Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
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Design methods for geocell stabilisation of roads and railways

Méthodes de conception pour la stabilisation par géocellules des routes et des voiesferrées

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ABSTRACT: The effect of repeated and cyclic loads on soft soils generates absolute and differential settlements, which may quickly degrade the quality of roads and railways. Geocells improve the modulus and strength of the stabilised composite and durability of the road structure by drastically reducing the required quantity of aggregate material. The paper aims to present the current practice on design methods for geocell stabilisation of roads and railways, highlighting the key properties and testing required for geocell design. The design methods take into account the wheel loads, the number of passages, the geometry, the subgrade characteristics and the geocell properties.

RÉSUMÉ :L'effet des charges répétées et cycliques sur les sols meubles génère des tassements absolus et différentiels, qui peuvent rapidement dégrader la qualité des routes et des voies ferrées. Les géocellules améliorent le module et la résistance du composite stabilisé et la durabilité de la structure de la route en réduisant considérablement la quantité requise d'agrégats. Le document vise à présenter la pratique actuelle sur les méthodes de conception pour la stabilisation des géocellules des routes et des voies ferrées, en mettant en évidence les propriétés clés et les tests requis pour la conception des géocellules. Les méthodes de conception tiennent compte des charges de roue, du nombre de passages, de la géométrie, des caractéristiques de la fondation et des propriétés de la géocellule.

KEYWORDS: Geocells, Paved roads, Unpaved roads, Railways.

1 CONCEPTS AND FUNDAMENTAL PRINCIPLES

Geocells are tridimensional geosynthetics that have been used successfully in practice for many years since the 1980s.

Geocells are usually applied as a panel of connected strips that, when opened, form a network of open cells (see Fig. 1). Individual geocell sections can be connected using suitable connection devices that provide sufficient strength to prevent panel separation during installation and throughout the entire design life.

Geocells may differ in terms of their basic physical and material characteristics, including open cell dimensions, number of cells per unit area (cell density), cell depth (height), or presence/absence of perforations or texture.

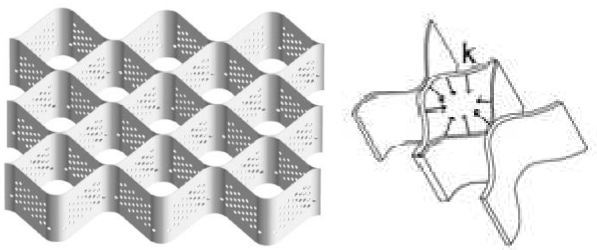

Figure 1: Typical geocell structure and primary mechanism of confinement by the 3D structure of geocells (k = 3D confining stress)

Individual cells consist of two strips that are connected together on either end, and held open prior to filling. The primary mechanism by which geocells provide soil stabilisation is through lateral confinement of the infill; therefore, it is necessary that the entire hoop of material that makes up each individual cell remains intact during construction and throughout the life of the structure. Each hoop consists of the cell wall material and the seams on either end. The entire hoop, including the seams, must remain intact and be sufficiently strong to carry the applied hoop stresses without breaking, deforming excessively, relaxing, or degrading during construction and for the entire design life of the structure. Any of these three failure modes in either the cell wall or seams will allow the infill to expand laterally, rendering individual cells or the entire geocell layer ineffective.

The main distinction between stabilization and reinforcement functions lays in the fact that reinforcement strictly requires tensile forces to be developed by geosynthetics to achieve the equilibrium and the stability of the reinforced structure, while stabilization is based on limiting strains.

The primary mechanisms by which geosynthetics can limit the deformations of a granular layer is the confinement mechanism.

The confinement mechanism requires that confining stresses on the soil particles are developed; in case of tridimensional geosynthetics, like geocells, confinement is afforded by the thin walls of the cells of the 3D structure (Fig. 1).

