Use of Wood Fiber and Geotextile Reinforcement To Build Embankment Across Soft Ground

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A case history describing the use, by the Washington State Department of Transportation, of wood fiber and geotextile reinforcement in combination to build a lightweight fill across very soft ground is presented. The fill was completed in 1988 as part of a newly constructed two-lane highway, State Route 109 Spur, west of Hoquiam, Washington. The fill, 180 m long and 13.4 m high, was built over organic sandy and clayey silt up to 15.2 m thick having an undrained shear strength of 7.2 kPa and SPT values of $^{1}/_{61}$ cm. A conventional earth fill was not feasible for stability reasons. Wood fiber was used to reduce the driving forces, to enhance stability, and to reduce fill settlement to an acceptable magnitude. Five layers of geotextile were used to prevent lateral spreading and enhance stability. The geotextile layers were in the bottom 2.1 m of the fill. The rate of fill placement was controlled to take advantage of strength gain in the foundation soil to enhance stability. Total settlement of the fill over 2 years, before paving, was 1.2 m. The fill was allowed to settle approximately 1.1 year before paving. The use of the wood fiber with geotextile reinforcement was $730,000 less costly than a bridge.

This paper describes the design and construction of a portion of new highway, State Route 109 Spur, by the Washington State Department of Transportation (WSDOT) in a coastal area of western Washington. The new 2.86-km segment of two-lane highway begins just outside the western city limits of Hoquiam, Washington, and extends northeasterly connecting with SR-101 (Figure 1). Grading construction at the site began in late 1986 and was complete in fall 1987. The roadway was paved in late 1988.

The southern end of the highway begins near sea level and traverses undeveloped timber and swampland. Initially the roadway makes a 56-m cut through a bluff. Then for about 180 m it crosses swampland, which is the subject site area, and continues through a cut, across the Little Hoquiam River, and then roughly parallels the Little Hoquiam River with sidehill cuts and fills to its terminus.

The design and construction of a lightweight wood fiber fill, reinforced with geotextile layers, built across the very soft valley soils are discussed. In addition, controlled rate of construction and instrumentation control were used to maintain stability and a delay period to mitigate settlement.

SITE DESCRIPTION

At the site area the roadway grade crosses about 13.4 m above the valley floor. The valley floor is at an approximate elevation of 2 m. Foundation soils are very soft and compressible, posing stability and settlement problems for any fills and necessitating deep foundation support systems for any bridge. An unnamed creek flows year round through the site. The water level in the creek is influenced by tidal action in Grays Harbor and with winter rainfall results in frequent flooding of the valley.

SITE GEOLOGY

During the Eocene to middle Miocene epochs, thousands of feet of sedimentary rocks were deposited on the much older volcanic rocks already present in the Olympic Peninsula area of northwest Washington State. Subsequent deformation and uplift of these rocks during the middle to late Miocene epoch formed the Olympic Mountains.

Consequent erosion and deposition of the eroded material from the Olympic Mountains and the Willapa Hills occurred during the late Miocene to the Pliocene epochs. The lowlands bordering what is now Grays Harbor received the eroded sedimentary material. These sediments range from fluvial sands and gravels to fine-grained lacustrine silts and clays.

The hillsides on both sides of the site area are composed of fairly well indurated river-laid sand, gravel, and silt, as shown in Figure 2. Recent alluvium filled the valley bottom at the fill site area, overlying the sands and gravels.

SOIL CHARACTERIZATION

Soil conditions at the fill area consist of very dense silty gravelly sand overlain by about 5 m of dense silty sand, 3 m of loose sandy silt, and 12 m of very soft organic sandy silt. A cross section of the soil stratigraphy beneath the fill is shown in Figure 3. The surficial layer of organic sandy silt controlled design of the highway fill.

The average standard penetration test blow count for the organic sandy silt was less than one. The effective unit weight was from 1.38 to 4.52 kN/m^3, with an average of 2.99 kN/m^3. In-place moisture content varied from 94.3 to 363.9 percent, with an average of 171.9 percent. The liquid limit varied from 61 to 90 percent and the plastic limit from 53 to 65 percent.

The average unconsolidated undrained strength as determined from triaxial shear testing was 7.2 kPa. Field vane shear testing was unsuccessful because of the existence of fibrous peat, twigs, and roots. During construction a temporary earth

