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GEOSYNTHETICS FACILITATE ROAD CONSTRUCTION AND MITIGATE ENVIRONMENTAL IMPACT IN AMAZON BASIN RAINFOREST – 10 YEARS OF PERFORMANCE

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Abstract: South America's Amazon River basin rainforest contains perhaps the world's greatest abundance of life, supporting over half of all known species of plants. Over the millennia, organic materials of similar origin have become buried and transformed into deep reservoirs of heavy crude oil. Commercial quantities are available within the Amazon's headwaters region in the Colorado-sized country of Ecuador. In a country whose economy is largely dependent on oil, the formidable challenge is one of developing this vital resource in an environmentally sound and responsible manner, recognizing both the sensitivity of the rainforest and the rights of its indigenous peoples.

The "lifeline" of the development (i.e., exploration, recovery, and transport) of the oil resource is the main road which serves as the haul-and-access corridor for personnel and equipment as well as the means by which pipeline is constructed and serviced. Left unsecured, the road could also create a conduit for unwanted colonists - speculators seeking to clear-cut the fragile forest for farmland or livestock pasture. Clearly, the patrolled road must be as narrow and inconspicuous as possible, while at the same time being economical and functional over the service life of the oilfield, and beyond. These challenges are further compounded by the area's tropical and geological setting, forcing the project's planners, engineers and builders to deal with the 500-cm (200-in) annual rainfall; weak, saturated, and highly plastic jungle floor subgrade; and acutely limited aggregates.

Conventional road construction in this part of the world has been graveled "log corduroy rip-rap" — split tree trunks laid side-by-side, perpendicular to the road alignment like so many matchsticks to create a stiffened roadbed. With about 70 percent of the felled timber requirement coming from beyond the road's edge, this methodology is environmentally prohibitive and economically unfeasible over the long term. A better solution was imperative.

This paper describes the design, construction, maintenance, and performance of a 150-km (90-mi) long, 6-meter (20-ft) wide road comprising dredged river-sand subbase sandwiched between and reinforced by two layers of stiff polymer geogrid, confined along its edges by a non-woven geotextile and topped with a single course of processed, unbound aggregate base/surfacing. By eliminating the use of felled timber, the road's right-of-way "take" could be minimized, and the resulting environmental and ecological impacts mitigated. Further, the use of geosynthetics permitted maximum structural utilization of precious sand and gravel, reducing borrow and haul requirements as well as enhancing the road's long-term serviceability, while maintaining the thinnest possible section.

Now 10 years after construction, the road continues to perform well. Government officials have realized the benefits of the new geosynthetic technology, and have re-written their environmental regulations for road building to encourage its use.

Introduction

The world's largest drainage basin, the Amazon, extends west across South America all the way to the Andes Mountains. In Ecuador, this area east of the Andes and surrounding Sierra is known as the Oriente. The Oriente is home to rainforest flora and fauna and its indigenous peoples, the Waorani, for whom the government of Ecuador has provided land rights and other protection via a large reserve and a national park. The Oriente is also home to large subsurface reservoirs of oil. The government of Ecuador leases blocks of Oriente land for development of this important natural resource. The subject of this paper is a particular oil lease, known as Block 16, and specifically the road built to access it. The road's location relative to above features, including the Napo River, a major tributary of the Amazon, and other rivers is shown in figure 1.
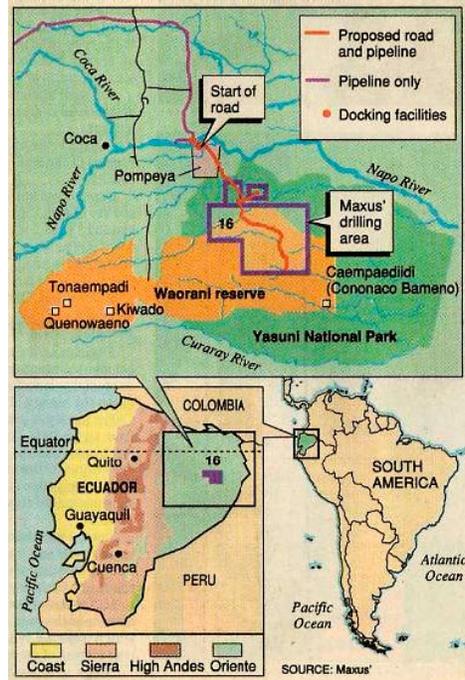
Fig. 1. Location (Jones/*The Dallas Morning News*, 1994).