In typical applications of the stabilization function (e.g. paved roads, unpaved roads, railways on soft soil), geocells provide the following stabilizing mechanisms:

- lateral restrain mechanism for horizontal stresses generated by the self-weight of soil;
- lateral restrain mechanism for horizontal stresses generated by wheel loading (or in general by dynamic / cyclic loads applied at the top surface);

The tensile forces produced in the geosynthetics by the self-weight of soil are permanent static loads by nature.

While the horizontal stresses produced by wheel loading are dynamic / cyclic in nature, and each cycle lasts just a fraction of a second: hence the confining stresses are produced by the geosynthetic as short-term stresses according to their short-term tensile curve, which is typically obtained by ISO 10319 wide width tensile test. Yet these confining stresses shall be produced continually at long term.

While reinforcement usually works at relatively high strains (even up to 10 %), stabilization requires much lower strains to be effective (typically up to 2 % at the end of design life for geocells).

The magnitude by which the horizontal and vertical strain in the aggregate layer can be reduced depends on the stiffness of the composite layer. This is, in turn, a function of the geosynthetic tensile stiffness required for the stress equilibrium as well as on the efficiency of the aggregate/geosynthetic interaction.

During the application of load to the granular layer (e.g. trafficking or compaction) the interaction distributes stresses throughout the stabilized granular layer and geosynthetic thus reducing any stresses transmitted to the underlying subgrade.

The creation of a confined zone with limited particle movement naturally limits the deformation of the granular layer as a whole. The resultant reduced stress transmission to the subgrade limits its deformation. It is typically the underlying subgrade that is the weakest material in the construction section and one of the principles aims in developing a confined and stabilized granular layer is to limit any stress and strain transmission to this weaker layer.

Reducing the horizontal strains means to decrease the Poisson ratio of the soil – geosynthetic composite material compared to the Poisson ratio of the unstabilized soil; reducing the Poisson ratio means to increase the horizontal stiffness; like for a beam, the increased horizontal stiffness means that the geosynthetic stabilized soil layer is able to distribute the vertical stresses σ_{v0} applied at the top surface on a wider area, as shown in Fig. 2; in terms of the well-known concept of load distribution angle, for the unstabilized soil layer the vertical stress on the subgrade σ_{vu} will get a distribution according to the load distribution angle α_u (Fig. 2); while for the geocell stabilized soil layer, the vertical stress on the subgrade σ_{vs} will get a much wider and uniform distribution angle according to the increased load distribution angle α_s (Fig. 2).

On the other hand, it is evident that at equal maximum value of σ_{vu} and σ_{vs} the load that the stabilized soil layer can support will be much higher than the load supported by the unstabilized soil layer: in other words, the improved vertical load distribution on the subgrade affords a higher bearing capacity of the stabilized system compared to that of the unstabilized system.

These concepts have been demonstrated by research and monitored stabilized vs unstabilized soil layers under different types of loads, and are widely used in the presently available design methods.

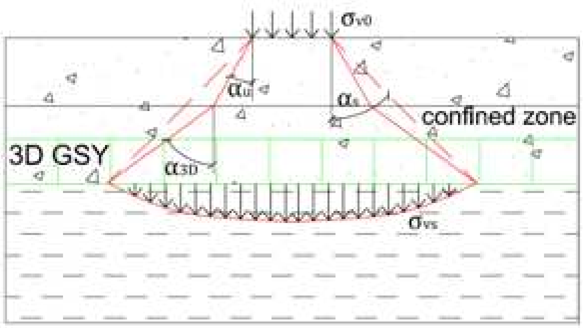

Figure 2. Increase of the load distribution angle with geocell confinement of granular layer (σ_{v0} = vertical stress applied at the top surface; σ_{vs} = vertical stress on the subgrade with stabilized granular layer; α_u = load spreading angle with unstabilized granular layer; α_s = load spreading angle with stabilized granular layer; α_{3D} = load spreading angle within 3D structure)

2 CONFINEMENT AND PARTICLE RESTRAINT

Stabilisation by geosynthetics requires the minimisation of particle movement through confinement and particle restraint. In order for geosynthetics to provide particle restraint, they would normally have adequate tensile stiffness and sufficient interaction with the soil and/or other materials.

