unreinforced roads was acceptable. For the geogrid-reinforced case they suggested a bearing capacity factor of 5.8 and recommended the use of geotextile as a separator. Application of the modified Steward et al. (1977) design method to geogrid-reinforced unpaved roads is the same as the method outlined in Section 5.4 and using a bearing capacity factor of 5.8. The geogrid is based on the properties listed in Table 5-5. The area of applicability and limitations of this design method are the same as those presented in Section 5.4 and are not repeated here. It is recommended that a geotextile be used as a separator beneath a geogrid unless the gradation of the aggregate can act as a separator for the subgrade (Section 5.3-4).

### 5.5-2 Empirical Design Method of Giroud and Han (2004)

Giroud and Han (2004) developed a theoretically based and empirically calibrated design method specifically designed for geogrid-reinforced unpaved roads and areas. They built upon earlier design methods developed by Giroud and Noiray (1981) and Giroud et al. (1985) using recent field and laboratory test data. Giroud and Noiray (1981) developed an empirical solution for unreinforced unpaved roads using field test data and quantified the benefits resulting from geotextile reinforcement. The solution was based on the limit equilibrium bearing capacity theory with a modification to consider the benefit of the tension membrane effect. The Giroud-Han theoretical formulation takes into account the distribution of stresses, strength of base course material, geogrid-aggregate interlock, and geogrid in-plane stiffness in addition to conditions considered in earlier methods (traffic volume, wheel loads, tire pressure, subgrade strength, rut depth and influence of reinforcing geosynthetics of the failure mode of unpaved roads). The influence of different factors on the theoretical formulations, the assumptions and the limitations of the Giroud-Han design method are briefly presented below.

The properties of the base course material are considered in the solution which is an advancement compared to previous methods. The base course material is characterized by its CBR using the AASHTO chart for correlation with the resilient modulus for subbase (AASHTO, 1993).

The subgrade soil is assumed to be saturated and exhibit undrained behavior under traffic loading. The subgrade soil modulus is used based on correlation between the field CBR and the field resilient modulus for fine grained soils (Heukelom and Klomp, 1962). Other relationships can also be used to derive the resilient modulus of the subgrade soil. In the formulation of the design equation, the ratio of the resilient modulus of base course to subgrade soil is limited to 5. Additional data are necessary to justify the use of higher values for stiff geogrids which appear to improve the compaction of base course material even on very soft subgrades.

**Serviceability Criterion Based on Rut Depth.** Failure of the unpaved roads is assumed to be controlled by the shear failure or the excessive deformation of the subgrade. The formulation of the design method is based on a typical surface rut depth of 3 in. (75 mm) which a serviceability criterion. It allows for rut depths between 2 and 4 in. (50 and 100 mm) to be analyzed. Additional field data are needed to support the use of the method beyond these limits.

**Characterization of Geogrid Reinforcement.** The properties of geogrids relate to their ability to interlock with the base course material and provide confinement. Based on research by Kinney (1995) and Collin et al. (1996), the aperture stability modulus was the stiffness property selected, based on correlation with measured performance in roads. The aperture stability modulus is obtained by measuring the in-plane torsional behavior directly across the junction of a biaxial geogrid. It is a direct measure of the in-plane stiffness and stability of the ribs and junctions of the geogrid. The method was calibrated using data for stiff biaxial geogrids with aperture stability modulus of 0.32 and 0.65 N-m/deg (Kinney, 2000). In the design method the aperture stability modulus can vary from zero to a maximum value based on the data used in the calibration (Giroud and Han, 2004b). A draft test method for determining the aperture stability modulus of a geogrid has been developed by Kinney (2000) and a standard method is currently under development by ASTM.

**Bearing Capacity Factors.** The bearing capacity factors for unreinforced unpaved roads as presented in Section 5.4 ranged from 2.8 to 3.3. Giroud and Han (2004a) adopted a bearing capacity factor of 3.14 (i.e., $\pi$) which is the value of the elastic limit for saturated undrained subgrade soil for plain-strain and axisymmetric conditions and zero interface shear stress. As discussed earlier the strike through and the interlock at the geogrid-reinforced interface resists the lateral movement at the top of the subgrade, and creates inward shear stresses on the subgrade. The theoretical value of the ultimate bearing capacity factor for axisymmetric conditions and maximum inward shear stress of 5.71 (i.e., $3\pi/2$) is adopted for the geogrid-reinforced unpaved roads. For the case when the base course is separated by a geotextile and there is no interlock, Giroud and Han adopted the value of 5.14 (i.e., $\pi+2$) initially proposed by Giroud and Noiray (1981), which is the ultimate bearing capacity factor for plain-strain conditions and zero shear stress at the base-subgrade interface.

**Equation for Required Thickness of Base Course.** The thickness of the base course material was determined on the basis of the bearing capacity theory to prevent the development of rut depths exceeding the predetermined serviceability criterion. The deformation of the subgrade depends on the stresses applied at the base-subgrade interface and the development of the rut depth as a function of the stresses at the base-subgrade interface and the bearing capacity of the subgrade. The influence of traffic, properties of base course material, and geogrid properties are expressed through two important parameters – the Bearing Capacity Mobilization Coefficient ($m$), and the Stress Distribution Angle ($\alpha$). The Bearing Capacity Mobilization Coefficient defines the level of mobilized bearing capacity, which depends on the deflection at the top of subgrade when the surface rutting reaches the allowable rut depth. The Stress Distribution Angle defines the capability of the base course material to transfer traffic loads to the subgrade. The effect of traffic and geogrid on the rate of change of stress distribution angle as the unpaved roads deteriorate under repeated loading is considered in the formulation.

