Design of geosynthetics for rigid inclusion ground improvement: a simplified analytical method

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Abstract. The French national project ASIRI+ (2019-2025) is the continuation of the ASIRI project (2005-2012). It aims to provide design recommendations for ground reinforced by rigid inclusions, which, in France, are typically based on the analysis of a unit cell accounting for the behavior of an infinite inclusion group. These so-called "biphasic models" provide all the necessary components for the structural design of rigid inclusions. New topics are introduced in ASIRI+ project, such as horizontal reinforcement of the granular platform using geosynthetics which permits the improvement of the performance of the load transfer platform. In this framework, this paper presents a simplified analytical method that incorporates geogrids into biphasic models. At the level of geosynthetics, which transfers the load to the tops of the inclusions, a relationship coupling the geosynthetic displacement with this load is introduced into the biphasic model equations. The results obtained using this methodology are compared to full-scale tests conducted by the laboratory GEOMAS and the CEREMA of Rouen.

1 Introduction

The concept of rigid inclusions involves incorporating rigid elements into the soil and the particularity is that the load transfer towards these elements is done via an intermediate granular platform that can be reinforced or not by geosynthetics.

For large structures, such as slabs, rafts, or embankments, the design of reinforcements using rigid inclusions in France generally relies on the study of an elementary unit cell (Figure 1) that represents the behavior of a common grid centered on an inclusion [1]. These called « biphasic models », such as Taspie+ model, provide all the necessary elements for structural design. Their validity has been extensively confirmed within the ASIRI national project [2] through comparisons with results from full-scale experiments, physical models, and numerical simulations.

The integration of geogrid reinforcements into these models is further explored within the framework of the ASIRI+ project (2025). In this context, this paper presents a simplified analytical method [3] that incorporates geogrids into biphasic models. The results obtained

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using this methodology are compared with tests conducted by the laboratory GEOMAS and the CEREMA in Rouen [4] as part of a benchmark study for the ASIRI+ project.

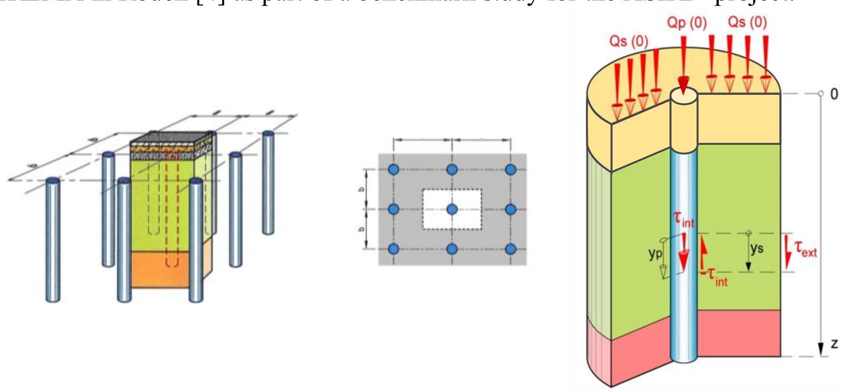

Figure 1. Unit cell concept illustration [1]

2 Description of the method

2.1 Taspie + model

Taspie+ model aims to study the behavior of an elementary cell centered on an inclusion subjected to vertical loading. This volume is decomposed into two domains: the « pile » domain, consisting of the inclusion and the surrounding soil volumes that extend it to the lower or upper limits of the model, and the « soil » domain, consisting of the complementary soil volume (see Figure 2). The interaction between these two domains is assumed to be fully described by the shear τ that develops on their vertical boundary. A « t-z » load transfer curve, characterized by a slope parameter k_t and a limiting shear value q_s, is used to describe the shear at the interface.

For large structures such as slabs, rafts, or embankments, the model is assumed to be periodic, which implies that the shear is equal to zero on the outer vertical faces.