While vertically loaded, additional shear stresses are transmitted from the aggregate to the geosynthetic which results in horizontal strains. The shear resistance caused by friction or mechanical interlock generates a physical restraint of the aggregate particles. The stiffness provided by the geosynthetic reduces the development of lateral tensile strains and stresses in the base aggregate over a defined height above the geosynthetic, called the 'confined zone', by preventing the development of explicit displacements of the aggregate (Fig. 3).

In the case of geocells, the fully confined zone includes two parts: 1) the cell height, and 2) a limited thickness above and possibly beneath the geocell. Above the confined zones, a transition zone is developed which extends until there is no influence on the granular layer from the geocell (unconfined zone). Figure 3 illustrates the various zones.

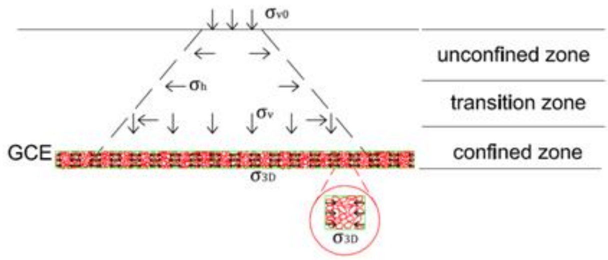

Figure 3. Interaction with geocells (σ_{v0} = vertical stress applied at the top surface; σ_h = horizontal stress; σ_v = vertical stress at the subgrade interface; σ_{3D} = geocell confining stress; GCE = geocells)

The efficiency of confinement and the thickness of the confined and transition zones varies with different geocells and soil types. The details therefore have to be defined for each type of geocell and soil types individually.

From Fig. 3 it is evident that, when a relatively high aggregate thickness is required, designing with multiple layers of geosynthetics would allow to reduce or eliminate the unconfined zone, thus affording a more effective stabilization.

3 GEOCELL CONFINEMENT MECHANISM

The 3Dconfinement occurs when a certain volume of material is confined by a three-dimensional geosynthetic system, like a geocell. The geocell stabilisation mechanism limits horizontal infill soil deformation via the geocell walls thereby confining the infill soil. The limitation of horizontal deformation is based on three factors:

- hoop tension forces in the cell walls,
- resistance from the surrounding cells, and
- friction between cell walls and infill material.

Under vertical loads, horizontal earth pressure is restrained by cell walls, activating hoop tension forces (Fig. 4). The resulting strains in the cell wall mobilise hoop stresses within the loaded cell. The magnitude of the activated hoop stress depends on the geocell material, stress-strain behaviour and load level, number of load cycles, the location of the applied load, the type of infill material, and the subgrade characteristics.

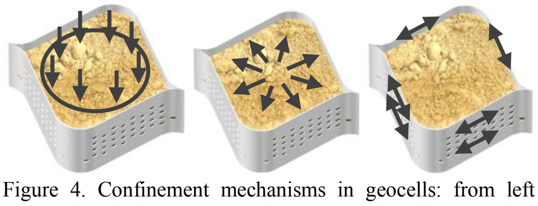

Figure 4. Confinement mechanisms in geocells: from left to right: External vertical stress; Lateral stress on cell walls; Lateral confinement and hoop tensile stress in cell walls

The hoop stresses and resistance provided by surrounding cells restrict lateral deformation of the fill by producing confining stresses σ_{3D} (Fig. 3). The intensity of the confining stresses σ_{3D} strongly depends on the height to diameter ratio of the geocell and on the tensile stiffness of cell walls.