The 200,000-hectare (81,000-acre) Block 16 was originally prospected by a consortium led by Houston-based Conoco Inc., and later developed by a consortium led by Dallas-based Maxus Energy Corp. Maxus was subsequently purchased by Buenos Aires-based YPF, which subsequently merged with Madrid-based Repsol. Repsol YPF now leases and operates Block 16. The term of the lease is 30 years.

Environment

The road-building environment is heavily vegetated and moderately undulating topography with numerous drainage features. Annual precipitation averages 500 cm (200 in) making the "rainy season" virtually year-round. Weak, fine-grained lateritic soils are saturated in-situ and sensitive to disturbance — that is, they lose strength upon remolding. Thus, once vegetation is cleared, subgrade soils provide very limited support for equipment. Figure 2 shows the condition of a "pioneer" road under high-flotation-tire equipment.

Fig. 2. "Pioneer" road shortly after vegetation has been removed.

Road-building construction materials are in relatively short supply. The only reliable source of gravel is a mine located 66 km (41 mi) north of the Napo River. Sand is available in the 1-km-wide (0.62-mi-wide) Napo River, but the road itself extends another 150 km (93 mi) beyond the river to the south. To date there is no local source of bulk cement, asphalt, or similar structural agent in this remote region.

Traditional Construction

Weak ground and limited aggregates have contributed to promulgation of the age-old road-building practice — log corduroy (sometimes also called riprap). Here, select split trunks of hardwood trees are placed

perpendicular to the roadway alignment similar to the way in which ties are placed within a railroad, but without the uniform spacing. With logs placed side by side (to the extent possible), the resulting stiff platform facilitates placement of sand and gravel fill, and the composite structure distributes the concentrated loads of applied vehicular traffic over the underlying subgrade.

The first geosynthetics to be used in the Oriente were applied as separators — that is, when placed beneath log corduroy, they were intended to keep subgrade fines from fouling the overlying log-corduroy/aggregate road, particularly under repeated heavy truck traffic.   Photos of log corduroy construction in the Oriente are shown in figures 3a & 3b.

Figure 3a. Log Corduroy Road Before Topping with Aggregate Fill.   Figure 3b. Close Up.

While log corduroy can be structurally effective in the short term, with time the wood rots and road serviceability decreases substantially. Moreover, with about 70 percent of the required logs coming from outside of the road right-of-way (Maxus 1992), the environmental impact of log corduroy construction is substantial.

The Road-Building Challenge
Road builders were faced with a formidable task: find an alternative to log-corduroy construction — one that is environmentally friendly, structurally superior, economically feasible, and compatible with conventional construction equipment and practices — a context sensitive design to be sure. Further, because the gravel haul was so long, the structural section was to favor unprocessed, more locally available sand.   All of this was needed to accommodate 70-ton loads of oilfield equipment (ENR 1994). But even more demanding was the haul traffic since all of the aggregate fill would come from behind the advancing road. For 150 km of road, this would amount to approximately two years of hauling over the built road — up to 200 trucks per day at 225 kN (50 kips) each, fully loaded. Thus, the roadway sections at the start (north end) of the road would have to hold up to very heavy traffic while those at the terminus (south end) would have relatively light traffic.

The two-lane road was to be 6 meters (20 ft) wide with an all-weather, unpaved surface. Because the roadbed soils (subgrade) were sensitive to disturbance, the road would be constructed in cut, rather than fill, as much as possible, with a route that generally followed ridge lines. Engineering characteristics of the subgrade are presented in table 1.