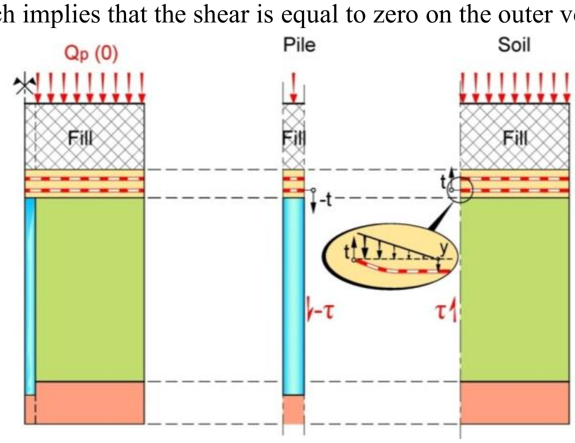

Figure 2. Taspie+ model

The presence of a load transfer platform (LTP) and/or a fill layer is treated by fictively extending the « pile » domain to the top of the model. The load transfer induced by the arching effect is modeled through a negative vertical friction between the « pile » and « soil » domains. The limiting value of this friction is taken as $q_{sn} = k\tan\delta.\sigma'_v$. The factor $k\tan\delta$ is an empirical parameter that represents the product of a soil-pile friction coefficient tanδ and a passive earth pressure coefficient k (such that $\sigma'_N = k\sigma'_v$). In practice, the factor ktanδ is capped at a value of 1 within the mattress.

2.2 Integration of geosynthetics in Taspie+

The incorporation of geosynthetics into the Taspie+ model is done by introducing, at the geosynthetic level, the relationship between the geosynthetic displacement Δy and the load R it transfers to the « pile » domain.

The Δy value corresponds to the deflection of the geosynthetics and can be approximated in the elementary unit cell model as the differential settlement between « soil » and « pile » domains at the geosynthetics level (Figure 3):

$$\Delta y = y_{sol} - y_{pieu} \qquad (1)$$

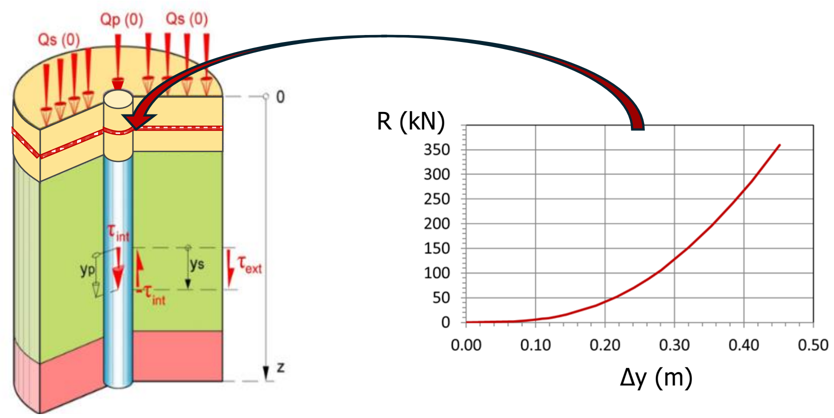

Figure 3. Relationship between the geosynthetic displacement Δy and the load R

The relationship R= f (Δy) is derived from an analytical model that considers the geogrids as membranes facilitating the transfer of some extra load to the « pile » domain. This load transfer is mainly operated by orthogonal strips within the geogrid (Figure 4). The strips are assumed to be loaded by an inverse triangularly distributed load and rest on a width a, determined by a 1H:2V diffusion ratio from the inclusion heads (a = B + h).

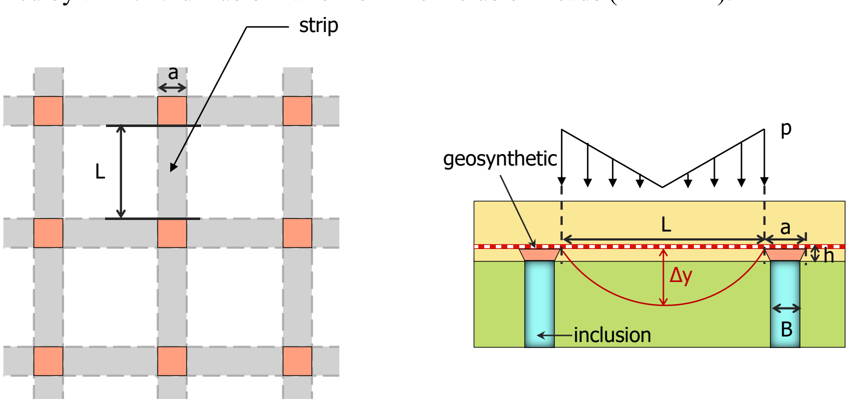

Figure 4. Inverse triangularly distributed load

The elastic equilibrium of the strip is studied taking into account second-order effects, and its resolution allows for establishing a direct nonlinear relationship between the pressure p and the resulting deflection Δy (Figure 5). This relationship depends on the secant stiffness J (kN/m) of the strip and the distance between the supports, noted as L (Figure 4).