The stabilisation effect relies on the composite behaviour of the infill-geocell system, in which lateral earth pressures are mobilized and transferred across a three-dimensional network of interconnected cells. The properties of the infill material (i.e. particle size distribution, angle of internal friction, relative density, etc.) act in conjunction with the characteristics of the discrete elements of the geocells (comprised of cell walls, seams/joints, connection devices, perforations/texture, and in some cases, earth anchoring devices) to facilitate the desired ground improvement effect. The infill materials, along with each of the discrete elements of the geocell system, will each impart some level of influence over system performance.

Accordingly, the behaviour of the composite system is similarly influenced by these factors, along with the geometry of the geocells, the number of adjacent geocells acting in response to an applied load, and the stiffness of system components. In general, with increasing numbers of adjacent cells (cell density) surrounding the location of an applied load, the resulting horizontal pressure is distributed over a wider area.

The primary benefit of geocells used in load support and roadway and railways projects is through increased stiffness of the stabilized layer achieved by a reduction in volumetric changes of the infill during loading by means of lateral confinement. The geocell-enhanced layers are improved through the addition of tensile strength at low strain levels provided by the geocell. The cellular structure limits the vertical settlements of the stabilized infill by laterally restricting movement of the individual particles. The ability to maintain low permanent deformation levels from applied loads and provide long-term, stable confinement of the infill material are directly dependent on the ability of the geocell to retain its key material properties and dimensions throughout the design life (Vega et al., 2018).

Limiting strain in the geocell hoop is the primary mechanism that restrains particle movement within each cell in the lateral direction, and results in a direct reduction of the vertical displacement of the infill (Hegde and Sitharam, 2014). The second mechanism that helps restrict lateral movements within the geocell layer is the increased lateral support provided by adjacent cells (Dash et al., 2007).

4 LOADING CONDITIONS (CYCLIC / STATIC)

As vehicles continue to traffic a pavement overlying unbound aggregate, the stress distribution angle within the unbound aggregate typically decreases (see Fig. 5), due to cyclic loading.

The accumulation of plastic deformations due to loading and unloading cycles normally leads to a reduction of the shear strength of the base course material. As a result, the maximum stress at the base/subgrade interface tends to increase over time.

Bearing capacity failure of the subgrade occurs when the stress distribution angle decreases to a point at which the stress at the interface exceeds the mobilized shear strength of the subgrade (Giroud and Han, 2011). The utilised shear strength of the subgrade depends on the undrained shear strength of the subgrade, the surface deformation or rut depth, the tire contact area, and the thickness of the base (Giroud and Han, 2011).

Geocells for stabilization have been shown to be able to delay and minimize the decrease of the stress distribution angle with increasing number of wheel passages.

Under static loading conditions, the load distribution angle remains the same over time for an uncontaminated layer of unbound aggregate.

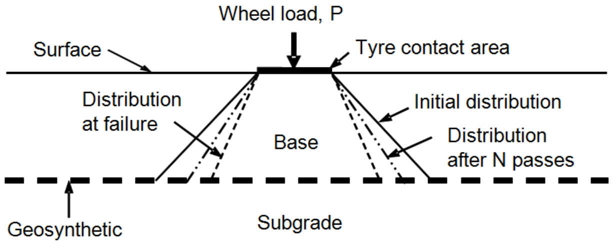

Figure 5. Stress distribution angle (adapted from Giroud and Han, 2011)

5 DESIGN METHODS

5.1 *General*

The design methods for the stabilisation of unbound layers in roads and railways on soft soil are characterized by their empirical origins. Many methods are based on the specific application and provide standard thicknesses of various layers of aggregate.

Lateral restraint of the infill material is provided by the hoop of material that forms the cell wall, and the improved lateral support of adjacent cells. The suitability of the geocell in specific design cases and the magnitude of confinement provided by the geocell are directly dependent on the key material properties, the geometry of the individual cells, and the position of the geocell layer within the geotechnical structure.

Geocells have been included in specific design methods to provide an empirically obtained improvement of the system performance. Evidence of the improvement in system parameters may alternatively be provided by field and full-scale laboratory testing of the specific product in the appropriate aggregate and loading for the application.