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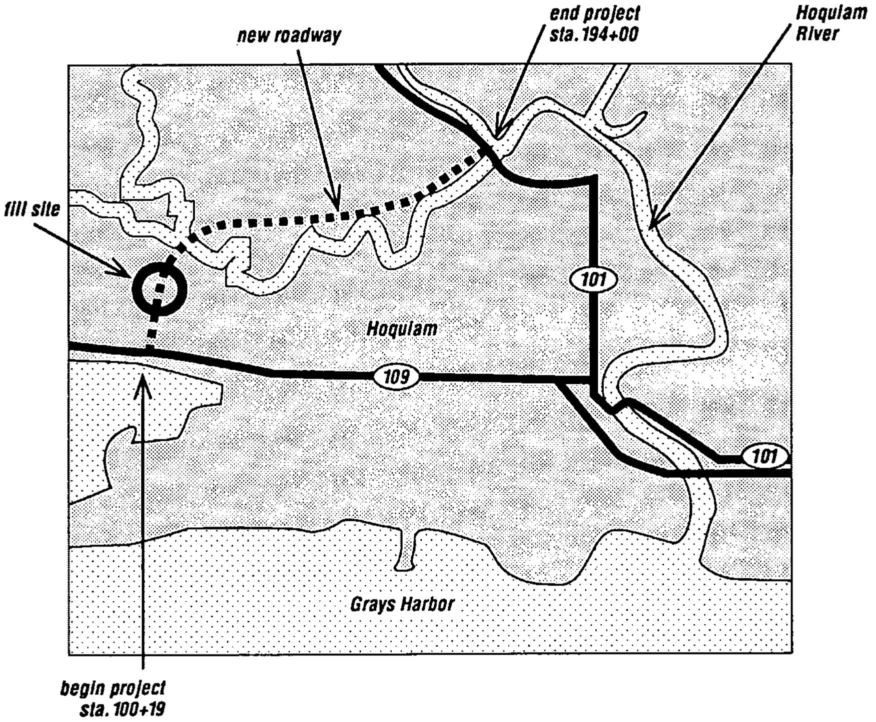

FIGURE 1 Project vicinity map.

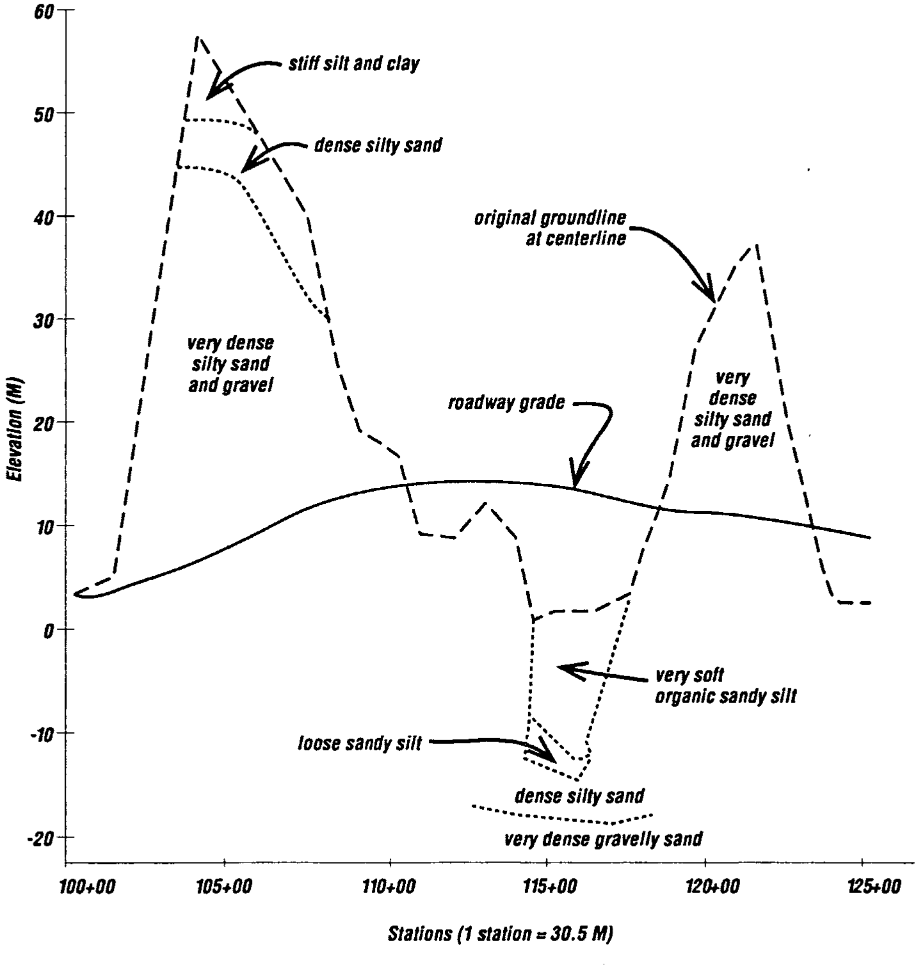

FIGURE 2 Generalized soil profile at site.