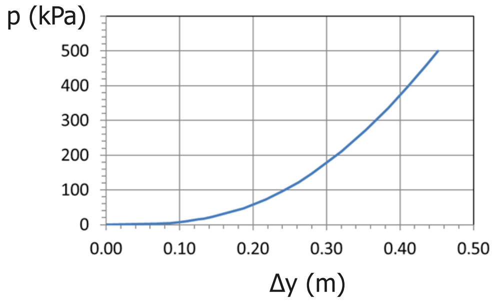

Figure 5. Example of the relation between the pressure p and the resulting deflection Δy

The total force R transferred by the geogrid to the inclusion tops is calculated by integrating the pressure p over a specific portion of the mesh area. This portion is defined as twice the strip area: an area with the same length but twice the bearing width (d=2a, **Figure 6**). This approach assumes that each strip captures a fraction of the load applied to the mesh area through a membrane effect.

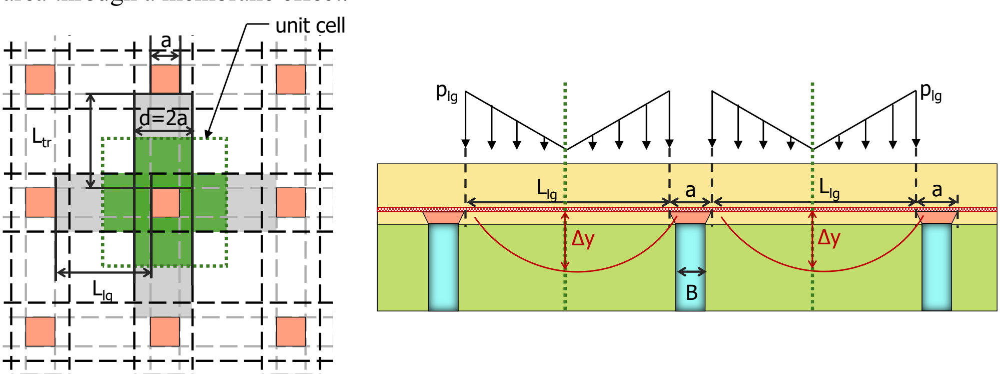

Figure 6. Portion of the mesh area used for the integration of pressure p

The approach also accommodates the anisotropic behavior of geosynthetics by summing contributions from strips in both longitudinal and transverse directions:

$$R_{lg} = p_{lg} \times L_{lg} \times d/2 \qquad R_{tr} = p_{tr} \times L_{ltr} \times d/2 \qquad R_{tot} = R_{lg} + R_{tr} \qquad (2)$$

Here, p_{tr} and p_{lgr} are the pressures in the transverse and longitudinal directions, respectively, derived using the secant stiffnesses J_{tr} et J_{lg} and the respective support lengths L_{tr} et L_{lg}

3 Benchmark application

3.1 Test plot geometry

In the framework of the ASIRI+ project, full-scale test plots are conducted at CEREMA [4] in Rouen to evaluate various configurations of embankments reinforced with rigid inclusions. Sixteen rigid inclusions are installed in an 8 m x 8 m pit with a depth of 1 m. The inclusions, of 300 mm in diameter and a length of 1 m, are arranged in a square grid with 2 m spacing.

The settlement of the compressible soil is simulated using the compressibility of rubber aggregates (Deltagom derived from tires) and the dissolution of Biocofra planks (honeycomb cardboard). Complete instrumentation is implemented to measure load transfer, settlement, and strain of geosynthetic.

Various test plot configurations are implemented. This study focuses on **Test Plot 5**, while a reference plot, **Test Plot 1**, is also analyzed, having the same geometry as Test Plot 5 but without geosynthetics. The plan and cross-sectional views of **Test Plot 5**, along with the sensor locations, are shown in Figure 7.