The design methods here presented constitute the present state of practice.

5.2 *Design method for unpaved roads*

Pokharel (2010) developed a design method for geocell stabilisation of unpaved roads, based on studies of geocell stabilisation mechanisms, numerical modelling and field trials.

Pokharel (2010) modified the Giroud and Han (2004) design methodology for geosynthetic stabilization of unpaved roads by changing planar geosynthetic dependent parameters (such as aperture stability modulus) to geocell dependent parameters, such as elastic stiffness, creep resistance and tensile strength.

These parameters were calibrated by laboratory cyclic plate loading tests and full-scale moving wheel tests on granular bases over weak subgrade stabilised with a specific type of geocells made of a peculiar class of polymers, the Low Strain Nanopolymeric Alloy (LSNA). In the design methodology a maximum allowable rutting is set (together with all other parameters), and the pavement thickness is determined by:

$$h = \frac{\left(0.868+0.52\left(\frac{r}{h}\right)^{1.5}\cdot\log N\right)}{[1+0.204\cdot(R_E-1)]}\cdot\left(\sqrt{\frac{P}{\pi\cdot r^2\cdot m\cdot N_c\cdot c_u}}-1\right)\cdot r \qquad (1)$$

where:
h = required base course thickness (m)
r = radius of tire contact area (m)
N = number of equivalent standard axle load (ESAL)
P = wheel load (kN)
c_u = undrained cohesion of the subgrade soil (kPa)
R_E = modulus ratio of base course to subgrade soil
m = bearing capacity mobilization factor

The reduction in the load distribution angle with the number of passes caused by the deterioration of the base course material under the repeated loading in laboratory was previously observed by Leng & Gabr (2006) for geogrid stabilisation. Recent research showed that geocells significantly slowed down the rate of deterioration in the base quality. This phenomenon is attributed to 3D geocell confinement to increase and maintain the modulus of the base course.

The Modulus Improvement Factor (MIF) I_f was proposed by Han et al (2010) to account for this benefit:

$$MIF = I_f = E_{bcs} / E_{bcu} \quad (2)$$

where E_{bcs} and E_{bcu} are the moduli of stabilized and unstabilized base course.

Considering I_f, the modulus ratio R_E in the Pokharel formula (1) can be expressed as:

$$R_E = I_f \cdot (E_{bcu} / E_{sg}) = \max(7.6; I_f \cdot [(3.48\ CBR_{bc}^{0.3}) / CBR_{sg}]) \quad (3)$$

where CBR_{bc} and CBR_{sg} are the California Bearing Ratio values of the unstabilized base course and of the subgrade.

Han et al (2010) reported that the modulus ratio with geocell stabilization ranges between 4.8 and 10.0. Anyway, based on cyclic plate loading tests and accelerated moving wheel tests, Pokharel (2010) suggests to limit the value of R_E to 7.6, specifically for LSNA geocell stabilized bases.

The bearing capacity mobilization coefficient (m) is given by:

$$m = \left(\frac{s}{f_s}\right) \cdot \left[1 - 0.9 \cdot e^{-\left(r/h\right)^2}\right] \quad (4)$$

where:

s = limit rut depth at the top of the stabilized base course (mm)

f_s = rut factor = 75 mm.

Since usually a separation nonwoven geotextile is placed below the geocells, the bearing capacity factor N_c for geocell stabilized unpaved road base in Formula (1) is assumed, according to Giroud& Han (2004), as:

$$N_c = 5.14 \quad (5)$$

The factor used by Giroud – Han (2004) to control the rate of reduction in the load distribution angle, which depends on the aperture stability modulus J for geogrids, for LSNA-based geocell stabilization have been replaced by the term:

$$\left(0.868 + 0.52\left(\frac{r}{h}\right)^{1.5} \cdot \log N\right) \quad (6)$$

The parameters of the Pokharel method, including MIF, RE, rate of reduction in the load spreading angle, and others, have been calibrated for LSNA geocells (Pokharel, 2010; Pokharel et al, 2011; Pokharel et al, 2015; Pokharel et al, 2016).