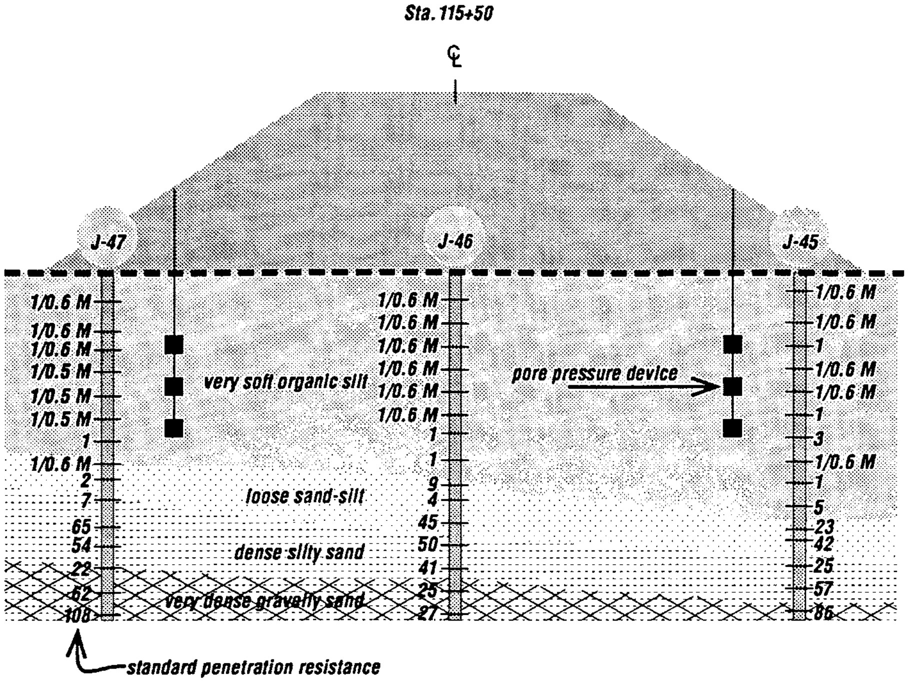

FIGURE 3 Soil cross section at wood fiber fill location.

stockpile was rapidly built 4.6 m high over the same geologic deposit about 1.6 km away, and failed. Back analysis of that fill failure yielded an undrained shear strength 10.6 kPa. The average undrained sheer strength used for the design was 7.2 kPa. On the basis of consolidated undrained triaxial tests, with pore pressure measurement, an effective angle of internal friction of 15 degrees was used.

Laboratory consolidation testing was also performed for the site. On the basis of test results, a compression index of 0.13, a coefficient of consolidation of 33.8 m^2/yr, and a coefficient of secondary compression of 0.008 were used for design.

DESIGN OF GEOTEXTILE-REINFORCED WOOD FIBER FILL

The stability of the fill was evaluated initially for two potential modes of failure—rotational slope stability and bearing capacity. Fill settlement was also considered. The total height of fill required, including surfacing, was to be 13.4 m to meet roadway grade requirements. Proposed side slopes were limited to 2H:1V to limit the right-of-way and fill volume required and to minimize the wetlands taken.

Through inspection and engineering judgment it became obvious that the use of granular soil for the entire fill would be impractical because of stability and settlement problems resulting from the soft, weak nature of the foundation soil. The fill construction rate needed to ensure stability would require the fill to be built slowly over 20 months to provide the necessary soil strength gain, which was considered to be impractical. Without strength gain of the foundation soil, the maximum height of granular fill that could safely be constructed was determined to be approximately 3.7 m, which correlated well with observations of the performance of previously built fills near the site 3.0 to 3.7 m high. Settlement of a granular fill 13.4 m high was estimated to be 2.4 m, with primary consolidation taking approximately 3 years to occur once fill construction began. This amount of settlement was considered to be excessive, especially considering that a culvert 1.5 m in diameter would be required at the base of the fill.

On the basis of this initial analysis, it was determined that alternative methods of fill construction would be required. Options considered included the use of lightweight wood fiber fill, controlled fill construction rates, geotextile reinforcement, or a combination of two or more of these. The final design selected for the embankment was a combination of all three. The design was optimized to minimize settlement, construction time, and the right-of-way and fill volume required, yet still provide a stable embankment with a minimum factor of safety of 1.25 for slope stability and 1.5 for bearing capacity.

Wood fiber could not be used to construct the entire fill. Environmental constraints dictated that the wood fiber must not extend below the mean high-water level. Because of the potential for a large settlement and this environmental constraint, the bottom 1.5 m of fill was constructed using a silty gravelly sand. A significant thickness of surfacing was also required, because of the compressibility of the wood fiber fill and heavy truck traffic, to provide acceptable roadway performance. A 1.2-m surfacing thickness was used for design. The remainder of the fill was constructed using lightweight wood fiber fill. The lightweight fill material was assumed to have a unit weight of 6.3 kN/m^3 and an angle of internal friction of 40 degrees. The granular soils used in the fill were assumed to have a unit weight of 19.6 kN/m^3 and an angle of internal friction of 37 degrees.

The number of geotextile reinforcement layers required was determined such that the amount of soil shear strength gain required for stability would be approximately the same for both the bearing capacity and slope stability mode of failure. Therefore, the soil shear strength required to meet factor of safety requirements for bearing capacity was first determined. On the basis of that shear strength, the number of geotextile layers required to meet factor of safety requirements for slope stability was determined. It was necessary to keep the required geotextile tensile strength low enough that commonly available geotextiles could be used if possible.