The following design equation for base course thickness was developed through calibration and verification with laboratory and field data (Giroud and Han, 2004b):

$$h = \frac{0.868 + (0.661 - 1.006J^2)\left(\frac{r}{h}\right)^{1.5} \log N}{\left[1 + 0.204\left(R_E - 1\right)\right]} \left( \sqrt{\frac{\frac{P}{\pi r^2}}{\frac{s}{f_s}\left[1 - 0.9e^{-\left\{\frac{r}{h}\right\}^2}\right] N_c f_c CBR_{sg}}} - 1 \right) r \qquad (1)$$

where:

$(0.661\text{-}1.006\,J^2) > 0$

$h$ = required base course thickness (in. or m)

$J$ = aperture stability modulus in metric units (N-m/degree)

$P$ = wheel load (lbs or kN)

$r$ = radius of tire print (in. or m)

$N$ = number of axle passes

$R_E$ = modulus ratio = $E_{bc}/E_{sg} = 3.28\ CBR_{bc}^{\ 0.3} / CBR_{sg} \leq 5$

$E_{bc}$ = base course resilient modulus (psi or MPa})

$E_{sg}$ = subgrade soil resilient modulus (psi or MPa)

$CBR_{bc}$ = aggregate CBR

$CBR_{sg}$ = subgrade CBR

$f_s$ = rut depth factor

$s$ = maximum rut depth (in. or m)

$N_c$ = bearing capacity factor
= 3.14 for unreinforced roads
= 5.14 for geotextile reinforced roads
= 5.71 for geogrid reinforced roads

$f_c$ = factor relating subgrade CBR to undrained cohesion, $c_u$ = 4.3 psi (30 kPa)

**Limitations of the Design Method.** The validity of the Giroud and Han method is limited by the following conditions:

- Rut depth from 2 to 4 in. (50 to 100 mm);
- Field subgrade CBR less than 5;
- Maximum ratio of base course modulus $E_{bc}$ to subgrade soil modulus $E_{sg}$ of 5;
- Maximum number of passes – Based on the current state of practice, the trafficking for unpaved roads is limited to 10,000 ESALs.
- The tension membrane effect was not taken into account since it is negligible for rut depths less than 4 in. (100 mm);
- The influence of geogrid reinforcement is considered through a bearing capacity factor of $N_c = 5.71$, and the aperture stability module ($J$) of geogrid;
- The influence of geotextile reinforcement is considered through a bearing capacity factor of $N_c = 5.14$, and aperture stability module equal to zero;
- For the unreinforced unpaved roads, the solution is valid for bearing capacity factor of $N_c = 3.14$, and aperture stability module equal to zero;
- Minimum thickness of 4 in. (100 mm) of base course aggregate.

Giroud and Han (2004b) suggest that these limitations may change as additional empirical data become available.

**Design Procedure.** The design steps from the previous Section 5-4 should be followed. Steps 4 – 6 are replaced for a geogrid-reinforced alternative using the Giroud and Han (2004) procedure as follows:

**STEP 4:** Preliminary calculations

- Select allowable rut depth depending on the road use
- Calculate the radius of the equivalent rut depth

$$r = \sqrt{\frac{P}{\pi p}}$$

where: $P$ = wheel load (lb or kN)
$r$ = radius of tire contact (in. or m)
$p$ = tire pressure (psi or kN/m$^2$)

- If necessary determine the undrained shear strength of the subgrade soil from available data or correlations.

**STEP 5:** Check capacity of subgrade soil to support wheel load without reinforcement

$$P_{h=0,unreinf} = \left(\frac{s}{f_s}\right)\pi r^2 N_c c_u$$

where:

$P_h$ = support capacity of subgrade *(lb or kN)*
$s$ = the allowable rut depth (in. or mm)
$f_s$ = 3 in. (75 mm)
$r$ = radius of tire contact (in. or m)
$N_c$ = 3.14 bearing capacity factor for unreinforced case
$c_u$ = subgrade undrained shear strength (psi or kN/m$^2$)

If $P < P_{h=0,\ unreinf}$ the subgrade soil can support the wheel load and a minimum thickness of 4 in. (100 mm) base course is recommended to prevent disturbance of the subgrade. If $P > P_{h=0,\ unreinf}$ the use of reinforcement is required and the solution continues to the next step.

**STEP 6:** Determine the required base course thickness for reinforced or unreinforced roads using Equation (1). The calculation of the base course thickness requires iteration. The minimum thickness of the base course is 4 in. (100 mm).

The Giroud and Han method will be illustrated in the example presented in the next section.

### 5.5-3 Design Examples for Geogrid Reinforced Unpaved Road

The design of geogrid-reinforced unpaved road will be illustrated with two examples. The first example is based on the Giroud and Han method (2004a,b), where the geogrid reinforcement benefits are considered through the bearing capacity factor ($N_c$) and the aperture stability of the geogrid ($J$). An important feature of the Giroud and Han is that it can differentiate the benefits of different types of geogrids.

The second example is based on the Modified Steward et al., 1977 method (USCOE, 2003), where the geogrid reinforcement benefits are considered only through the bearing capacity factor, $N_c = 5.8$, derived from empirical studies for extruded biaxial geogrids under laid with a geotextile separators.

### DESIGN EXAMPLE 1: GIROUD AND HAN METHOD (2004 a, b)

### PART I: GEOGRID REINFORCEMENT

Determine an appropriate aggregate thickness for a haul road over weak subgrade that is required for a highway construction project. Investigate a conventional unreinforced solution and a geogrid-reinforced alternative, using the Giroud and Han method (2004 a, b) for the given set of design parameters.