The method is applicable to other types of geocells, but the extension of the method to other types of geocells may require different parameters, which can be calibrated by laboratory cyclic plate loading tests and full-scale moving wheel tests on the specific geocells.

5.3 *Design method for paved roads*

For paved roads on soft subgrades the design method for geocell stabilisation can be based on the elastic behaviour of pavement structures following the Mechanistic-Empirical design procedure (Kief, 2015). A mechanistic model of each pavement layer can be developed by including its thickness, elastic modulus and Poisson's ratio into commercially available layered-elastic analysis programs for pavements; the mechanistic model produces an elastic response of tensile and compressive strains for fatigue and rutting failure modes.

The Mechanistic-Empirical method applied to geocell stabilization of paved roads normally utilizes the following parameters:

- Resilient modulus of subgrade;
- Number of ESAL (80 kN equivalent single axle load) in the design life;
- Modulus Improvement Factor (MIF).

The MIF of the layer stabilised with geocells relates to the improvement of the layer modulus (base and/or sub-base), which is expressed by the following formula:

$$MIF = E_{withgeocell} / E_{without\ geocells} \quad (7)$$

where:

$E_{with\ geocell}$ = modulus of geocell stabilized base / sub-base

$E_{without\ geocells}$= original modulus of the unstabilized base / subbase.

MIF for geocells is obtained through performance testing including validation of specific geocell properties for the design life (Rajagopal, et al, 2014), specific infill type and resilient modulus of subgrade.

MIF is higher for:

- Smaller cell size;
- Higher cell height;
- Higher ratio of cell height to cell size;
- Lower modulus of infill materials;
- Higher resilient modulus of subgrade / support;
- Higher tensile strength and stiffness of geocell strips.

Measured MIF values for LSNA geocells are typically in the range 1.8 - 4.5, depending on the above factors.

The original modulus of the unstabilized base / subbase depends on:

- the bearing capacity of the underlying layers and subgrade;
- the layer thickness of the subbase.

With increasing values of bearing capacity of underlying medium and increasing thickness of the subbase, the stiffness of a subbase in an unstabilized situation increases.

The chart in Fig. 6 (modified from Vega et al, 2018) can be used for a preliminary evaluation of the MIF value as a function of the modulus of the unstabilized base / subbase and of the modulus of the layer below. The MIF from the chart are based on geocells with perforated strips having tensile strength (ISO 10319) higher than 16 kN/m with less than 3 % accumulated permanent deformation, evaluated according to ASTM D6992 with three isothermal steps at 44°C, 51°C and 58°C (Vega et al, 2018).

If additional unstabilized layers are placed above the geocell stabilized layer, then their modulus may be improved as well due to the stronger support provided by the geocell stabilized layer.

5.4 *Design method for railway stabilization*

A primary contribution of geocells to a railway structure is the improved modulus of the stabilised layer (quantified by MIF, as above defined), and of layers above it, if exist.

Based on the MIF value, the geocell stabilization affords to increase the overall stiffness of the sub-ballast structure. The stabilised sub-ballast layer can then be optimised in terms of reduced thickness and/or the use of lower quality/marginal materials. The design criteria in such a structure can include the required E_{V2} modulus (modulus of subgrade reaction measured in a plate loading test according to DIN 18134) on top of the sub-ballast structure, according to railways standards (typically between 20 and 100 MPa).