The reinforced fill was designed using the methodology in the FHWA *Geotextile Engineering Manual* (*1*). The geotextile reinforced portion of the embankment was assumed to act as a mat, distributing the vertical load due to the weight of the fill evenly over the width of the fill. This assumption was considered valid if the reinforced embankment is designed to resist lateral spreading (*1*). The bearing capacity of the soil, determined using two-layer theory (*2*), was compared with the average vertical stress at the base of the embankment to determine the bearing capacity safety factor. Slope stability was determined using the Bishop method.

The final embankment configuration resulting from this design is given in Figure 4. Six geotextile reinforcement layers at an allowable tensile strength of 23 kN/m were required because of slope stability and lateral spreading considerations. The geotextile reinforcement is needed only until the soil gains enough strength to support the fill without reinforcement, which would result in the geotextile reinforcement layers being fully loaded for up to 8 months, on the basis of the calculations. The geotextile layers were therefore considered to be temporary, allowing a relatively high creep limit of 60 percent of ultimate to be used. This resulted in an ultimate wide width tensile strength of 38 kN/m to be required. The reinforcement was also designed to resist lateral deformation of the embankment by requiring a secant modulus of 230 kN/m at 10 percent strain. The geotextile selected by the contractor to meet these property requirements was a polypropylene slit film woven geotextile with a unit mass of 190 gm/m^2.

An organic root mat was at the ground surface below the proposed fill. The root mat was considered to possess tensile strength not accounted for in the soil shear strength design values used. The root mat tensile strength was assumed to be equivalent to the tensile strength of one geotextile reinforcement layer, or 23 kN/m. Therefore, the number of geotextile layers required at the maximum embankment height could be reduced to five (see Figure 4). The strength of the root mat was preserved by requiring a working platform to be constructed and the surface root mat not to be disturbed.

The calculations indicated that the soil shear strength had to increase to 16.8 kPa to provide the needed embankment stability, assuming five layers of reinforcement were used.

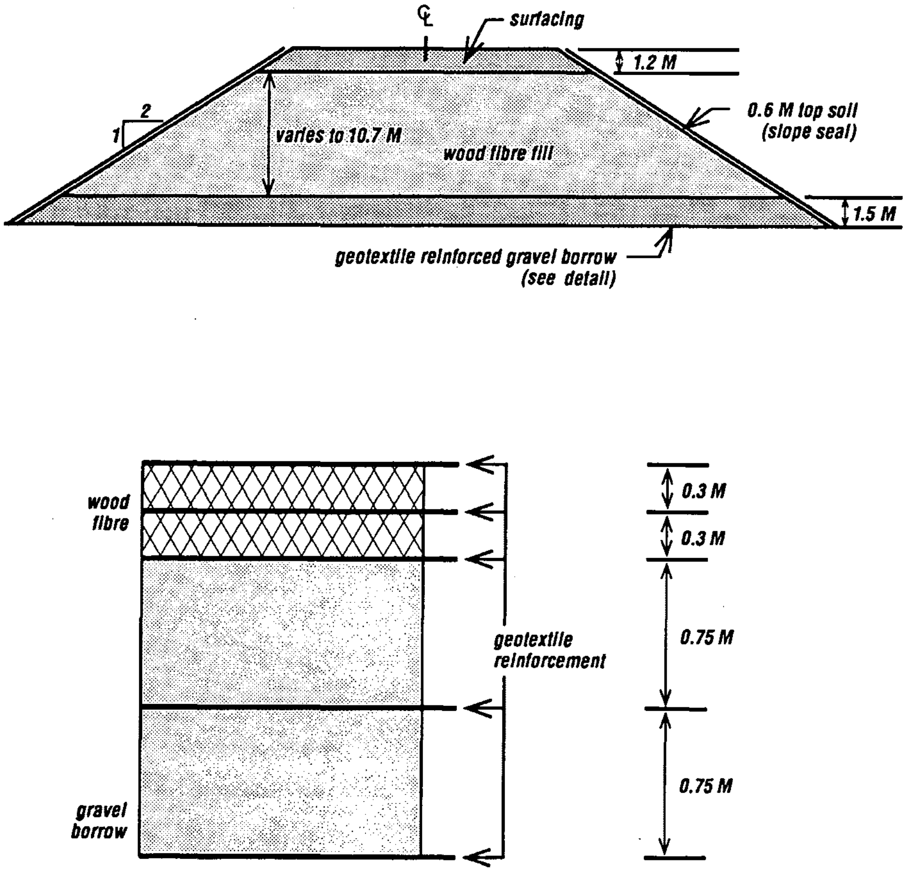

FIGURE 4 Design cross section for reinforced wood fiber fill: *top*, fill cross section; *bottom*, geotextile reinforcement detail.