Table 1.
Engineering Characteristics of Materials Comprising the Road

Subgrade (Roadbed):	**Subbase (Sand):**
Classification: MH-CH (USCS)	Classification: SP (USCS)
Strength: CBR = 1.5	Strength: 10 < CBR < 25 (estimated)
Atterberg Limits:	Atterberg Limits: Non-Plastic
Liquid Limit = 75%	Gradation:
Plastic Limit = 38%	Medium Sand = 11%
Plasticity Index = 37%	Fine Sand = 83%
In-Situ Moisture = 42% (Saturated)	Fines (- #200) = 6%
Gradation:	Coefficient of Uniformity = 2.5
Fine Sand = 17%	Coefficient of Permeability = 0.02 cm/sec (0.04 ft/min)
Fines (- #200) = 83%	
Liquidity Index = 0.07 (indicative of preconsolidation pressure)	**Base/Surface ("Gravel"):**
"Activity" = 1.7 (indicating high volume change potential)	Classification: SW-GW (USCS)
	Strength: CBR = 80 (assumed)
Geogrid (Tensar BX1100):	Atterberg Limits: Non-Plastic
Unit Weight: 210 g/sq m (6.2 oz/sy)	Gradation:
Tensile Strength at 2% strain: 4.1 kN/m x 6.6 kN/m (280 lb/ft x 450 lb/ft)	Gravel = 53%, max. size = 38 mm (1.5 in.)
Open Area = 70%	(max size was 90 mm (3.5 in.) prior to crushing)
Thickness = (see Figure 4)	Sand = 45%
Junction Efficiency = 93%	Fines (- #200) = 2%
Flexural Rigidity = 250,000 mg-cm	
Aperture Stability = 3.2 kg-cm/deg	**Geotextile (Amoco 4506):**
	Unit Weight: 203 g/sq m (6.0 oz/sy)
	Grab Tensile at 50% strain: 0.67 kN (150 lb)
	Apparent Opening Size: U.S. Standard Sieve size 70
	Thickness = 1.65 mm (65 mils)

The Solution

Meeting the challenge involved two principle structural considerations: support of heavy construction equipment as the road was being built, and support/serviceability thereafter. The former required an analysis of the subgrade bearing capacity under the imposed stresses of fully loaded dump trucks hauling sand. From the "pioneering" operations it was clear that there was a need to "protect" the subgrade from overstress during this critical stage of the construction.   While sand alone may have done the job, the thickness requirement was prohibitive. Several alternatives were tried as tests and the one that demonstrated the most cost effectiveness, particularly in terms of minimizing the structural thickness of sand, was use of a stiff, biaxial geogrid at the subgrade/subbase interface. The snowshoe-like load distribution of the geogrid creates a stiffened composite with the sand, thereby protecting the underlying weak subgrade from overstress.   In the geosynthetics industry, the application is known by the interchangeable terms: "subgrade improvement," "subgrade restraint," and "subbase reinforcement."

Next was the matter of minimizing the structural thickness of the "gravel" base/surfacing. The same geogrid was used at the subbase/base interface. Here, the confinement effect of the geogrid's dimensionally stable apertures imparts lateral restraint to otherwise unbound aggregate particles thereby increasing their collective performance under repeated heavy traffic. The net effect is that a thinner, reinforced section has the same serviceability as a thicker, unreinforced section. In the geosynthetics industry, the application is known by the term "base reinforcement."