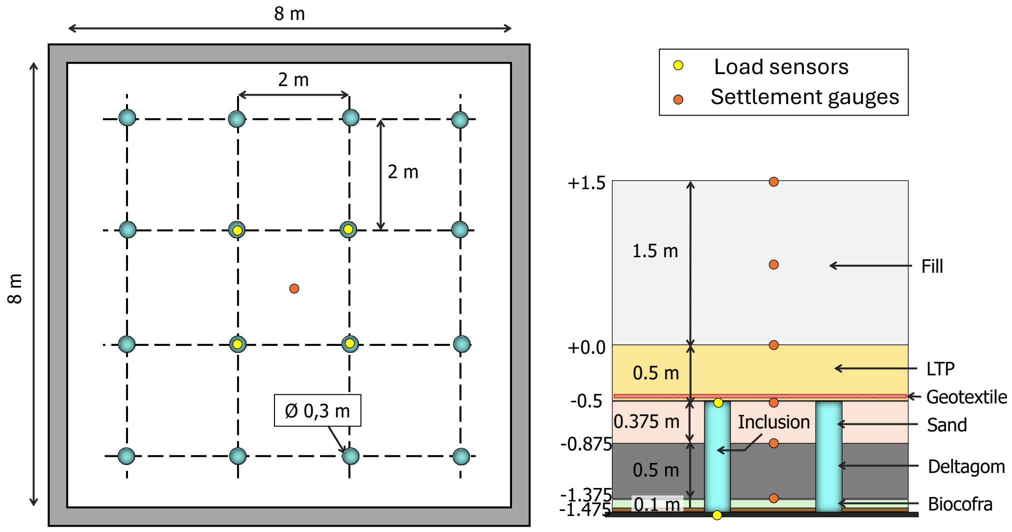

Figure 7. Geometry - Full-Scale Tests CEREMA Rouen – Test Plot 5 [4]

3.2 Reinforcement configuration

The reinforcement of **Test Plot 5** comprises two crossed and superimposed layers of monoaxial geotextiles (GTX) placed directly on the inclusion heads. The stiffness of the GTX is given Table 1. A mean stiffness of J = 6500 kN/m is used in calculations.

Table 1. Geotextiles stiffness

Parameter	Specification	Strain	Standard
J_{lg}: stiffness in the longitudinal direction	6 000 kN/m < J_{lg} < 7 000 kN/m	ε = 2 %	NF EN ISO 10319
J_{tr}: stiffness in the transverse direction	Negligible		

3.3 Phasing

The construction phases are as follows:

1. Installation of the Load Transfer Platform (LTP).
2. Construction of the embankment in three successive layers, each 0.5 m thick.
3. A one-month hold period.
4. Application of a concentrated load, corresponding to a distributed load of approximately 10 kPa after diffusion.
5. Dissolution of the Biocofra material.

3.4 Calibration without geosynthetics (test plot 1)

3.4.1 Calculation parameters

The calculations were performed using the Taspie+ model. Preliminary calibration based on Test Plot 1 helped establish the modulus values to be used for the Deltagom and Biocofra materials.

Table 2. Calculation parameters

	Thickness (m)	Base level (m)	γ (kN/m^3)	E (MPa)	ν (-)	G (MPa)	k_t (kPa/m)	ktanδ (-)
Fill	1.5	0	18	35	0.3	13	41	1
LTP	0.5	-0.5	19	50	0.3	19	58	1
Sand	0.375	-0.875	19	35	0.3	13	41	1
Deltagom	0.5	-1.375	10	0.11	0.25	0.044	0.133	0.15
Biocofra (before dissolution)	0.1	-1.475	0	50	0	25	76	0.15
Biocofra (after dissolution)			0	0.035	0	0.018	0.053	0.15

3.4.2 Calibration results

The results are presented in Figure 8. The calibration was performed based on the settlements measured at the base of the load transfer platform (LTP) for the phases following the one-month pause and after the dissolution of the Biocofra. It should be noted that experimental results showing that the settlement of the fill is smaller than the settlement of the LTP, suggesting a vertical extension of the embankment fill, were not considered during the calibration process.