The amount and rate of strength gain expected were established using the triaxial drained strength and consolidation parameters obtained from the laboratory test program provided and using the methodology of Su et al. (*3*). It was estimated that fill construction would take a minimum of 4 months, or 0.7 m/week, to ensure that the embankment would remain stable during construction. The pore pressure response of the foundation soil to embankment loading was actually used to control the embankment construction rate. On the basis of the laboratory test data and subsequent analysis, the ratio of pore pressure increase to the maximum embankment vertical load was required to be 0.33 or less to ensure embankment stability during construction.

Embankment settlement was determined using the laboratory consolidation data obtained at the site and conventional settlement estimating techniques. The two issues regarding settlement that had to be addressed were (a) the effect of the settlement magnitude on the culvert at the base of the fill and on the amount of embankment overbuild required and (b) the time required for settlement to be complete so that the time to begin paving could be determined. Primary settlement for the wood fiber fill was estimated to be approximately 1.5 m. Accounting for a fill construction time of 4 months, this settlement was estimated to take up to 21 months to be completed once fill construction began. Secondary consolidation was estimated to be approximately 0.13 m over the following 20 years.

The settlement magnitude estimated was used to determine the amount of overbuild required. It was necessary for wood fiber to be used for the additional fill, instead of granular surfacing above the wood fiber, as much as possible to minimize the load added to the embankment. The length of time required for settlement was longer than normally desirable for a highway fill. In this case, however, the long settlement period could be tolerated in the highway completion schedule.

Because the culvert had to be installed before embankment construction because of the presence of a small creek, the culvert had to be designed to tolerate the large settlement expected. First, the culvert and creek were moved to the edge of the fill area where the depth of compressible soil was less and settlement was less severe. The 1.5-m culvert was also sized 0.3 m in diameter larger than needed so that if a sag in the culvert developed, the culvert would still have adequate flow capacity. Finally, a minimum camber of 0.3 m was placed in the culvert to account for differential settlement along the length of the culvert.

FILL SPECIFICATION AND CONSTRUCTION

Specifications for installing the geotextile reinforcement in the fill were developed on the basis of the FHWA *Geotextile Engineering Manual* (*1*). A working platform using granular soil with enough thickness to cover all stumps, logs, or other protrusions with 15 cm of material was required to preserve the root mat and minimize damage to the first geosynthetic layer. Stumps were cut flush with the ground as much as possible.

The contractor placed an unauthorized haul road in the area where the reinforced wood fiber fill was to be placed. The haul road was constructed of 2.4 to 4.6 m of silt fill. The contractor placed some trees and branches below the fill to help it float over the soft foundation soil. Test holes drilled through the fill showed that it did not break through the root mat and branches at the ground surface, although a considerable amount of displacement and settlement occurred. The contractor was required to completely remove the haul road fill from the site because of concern about creating an area under the final fill that would be partly consolidated and could cause the wood fiber fill to settle differentially.

Materials used for the fill consisted of gravel borrow and wood fiber fill, as mentioned. The gravel borrow, a silty 3.2 cm minus gravelly sand, was used for both the working platform and the bottom 1.5 m of fill. The remainder of the fill, with the exception of the top 1.2 m of surfacing, was well-graded wood fiber fill, consisting of fibrous, irregularly shaped particles that varied from 0.6 to 15 cm, predominantly 1.3 to 5 cm. The wood fiber as placed in the fill was fresh (not degraded), as required by the specifications. The as-compacted unit weight of the wood fiber fill was 6.0 kN/m^3, just under the 6.3-kN/m^3 unit weight assumed for design. A 0.6-m-thick top soil slope seal was placed on the outer surface of the wood fiber fill to protect it from oxygen and fire. The gravel borrow was compacted in maximum 20-cm lifts to 90 percent of maximum density using vibratory and static compaction rollers. The wood fiber fill was compacted by routing hauling equipment a minimum of two times with complete coverage over each lift. The maximum lift thickness allowed was 0.3 m. The minimum weight of the hauling equipment used to compact the fill was 15 T.

The geotextile was to be laid in the fill so that the machine direction would be perpendicular to the embankment centerline to ensure that maximum geotextile strength would be available in the direction of maximum stress. The strips of geotextile were to be joined together with sewn seams, using a double-sewn "J" seam, Type SSn-1, with parallel stitching placed 1.3 cm apart. The geotextile was actually shipped to the site with two rolls of geotextile sewn together using factory seams, forming 7.6-m-wide panels. In general, the factory-sewn seams were of a higher quality than the field-sewn seams. The poorer quality of the field-sewn seams was the result of worker inexperience with sewing, difficulty in getting the geotextile panels properly lined up, attempting to work with too much geotextile at one time, and wind moving the geotextile panels around. The field sewing operation was labor intensive at times.