So each layer of geogrid reinforcement minimized the respective aggregate fill thickness above it.   The two layers also effectively encapsulated the sand subbase, creating a stiffened composite "beam" — the attribute of log corduroy heretofore unequalled.   The only element remaining was containment of the otherwise exposed edges of the sand subbase. For this, a geosynthetic with a much smaller opening was required to prevent the sand from eroding and scouring along otherwise exposed shoulders of the road.   A nonwoven geotextile served the purpose well. Like the geogrid, it is made of polypropylene and stabilized for exposure to ultraviolet light with carbon black. Unlike the stiff, open structure of the geogrid, the geotextile is pliable and with openings almost finer than the naked eye can detect — more like a felt.   The resulting cross-section is shown in figure 4. The geogrid and geotextile are described in table 1 along with the other materials comprising the road. Geogrid geometry is shown in figure 5.
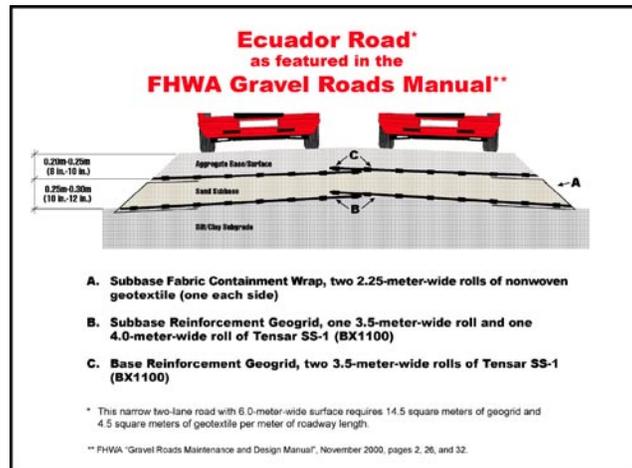

Fig. 4. Block 16 cross-section.

Fig. 5. Geogrid reinforcement geometry.

Construction

Construction of the cross-section began with shaping the subgrade to facilitate internal drainage. Within tangent sections, the shape was a crown as shown in figure 4. In curves, the subgrade shape was superelevated, just like the road surface, from outside to inside. This doubled the drainage path for internal moisture flow, an effect that will be discussed later under Drainage. The purpose of the shaping was to shed rainfall quickly from the road to the ditches.

When possible, subgrade was compacted with roller equipment.   Sometimes this was limited to a proof roll, or even just smoothing.

Geotextile was placed along each edge of the prepared subgrade. Design calculations for pullout resistance required a minimum anchorage length of 0.8 m (2.7 ft) for the "legs" of the wraps, so a standard 4.5-m-wide (15-ft-wide) roll was simply cut in half to provide "subbase fabric containment" for both edges. Geogrid was then placed atop the subgrade (and fabric) and overlapped as shown in figure 4.

Sand subbase was placed atop the geogrid and shaped at the edges to allow a relatively taught wrap-around with the geotextile. Compaction of the sand was provided by haul equipment, and when possible, a roller. After the wrap, the second (upper) layer of geogrid was placed, followed by gravel base/surfacing. Only a limited station-to-station advancement of the sand was allowed before topping with geogrid and gravel. This necessitated close coordination of hauling and placement activities on the road, particularly since haul equipment could not leave the road during the construction process (see figures 6a and b.) Both sand and gravel were spread with bulldozer equipment; advancement was approximately 300 m per day, with a peak of 500 m (ENR 1994).

Fig. 6. Consequences of haul equipment leaving the road (a) during construction of the sand subbase (b) beyond the advancing 'front'.

Drainage/Filtration
While sand subbase thickness was established from structural analyses, it was also checked for internal drainage. In brief, the sand also needed to be thick enough to internally drain infiltrated rainfall quick enough to preclude development of hydrostatic pressure (partial submergence) and associated strength/support loss under applied load. The design rainfall was 125 mm (5 in) over a day's period of time, of which 50 mm (2 in) was assumed to seep through down into the sand subbase, and require drainage.

The analyses required estimation of the sand's effective porosity. Because some moisture would be held by capillary action and other forces, 60 percent of the total porosity, n = 0.435, was "effective." Thus, the effective porosity was (0.60 x 0.435 =) 0.25. Multiplying this value by the height and length of sand (half the section width for a crowned tangent section) and comparing this product with the 500 mm (2 in) inflow, indicates that 200 mm (8 in) is the minimum drainage thickness requirement for sand to fully discharge the inflow.