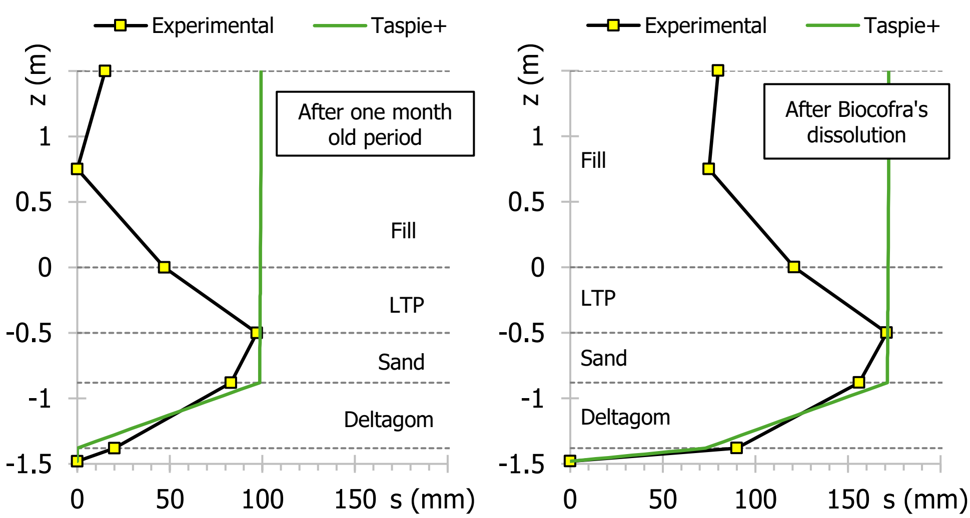

Figure 8. Settlements - without geosynthetics - Test plot 1 - Phase 3 and Phase 5

3.5 Taking into account the dissolution of Biocofra in the Taspie+ method

3.5.1 Differential pressure profile before Biocofra dissolution

In the proposed method, the geosynthetic strips are assumed to be subjected to a differential pressure p distributed according to an inverted triangular profile (Figure 4).

The inverted triangular profile represents the resultant stresses applied to the strip. These stresses combine the vertical stress from the soil above the strip and the vertical reaction exerted by the supporting soil beneath the strip.

This profile corresponds to measurements obtained from instrumented structures [5] and discrete element simulations conducted as part of the ASIRI+ project [6]. These measurements are considered representative of the loads acting on geosynthetic reinforcement strips in structures subjected to gradual loading, such as embankments with increasing height or subjected to surface loading. Moreover, in these scenarios, the strips are supported by the underlying soil from the beginning of the loading process, allowing both the strip and soil reaction to be mobilized.

The situation observed up to the dissolution of Biocofra closely resembles all those that validated the choice of the inverted triangular profile.

3.5.2 Impact of Biocofra dissolution

The dissolution of Biocofra introduces a new situation, not comparable to those serving as references for the triangular profile.

Indeed, the dissolution of Biocofra tends to reduce or even eliminate the soil reaction below the strip. As a result, the differential pressure profile on the strip takes a different shape from the inverted triangular profile, with a value that is no longer equal to zero at the center. This leads to new equilibrium conditions for the strip and the overlying embankment, which are reached after further displacement of the strip.

To account for this change, a uniform differential pressure profile is adopted as a simplification for phases following Biocofra dissolution.

It should be noted that the situation modeled by Biocofra dissolution can also be likened to cases where layers beneath the reinforcement would creep. In such cases, the reaction beneath the strips evolves due to factors originating below the strip rather than from the loading exerted above.

3.6 Results

Figure 9 and Figure 10 respectively present the settlement profile and the stress profile within the inclusions for Phase 3 (following the one-month hold period) and Phase 5 (after Biocofra dissolution). The results obtained using the Taspie+ method are compared with experimental data. For phase 5, the results obtained with both the inverted triangular and uniform profiles are compared to evaluate their impact.

The experimental results indicate that settlements at the base of the fill and LTP are smaller than those at the base of the sand. These results suggest an extension of these layers and are not considered in the analysis, in line with the approach used during the parameter calibration stage (see §3.4.2).

For Phase 3, the experimental data closely align with the Taspie+ results in terms of both settlements and the stress profile within the inclusions. This confirms the validity of the triangular load distribution for this phase.

For Phase 5, the experimental settlement profile aligns better with the uniform pressure distribution hypothesis (blue curve). Regarding the rigid inclusions loads, we can see that the ktanδ factor attributed to the Deltagom in the calculation underestimates the observed negative friction, resulting in a lower force at the base of the rigid inclusions.

Note: the settlement of Biocofra could not be fully modeled because Taspie+ doesn't allow for displacement to be directly imposed (it works with constraints, not displacements). Therefore, the deformation of the Biocofra is controlled by the modulus derived from the calibration phase (0.35 MPa) and the stress at the top of the layer, which is lower in the presence of geosynthetics compared to the stress applied during the calibration.