The specifications for fill placement over the geotextile were designed to (a) keep the weight and amount of fill uniformly distributed over the width of the fill, (b) minimize potential for damage to the geotextile during fill placement, and (c) use the weight of the fill to pretension the geotextile to limit deformation. A minimum thickness of 0.3 m of fill between the geotextile and the spreading equipment was required to prevent damage to the geotextile. One of two methods for fill placement was to be used to pretension the geotextile layers and keep the fill evenly distributed across the fill width, depending on whether a small, controlled mudwave formed as the fill was placed. If a mudwave formed, the fill was to be placed using a concave advancement pattern, as shown in Figure 5. If a mudwave did not form, the fill was to be placed in a convex advancement pattern (Figure 6). Generally for fills over soft soils, the mudwave will form only during place-

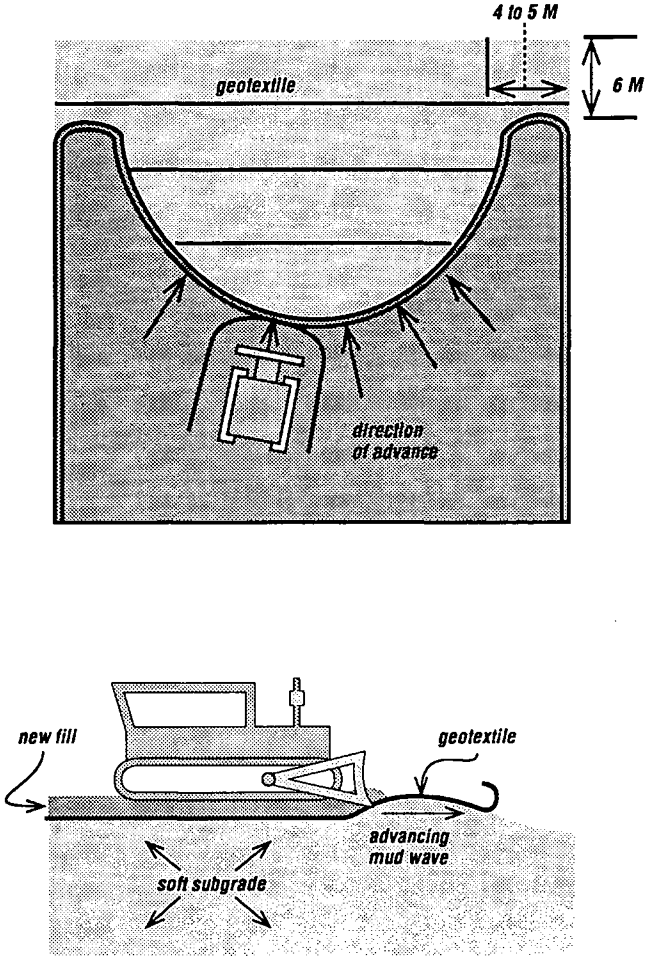

FIGURE 5 Reinforced fill construction method if mudwave forms (*1*): *top*, plan; *bottom*, mudwave formation during fill placement.

ment of the first 0.3 to 0.6 m of soil, if it forms at all. In the case of the subject fill, a mudwave never formed, possibly because of the working platform in place before the first layer of geotextile was placed and the presence of the root mat. Therefore, the convex advancement pattern was actually used for fill construction. Photographs of the actual fill construction are given in Figure 7.

Measurements from six pneumatic pore pressure devices installed below the fill (Figure 3) were used to control the rate of fill construction using a maximum pore pressure ratio of 0.33 as discussed. Settlement data from pneumatic settlement indicating devices at the base of the fill were also used to interpret the stability of the fill. Because of problems with the pore pressure devices, which were associated with installation and possibly the result of gas pressure caused by organic matter decay, six new pore pressure devices were installed in approximately the same locations after the first 1.5 m of fill was placed. Even some of the new devices did not appear to work properly, and eventually four of the six new devices failed.

The maximum allowable pore pressure ratio was equalled or exceeded twice during construction, on the basis of measurements from the few pore pressure devices that appeared to work, when the fill height was at 6.6 m and when it was at 9.5 m. Fill construction was stopped in both cases to allow the pore pressure to dissipate and the soft soil to consolidate and gain strength. In the first case, fill construction was stopped for 52 days, in the second case, for 130 days. In the second case, part of the delay was the result of construction scheduling and inclement weather. In both cases there was no visible evidence of embankment failure or mudwave formation. The total time required to construct the fill was just under 11 months, considerably longer than the 4-month fill construction period estimated from the laboratory test data during design.

