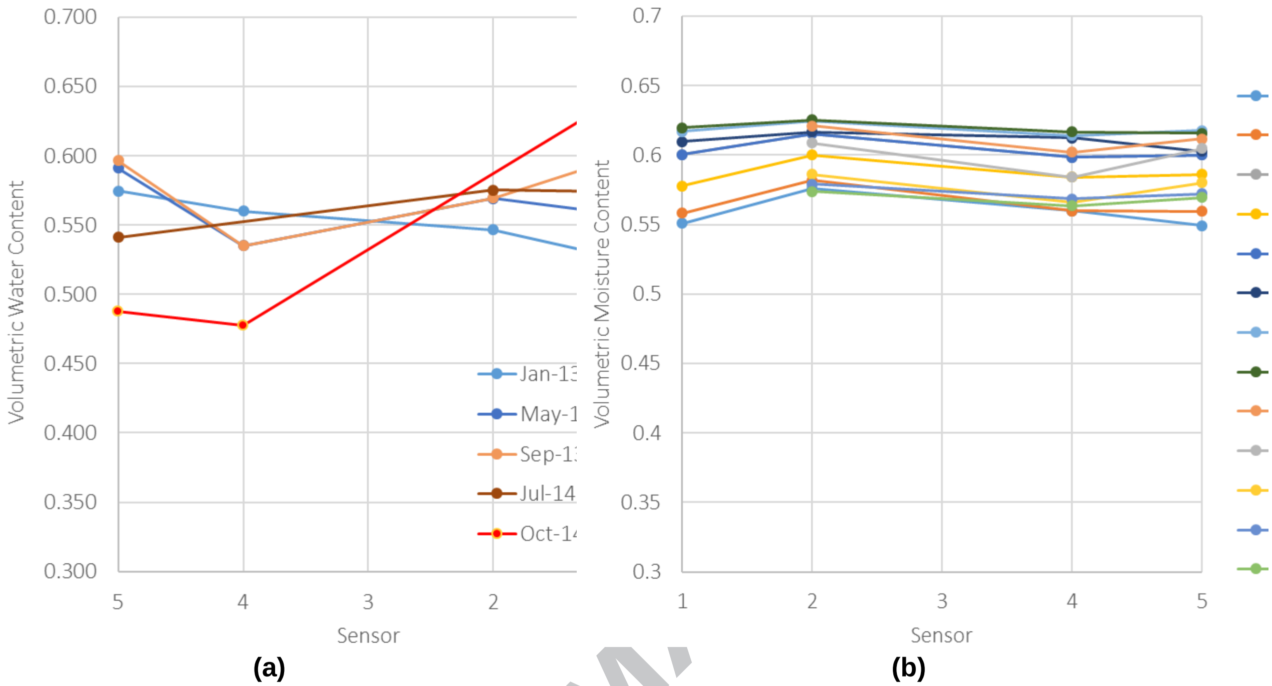


Figure 19: Distribution of moisture content along the shoulder of SH21: (a) In section without ELD geosynthetic (only with conventional geotextile), (b) In section with ELD geosynthetic

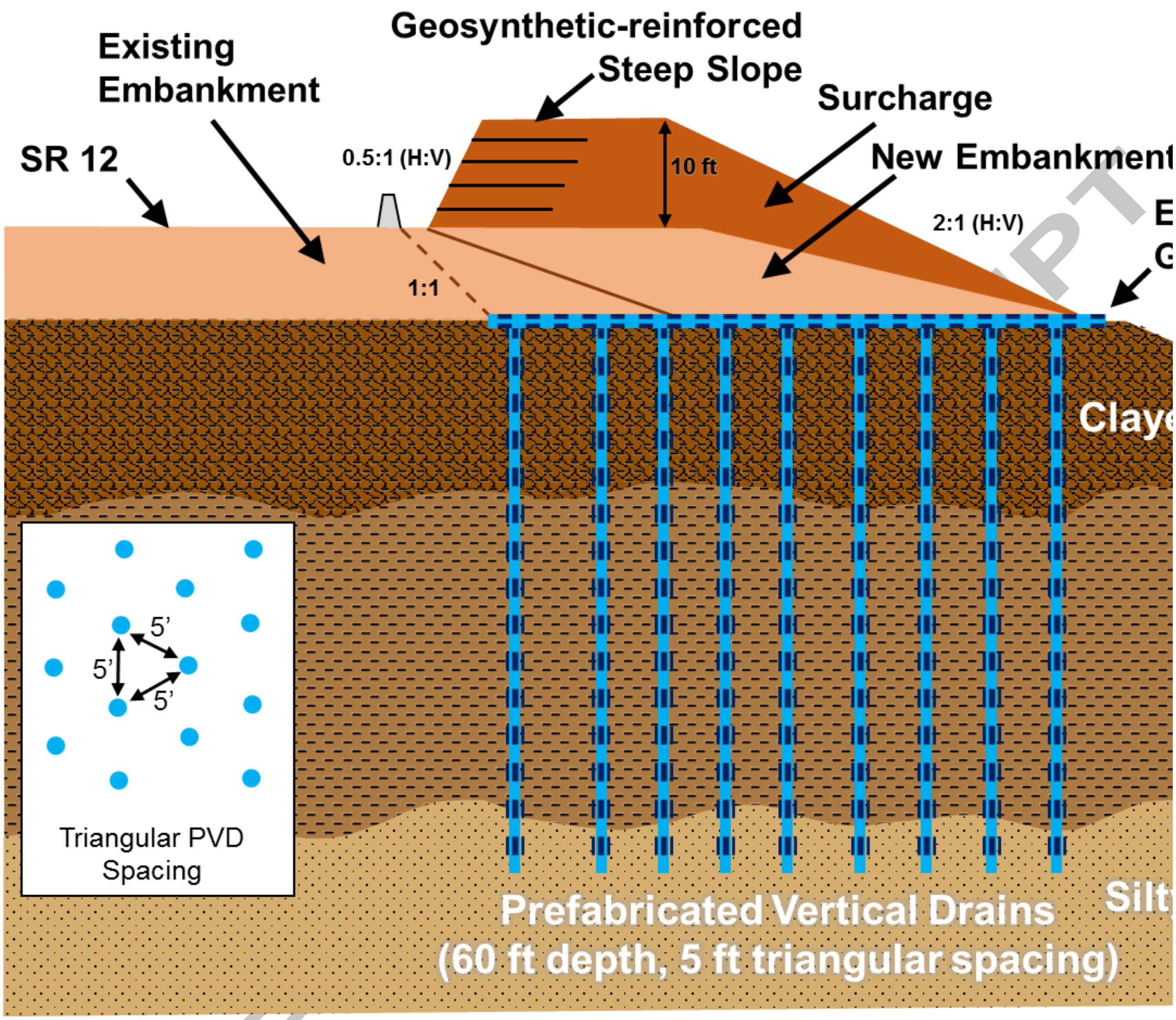


Figure 20: Cross-section of SR12 soil improvement plan, including ELD geosynthetic for lateral drainage of consolidation water

(a) (b)

Figure 21: Implementation of SR12 soil improvement project: (a) View of PVD for accelerated consolidation; (b) View of effective drainage through ELD geosynthetic