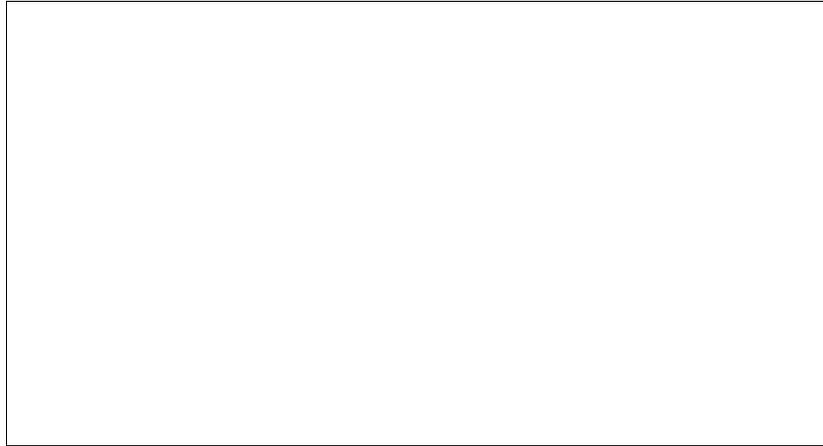Time required to fully drain this amount of water in the sand subbase is determined with the aid of figure 7.

Fig. 7. Internal drainage of sand subbase (NAVFAC 1982).

For a 20-mm-thick (8-in-thick) sand subbase on a 3-m-long (10-ft-long) drainage path (half the roadway width), the Slope Factor, S = 1.7. For complete drainage, U = 1.0, from figure 7, the Time Factor, Tv = 2.2. Assuming a Coefficient of Permeability, k = 0.02 cm/sec (0.04 ft/min) and solving for "t", yields 1.4 days. Thus, a tangent section comprised of an 200-mm-thick (8-in.-thick) sand subbase would take 1.4 days to drain a daily rainfall of 125 mm (5 in).   If the thickness was 250 mm (10 in), the corresponding parameters would be U = 0.8, S = 2.08, and Tv = 0.95. Solving for "t" yields 0.5 days. Again, this is for a tangent section with center crown. In superelevated curves the drainage path is not the half width, but rather the full width of the section. Here, if the thickness was 250 mm (10 in), the corresponding parameters would be U = 0.8, S = 1.04, and Tv = 0.6. Solving for "t" yields 1.25 days. Since this is reasonably close to 1 day, 250 mm (10 in) was an appropriate sand subbase thickness for internal drainage purposes.

Filtration at the subgrade/subbase interface was also an important consideration. Filtration is allowing water to pass, say across a boundary, without carry fine soil particles with it.   In a saturated environment like the Block 16 roadbed, filtration and separation — preventing the intermingling of two dissimilar materials — are provided by the combined interaction between geogrid and overlying fill, in this case sand.   The geogrid reduces subgrade pore-water pressure that tends to erode fines, and confines soil particles at the interface, thereby inhibiting mingling. In effect, geogrid separates and facilitates the filtration function of the sand. Checking the sand to ensure it is properly graded to prevent subgrade fines from moving up into it requires a compatibility analyses of the respective gradations.

Figure 8 shows the gradations of the two soils, sand subbase and clayey silt subgrade.   For the latter, hydrometer data were not available, so gradation finer than the #200 sieve (0.075 mm) was extrapolated based on Atterberg limits.
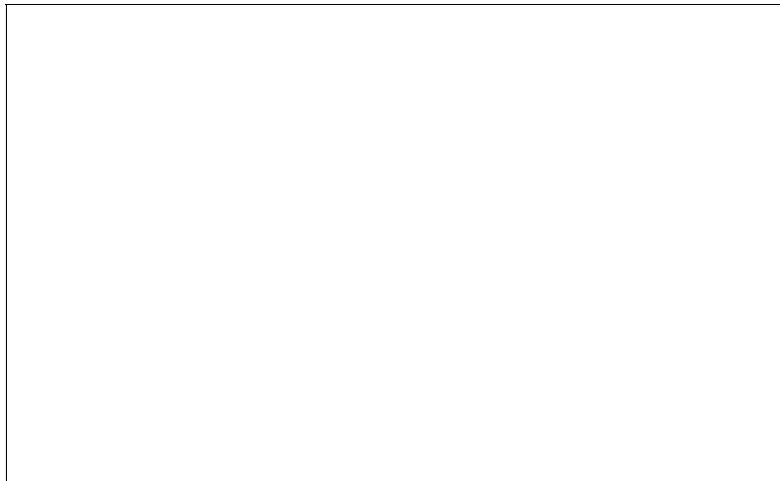