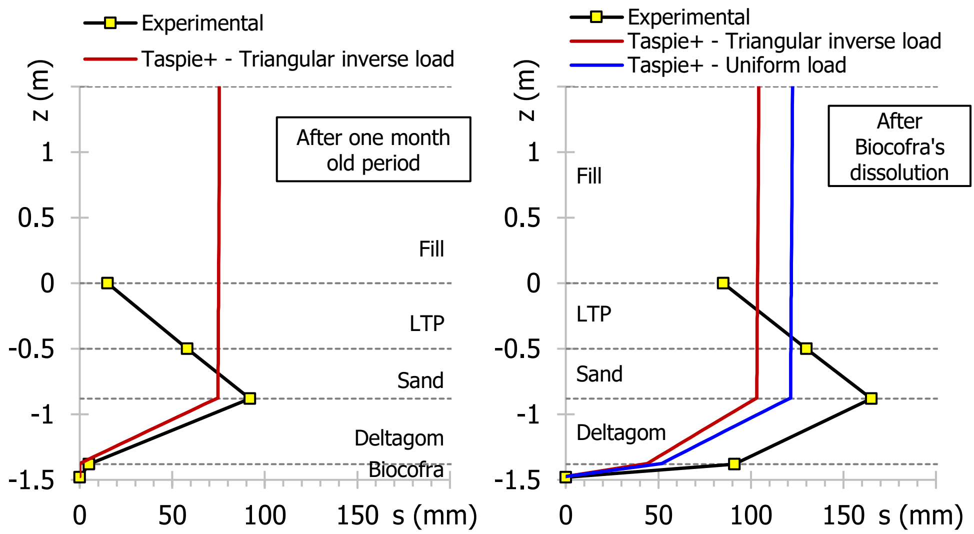

Figure 9. Settlements - with geosynthetic - Test plot 5 - Phase 3 and Phase 5

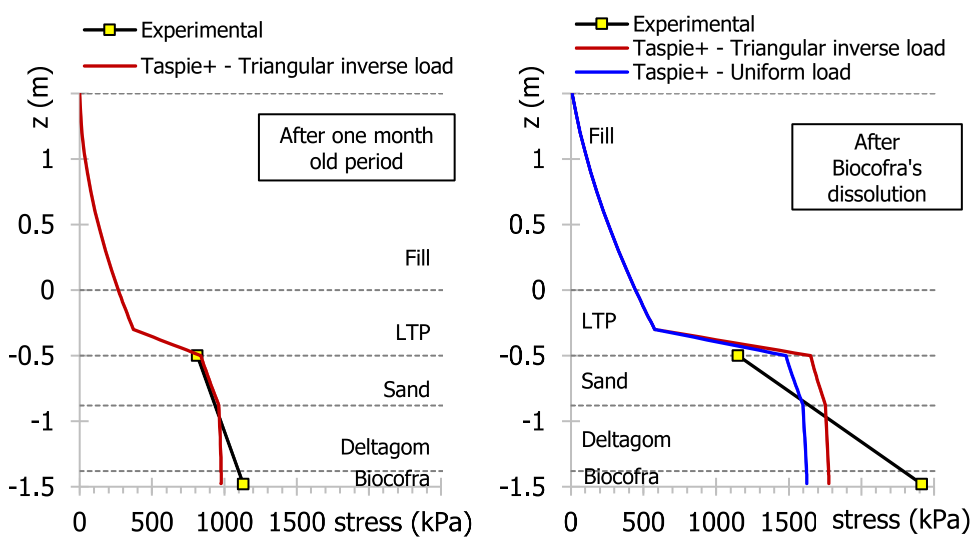

Figure 10. Loads in the rigid inclusions - with geosynthetic - Test plot 5 - Phase 3 and Phase 5

4 Conclusion

In this study, the integration of geosynthetics into biphasic models, particularly the Taspie+ model, has been explored in the context of rigid inclusion reinforcement for large structures such as embankments, slabs, and rafts. The Taspie+ model, validated through various experimental campaigns, provides a robust tool for assessing the interaction between inclusions and the surrounding soil under vertical loading conditions.

The comparison between the Taspie+ model and full-scale experimental data from CEREMA's test plots demonstrates that the model successfully predicts settlement profiles and stress distributions, particularly for structures subjected to gradual top loading, such as embankments.

In the proposed method, the geosynthetic strips are assumed to be subjected to a differential pressure p that represents the resultant stresses applied to the strip. The study further investigates the influence of different differential pressure profiles under varying conditions. For structures subjected to loading from the top, the triangular inverse differential pressure profile is the most suitable for modelling. However, in cases involving creep beneath the reinforcement, where the evolution of the strips is influenced by factors originating below rather than from above, a uniform pressure profile offers a better representation.

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