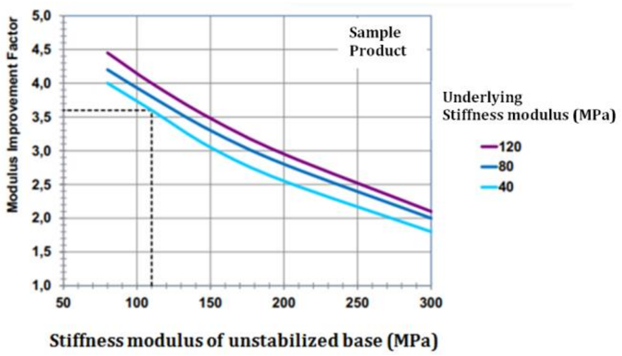

Fig. 6. Chart providing the MIF value of LSNA geocell stabilized layers as a function of the modulus of the unstabilized base / subbase and of the modulus of the layer below (modified from Vega et al, 2018).

The different layer moduli can be defined considering that the modulus of each layer is dependent on the layer underneath it, as listed in Tab. 2 (adapted from Livneh, 2013), where:

h_{sb} = Subbase layer thickness [mm]
h_b = Granular base layer thickness [mm]
E_{sg} = Subgrade elastic modulus [MPa]
E_{sb} = Subbase elastic modulus [MPa]
E_b = Granular base elastic modulus [MPa]
ν_b, ν_{sb}, ν_{sg} = Poisson's ratio of base, subbase and subgrade.

Table 2. Formulas for different layer moduli (adapted from Livneh, 2013)

	Elasticity Parameters	Notes
Base	$E_b = E_{ab}$ x (1+0.0067 x h_b [mm]) $\upsilon_b = 0.35$	E_b [MPa] ≤ 700
Sub-base	$E_{sb} = E_{sg}$ x (1+0.003 x h_{sb} [mm]) $\upsilon_{sb} = 0.35$	E_{sb} [MPa] ≤ 300
Subgrade	E_{sg} [MPa] = 14 x CBR [%] $\upsilon_{sg} = 0.40$	2 < CBR [%] < 12

After calculating E_{sg} and E_{sb} with the formulas in Tab. 2, it is possible to evaluate the MIF value using the chart in Fig. 6 (valid only for LSNA geocell) or with other charts available in literature.

If the subbase is stabilized with geocells, the modulus of the stabilized subbase E_{sbs} is:

$$E_{sbs} = E_{sb} \cdot MIF \quad (8)$$

Once the layer thicknesses and moduli of the unstabilized and geocell stabilized railway subballast have been set, the vertical settlement on the sub-ballast surface and the vertical stress on the subgrade surface below the centre of the sleeper can be calculated for both stabilized and unstabilized railways structure using standard stress/strain software for railway design.

The stress - strain characteristic of a railway substructure is dependent on the frequency and the size of the individual axle load applications. Accordingly, the loading on the subgrade is inversely proportional to the number of loading cycles raised to a power λ, according to the following formula:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{N_2}{N_1}\right)^{\lambda} \quad (9)$$

where:
σ_1, σ_2 = vertical stresses corresponding to N_1, N_2 loading cycles, respectively
λ = exponent with a mean value of 0.2.

If P denotes the load per axle and T denotes the daily traffic tonnage the equation above becomes:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{T_2 / P_2}{T_1 / P_1}\right)^{\lambda} \quad (10)$$

For constant axle loads, $P_1 = P_2$ and the equation above becomes:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{T_2}{T_1}\right)^{\lambda} \quad (11)$$

where:
T_1, T_2 = daily traffic tonnage corresponding to N_1, N_2 loading cycles, respectively.

Formulas (9), (10), and (11) allows to calculate the improvement in loading cycles and daily traffic tonnage afforded by the geocell stabilization design.

6 DESIGN FACTORS

From the reported design methods there are alarge number of factors which would normally be taken into account when considering the design of a stabilised granular layer.