Fig. 8. Compatibility (piping) analyses of Block 16 subbase and subgrade.

"Compatibility" analysis assesses whether or not subgrade fines can possibly infiltrate a coarser fill, in this case sand. The classic calculation is the "piping ratio," defined as D15 (fill) / D85 (subgrade). If this ratio is less than 5, subgrade fines cannot move into the sand subbase. For silty subgrades, an additional calculation is required: D50 (fill) / D50 (subgrade) < 25. Figure 8 shows how these respective diameters (D) are determined. For Block 16, the piping ratio is (0.12 mm / 0.052 mm =) 2.3 < 5, and the average size ratio is (0.22 mm / 0.009 mm =) 24 < 25. Since both ratios are within their respective limits, there is no danger of intermingling/ contamination, particularly with the geogrid immobilizing particle movement associated with repeated heavy traffic. Further, there is not only no need for synthetic filtration (i.e., geotextile) at this interface, the severe consequences of it clogging with silt fines is minimized.

As a final design check on the internal drainage and filtration conditions of the sand, figure 9 was employed. With D50 = 0.22 mm (from figure 8), the data show that capillary height = 280 mm (11 in), the approximate thickness chosen for structural and drainage purposes. With the underlying subgrade remaining saturated over the service life of the road, this means that the sand subbase will never dry out, shove, and become unstable as long as it is confined by the geogrid and protected by the gravel base/surfacing.
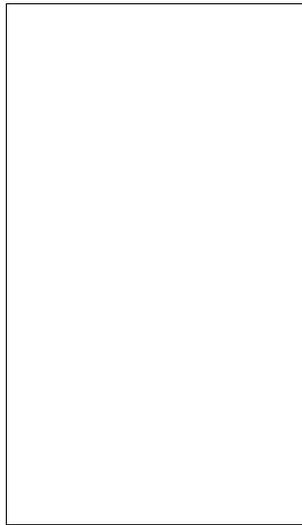

Fig. 9. Capillarity of sand subbase.

Maintenance

Like all unpaved roads, routine grading of the surface, especially providing an A-shaped crown, is an ongoing necessity. The frequent and heavy rainfall in Ecuador's Oriente makes this particularly important, especially as the gravel base/surfacing lacks cohesive binder. Ideally, the base and surface should not be one and the same material; preferably, the surfacing should contain a small amount of plastic fines. This is difficult in the Oriente because incorporating fines into an otherwise clean gravelly sand requires preciseness — too many fines can create slipperiness; too few fines, and smaller sand particles wash away leaving a surface prone to "washboarding." While rainy weather predominates, there are occasions of sunny, dry days, and in these situations, the binder-less surface is vulnerable to "dusting" (see figure 10).

Figure 10. During infrequent dry spells, dust is a concern.

Performance

In AASHTO terms, the Block 16 road was designed to accommodate approximately 200,000 Equivalent Single Axle Loads (ESALs) at a terminal serviceability index of 2.0. Although no traffic counts were made or estimated, actual traffic is believed to have far exceeded this load magnitude. Post-traffic exhumations like those pictured in figure 11 have confirmed the competency and functionality of the structural components, and have revealed no soil particle movement across the geogrid interfaces.

Fig. 11. Exhumations of the roadway structural section in service.