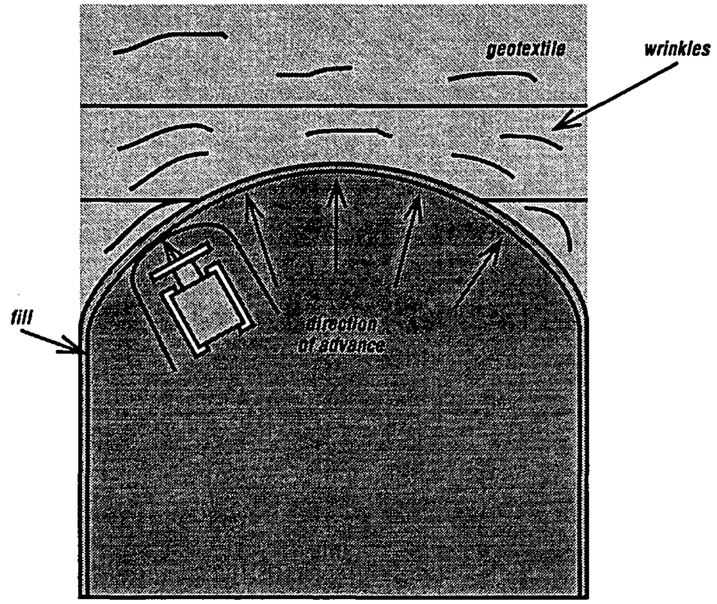

FIGURE 6 Fill placement over geotextile layer if mudwave does not form (*1*).

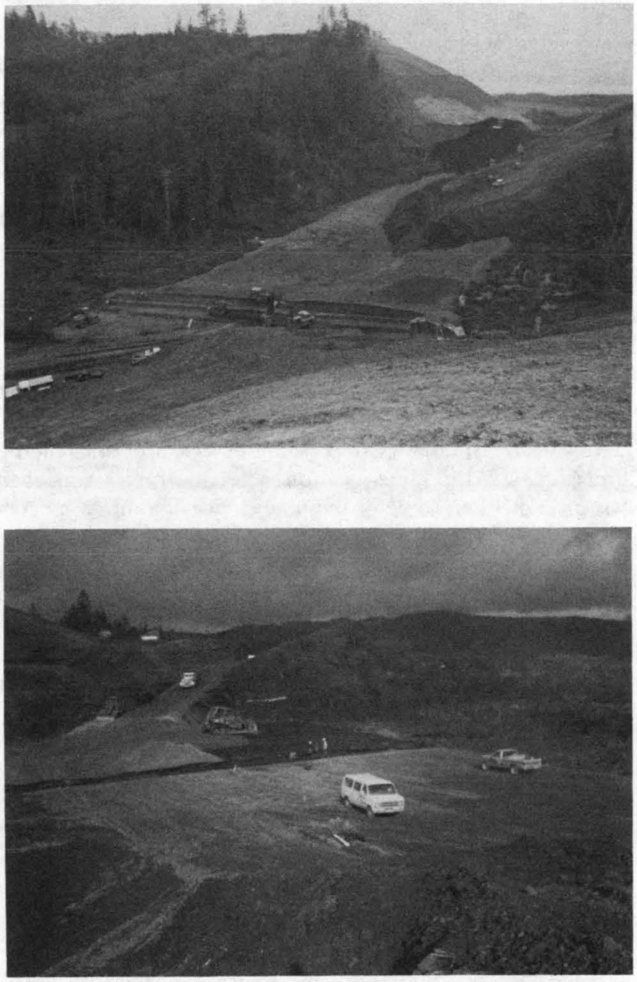

FIGURE 7 Wood fiber fill construction: *top*, granular fill construction and culvert installation; *bottom*, placement of geotextile and wood fiber fill.

PERFORMANCE

The wood fiber fill was completed to subgrade level in September 1987. Paving began more than 1 year later, October 1988. Figure 8 gives settlement data for the time since initial construction. Fill settlement, when subgrade level was reached, was 0.97 m. Before paving, fill settlement had increased to 1.2 m. As of September 1992, 1.4 m of settlement had occurred. Total settlement is projected to reach 1.5 m.

The contractor haul road mentioned caused the fill to settle differentially across its width as anticipated. The differential settlement across the roadway width at the top of the fill was approximately 0.1 to 0.2 m. The greatest settlement occurred on the side of the fill opposite the haul road.

The performance of the wood fiber has been excellent. Samples of 5-year-old wood fiber were exhumed from below the 0.6-m topsoil cover and found to be nearly fresh, with a classification of 2 by WSDOT (see Table 1).

The pavement to date has shown no distress despite settlement and predominately logging truck traffic, with the exception of a small crack where the pavement transitions from cut to fill. Water samples taken upstream and downstream of the site indicated no difference in water quality (no negative impacts from any leachate).

The culvert at the base of the fill was located, as noted, as close to the hillside as possible to mitigate the effects of settlement. The culvert has suffered significant differential settlement and now has a sag in the middle but is still functioning. The culvert has settled approximately 0.4 m more than anticipated at its center, primarily because the culvert was not as close to the edge of the very soft soil deposit as desired during design because of channel flow requirements.