In case of geocell stabilisation the design factors are product and project specific, and would normally be evaluated based on performance testing; factors to be considered may include the following:

- Lateral confinement of infill materials;
- Infill stiffness;
- Vertical confinement due to frictional resistance between infill and cell walls;
- Magnitude, type and frequency of loading;
- Distribution of lateral and vertical stresses;
- Aggregate movement and attrition;
- Junction and strip properties of the geocell;
- Zone of influence above and below the cellular confinement system where the stabilisation mechanism is active;
- Increased load spreading angle of applied loads;
- Height of geocell and cell diameter to cell height ratio;
- Location and number of geosynthetics in the stabilized layers.

7 KEY PROPERTIES FOR GEOCELLS

The impact of geocell stabilisation have been quantified through laboratory testing and large-scale field tests (Pokharel et al, 2011; Yang et al, 2011). Geocells were found to stiffen granular materials layers by external confinement, thereby increasing the modulus of the stabilized layer. This benefit is quantified as the Modulus Improvement Factor (MIF), as detailed in previous sections.

The geometry (cell height, distance between internal junctions, number of cells per unit area) and material properties of the geocell are key properties to maximize the magnitude of stabilisation and to validate it for the design life of the project.

The key material properties of the geocell, related to hoop tension forces in the cell walls, are its elastic stiffness and resistance to permanent deformation; these properties determine the magnitude of the stabilisation for the design life. The stiffer the geocell, the higher the hoop tension stress will be, and, thus, the higher the MIF. Short term tensile properties can be measured by wide width tensile test as per ISO 10319.

The installation damage suffered by geosynthetics has usually negligible influence on its tensile strength at low strain; anyway, it should be checked that the tensile strength at the design strain is not modified by installation damage, through testing according to ISO 10722.

Long term properties include the resistance of geocells to tensile creep and dynamic fatigue: in fact the improvement of the geocell stabilized layer for entire design life is dependent on the short and long term geocell properties (tensile stiffness, dynamic stiffness and creep) to assure very low deformation of the confining cell walls, i.e., less than 2 % accumulated strain for the entire design life.

The resistance to permanent tensile forces for the design life is measured by accelerated tensile creep tests by the stepped isothermal method (ASTM D6992) with a fixed load that simulates the design hoop stresses.

The stiffness modulus of a material is a measure of its elastic deformation behaviour and it is an indication of the relationship between the force exerted on a material and the associated elastic deformation. The elastic deformation behaviour is the main mechanical property for all types of pavement bases, from unbound to bound. The same principle applies to base stabilization with geocells. Tensile dynamic loading on a geocell may result in a reduction in strength referred to as fatigue. Fatigue testing of materials is frequently investigated by applying high dynamic loads, establishing the relationship between the load and number of cycles and then extrapolating the number of cycles to failure [Huang 2004].

A geocell must maintain stiffness under dynamic loading without significant permanent deformation or loss of geometry, which could result in a loss of confinement, invalidate design parameters or cause failure. In project design, the stiffer the geocell is (at short and long term), the less lateral and vertical movement there is, and therefore the confining compressive stress σ_{3D} (see Fig. 2) is increased (Pokharel & Kief, 2018).

The net dynamic stiffness modulus (DMA test) for geocells can be determined by ISO 6721-1 (Vega et al 2018). The test measures the polymer stiffness in the elastic region, that is the capacity of the geocell to resist dynamic fatigue stresses without permanent deformation. An excessive decrease in dynamic stiffness leads to unacceptable reduction in the stabilizing effect of geocells. Higher dynamic stiffness values result in lower permanent deformations even at higher temperatures and better structural behaviour in the long term. The DMA test should provide results at ambient and elevated temperatures to monitor the behaviour of the material in an accelerated mode. Typically, at least 3 different temperature-based measurements are required to explore the behaviour of the elastic stiffness.

Additional geocell properties to be evaluated include:

- Junction strength (ISO 13426-1 Part 1, Method C); resistance to relative movement, node rotation, lateral and vertical movement;
- UV tests to determine the maximum exposure time before covering the geosynthetic with soil (EN 12224);
- Durability tests by oxidation degradation applicable to the specific polymer of the geocells (ASTM D5885).

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