The remarkable performance of the Block 16 road has been cited in the most comprehensive gravel road guidelines published by the Federal Highway Administration (SDLTAP 2000). The manual features several photographs of the Block 16 road and describes it as a "good example of how an extremely weak subgrade can be stabilized and a gravel road built over it with minimum disturbance to the surrounding terrain and the environment." Currently, the manual may be accessed at either www.ltapt2.org/gravel/gravelroads.htm or www.epa.gov/owow/nps/gravelroads/gravelroads.pdf.

Ecuadorian Law

On February 13, 2001, Dr. Gustavo Noboa Bejarano, president of Ecuador, signed into law, per Official Register No. 265, regulations designed to protect and sustain the environment. Of particular importance for civil projects is Chapter 11, Articles 83 – 85, which address construction in the Oriente. Deforestation associated with road construction became severely restricted with no trees from outside of a narrow right-of-way being allowed to be used within the structural section (Ecuador 2001). With the success of the landmark Block 16 road project, The Republic of Ecuador, via this law, now encourages geosynthetic reinforcement of sand subbase, and gravel, within their rainforest roadways.

Conclusion

Up until about 10 years ago, conventional road construction in the Amazon highland rainforest had been graveled "log corduroy rip-rap" — a practice as old as road building itself. Over the short term, its stiffened load distribution qualities were undeniable; over the long term, its effectiveness diminished as the split tree trunks decayed. Woven geotextile helped, but it did not displace any of the required timber. With about 70 percent of the felled timber requirement coming from beyond the road's right-of-way, this methodology was environmentally prohibitive and economically unfeasible over the long term. A better solution was imperative.

This solution consisted of a dredged river-sand subbase sandwiched between and reinforced by two layers of stiff polymer geogrid, confined along its edges by a nonwoven geotextile and topped with a single course of processed, unbound aggregate base/surfacing. By eliminating the use of log corduroy the road's environmental and ecological impact could be mitigated. Further, the use of geosynthetics, and geogrid in particular, permitted maximum structural utilization of precious sand and gravel, reducing borrow and haul requirements as well as enhancing the road's long-term serviceability, while maintaining the thinnest possible section. Now 10 years after construction, the road continues to perform as designed. The government has recognized this preferred technology, and has written environmental regulations to encourage its use in the rainforest.

Biographical Sketch: Ron Anderson has over 25 years of experience in the design, construction, and monitoring of structures made from or founded upon earth. These include roads, embankments, dams, dikes, levees, walls, and buildings. Early in his career, he evaluated pavement serviceability at one of the nation's only full-scale test tracks modeled after the AASHTO Road Test. Here he quantified the structural contribution of chemically-stabilized bases courses (i.e., bituminous-, cement-, flyash-, and lime-treatments) which later proved to be invaluable in his pioneering work with mechanically stabilized (i.e., geogrid-reinforced) bases and subbases. At Dames & Moore's Earth Structures Design Division, he was a designer for one of the first roller-compacted concrete pavements in the world -- an intermodal facility for the Burlington Northern Railroad in Houston. He also was a designer for two of the world's first concrete-panel-faced geogrid-reinforced soil retaining walls, one along the Saint Lawrence Seaway in Quebec and one in the Sonoran Desert of Tucson, Arizona. He later was the lead on a team that conceived and furnished new modular concrete-block-faced mechanically stabilized earth retaining walls for the widening of Interstate 294 (the Tri-State Tollway) adjacent to O'Hare International Airport in Chicago. In 1993 he was the engineer on a three-man team that successfully introduced this system on a nationwide 'launch' in Australia. More recently, his pioneering work has led him into less developed areas of Central and South America. His concepts of and designs for geogrid-reinforced bases and subbases have now been implemented on hundreds of kilometers of roads through the Amazon's highland jungle(s).

Anderson is a registered professional civil engineer and is currently director of biaxial geogrid systems for Tensar Earth Technologies, Inc. He is based in Denver.

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