PROJECT COST SAVINGS

It was initially planned to cross the site area with an earth fill and divert the stream flow through a 1.2-m culvert. Because

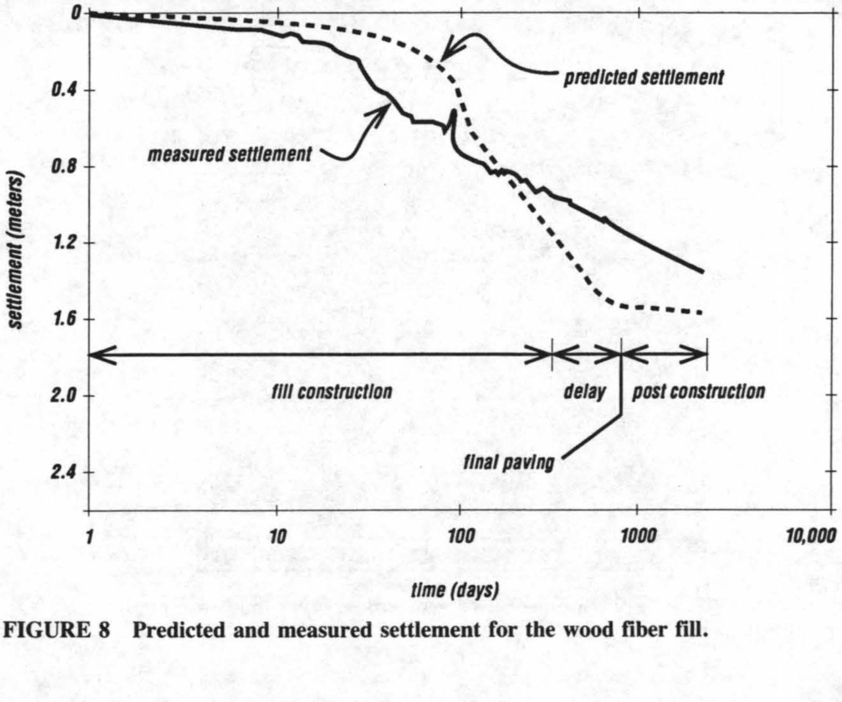

FIGURE 8 Predicted and measured settlement for the wood fiber fill.

TABLE 1 WSDOT Wood Fiber Classification Criteria

Class	General Appearance	Appearance of Decay[a,b]	Particle Strength (Breaking)[c,d]	Particle Stiffness (Bending Capacity)[d]
1	Woodlike, sharply defined graininess	Fresh: Sharp color, fresh woody smell, no disintegration	Cannot be broken with fingers	Retains its shape with force
2	75% of material is woodlike, well defined graininess	Initial signs of decomposition: Distinct color, definite wood smell, very little disintegration of wood fibers	Very difficult to break with fingers	Easily returns to original shape with release of force
3	50% of material is woodlike, complete but poorly defined graininess	Middle stage of decomposition: Fading color, weak wood smell, some disintegration of wood fibres	Breaks with firm finger force	Shape is permanently, but slightly, distorted with force
4	25% of material is woodlike, only partial graininess remains	Advanced stage of decomposition: Fading color, organic smell, mostly disintegrated	Breaks easily with fingers	Shape is permanently distorted with force
5	No longer woodlike, no graininess	Completely decomposed: Dull color, foul smell, completely disintegrated	Squeezes between fingers	No longer returns to original shape; spongy

[a] Primary emphasis is on disintegration
[b] All discriptors may not apply
[c] Standard testing size is 2" x 1/2" x 3/8"
[d] Moisture content for tested sample is "wet to touch"

of the soil conditions at the site, the initial option for crossing the site was not possible and a bridge was chosen. The estimated cost for a bridge was $1,700,000.

Because of the high cost of the bridge, alternatives were considered, including reconsideration of the earth fill. One option was to place an earth fill, force a bearing capacity failure, and thus displace the very soft foundation soils. This option was environmentally unacceptable. Unsuitable removal was also environmentally unacceptable, and impractical. The earth-fill option using berms was unacceptable because it required additional wetlands, which was undesirable, would at best be marginally stable, and resulted in unacceptable settlement.

An acceptable alternative was ground improvement using stone columns, at an estimated cost of $1,500,000. Environmental, stability, and settlement constraints could all be met with this alternative. A lightweight fill using wood fiber was considered feasible on the basis of previous successful use of wood fiber by WSDOT for permanent roadway applications (*4*). The combination of large fill height and very soft ground required the addition of geotextile reinforcement. The actual cost of the lightweight fill was $972,221. This was a more than

$500,000 cost savings compared with the next lowest cost alternative, and more than $700,000 less than a bridge.

SUMMARY

The use of wood fiber as a lightweight fill, with geotextile reinforcement, on this project proved to be a cost-effective solution for constructing a 13.4-m-high fill over 15.2 m of very soft organic silt soils. No stability problems were encountered during or after construction, and total settlement was within project requirements. Continued secondary consolidation is taking place in the foundation soils. There is no evidence of postconstruction settlement within the wood fiber.

The condition of the wood fiber, as of August 1992, is excellent. The wood fiber below the 0.6-m topsoil cover was graded as nearly fresh in a recent study. On the basis of the performance of the wood fiber at this and other WSDOT sites, it appears that wood fiber can be used for permanent applications with design lives of more than 50 years (*5*).

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