Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1120

Geotechnical Modeling and Analysis of Surcharge Loading Combined with Geosynthetic-Encased Stone Columns

Grace Stapley, Beatrice Beker, Frank Remmert
ILF Consulting Engineers Austria GmbH, Wien, Austria, grace.stapley@ilf.com

ABSTRACT: To address settlement and consolidation issues associated with the construction of roundabouts on poor soil, preloading with surcharge and geosynthetic-encased stone columns significantly reduces primary settlements and consolidation time. This study focuses on the geotechnical modeling and analysis of surcharge loading combined with geosynthetic-encased stone columns for the roundabout associated with the construction of the new federal state road B2 near Eschenlohe in Bavaria, Germany. To accurately capture the stress redistribution between columns and surrounding soil and to verify the structural integrity of both elements, a three-dimensional finite element (3D FE) model was developed as a part of the detailed design phase. This model addresses limitations of two-dimensional (2D) modeling, particularly the inability to represent the stabilising effects of geosynthetic encapsulation.

KEYWORDS: Geosynthetic-encased stone columns, soft soil, organic soil, numerical modelling, Plaxis 2D and 3D analysis.

1 INTRODUCTION

The construction of infrastructure on soft soil deposits presents significant challenges for geotechnical engineers, particularly in satisfying serviceability and stability requirements (Almeida & Marques, 2013). Among the various ground improvement methods available, stone columns are one of the most widely adopted techniques for reducing settlement and enhancing load-bearing capacity on soft clayey foundations (Poorooshasb & Meyerhof,1997; Greenwood, 1970; Mitchell & Huber 1985). However, in very soft clays with undrained shear strength below approximately 15 kPa, traditional granular columns may be inadequate, as the surrounding soil lacks the lateral confinement necessary to resist outward stresses, resulting in excessive bulging (Almeida et al. 2018). In such conditions, geosynthetic encasement has proven effective in providing additional horizontal support, preventing intermixing of clay particles, preserving drainage pathways, and significantly improving the stability and performance of the columns and embankment (Raithel et al. 2002; Alexiew et al. 2005; Raithel et al. 2005; Murugesan & Rajagopal 2010; Gniel & Bouazza 2010). To optimise the design and ensure the long-term integrity of these systems, it is crucial to develop a robust geotechnical model and conduct detailed analysis of surcharge loading combined with geosynthetic-encased stone columns, allowing for accurate assessment of stress redistribution between the columns and the surrounding soil.

To address settlement and consolidation issues, preloading with surcharge and geosynthetic-encased stone columns significantly reduces primary settlements and consolidation time. This study focuses on the geotechnical modeling and analysis of surcharge loading combined with geosynthetic-encased stone columns for the roundabout associated with the construction of the new federal state road B2 near Eschenlohe in Bavaria, Germany. To accurately capture the stress redistribution between columns and surrounding soil and to verify the structural integrity of both elements, a three-dimensional finite element (3D FE) model was developed as a part of the detailed design phase. This integrated approach provides insights into the performance of geosynthetic-encased columns under surcharge, demonstrating their efficacy in reducing settlement and ensuring stability during construction. The procedure for the analytical calculation method for geosynthetic-coated gravel columns in the current study is described in (Raithel, 1999) and (Almeida, Riccio, Hosseinpour, & Alexiew 2019).

2 METHODOLOGY

2.1 *Project*

As an early construction measure for the project B2 new Eschenlohe to Oberau North, a parallel road (St 2060) to the motorway A95 between the Eschenlohe junction and the current Eschenlohe South junction is to be built with a provisional connection via a roundabout. The St 2060 runs between two roundabouts at the Eschenlohe and Eschenlohe South junctions. For the southern roundabout, geotechnical measures are required according to the geotechnical report. The site contains a 6.5–8.0 m thick layer of soft peat underlain by alternating gravelly and cohesive valley fill deposits, making the ground conditions particularly poor. In this paper, the permanent version of the roundabout is examined as a variant in the Eschenlohe South area, which is the worser case of the two areas. The contents form the detailed design phase, therefore a comparison to the post-construction results is not within the current scope.

2.2 *Site and soil conditions*

Soil parameters for numerical calculations were derived using a combination of data from the geotechnical report (GIR), field observations, and conservative assumptions, indicating the peat layer's very soft consistency (evidenced by low penetration test blow counts).

In determining the stiffness of the model's materials, such as gravel, peat, silt and structural elements, the non-linear elastic nature must be carefully considered, as this impacts the change in stress. Defining the constrained modulus for the peat proved challenging due to the complexity of the interrelations between various soil properties. Evaluations of soil parameters, based on literature and practical experience, revealed that the stiffness values proposed in the GIR are higher than expected, suggesting caution in adopting these higher stiffness values.

2.3 *Model development*

The analysis comprises two models: a 2D model representing the roundabout with the exact geometrical dimensions, and a 3D-model covering a representative segment of the embankment, approximately 11 m×11 m (Figure 4), centered around a single column under the surcharge.

This is necessary, because the 3D stabilizing effect of the encased stone columns cannot be directly modeled and represented in the plane-strain 2D model. The stabilizing effect of the encasement in the 2D model is instead represented by an increased shear strength of the columns. This equivalent shear strength is derived from the results of the 3D model which serves to accurately capture the stress redistribution effects between the column and the soil, as well as to verify that no failure occurs in the columns or the soil. Additionally, the settlement calculation in the 3D model can be used to verify the settlements determined in the 2D model due to embankment filling.

During the development of the model's configuration, an axisymmetric model of the unit cell which models of a single gravel column with surrounding soil was tested. The axisymmetric model was intended to quantify the supporting effect of the geosynthetic cladding. The results revealed a number of simulation complexities with regard to modeling the geosynthetic coating and the redistribution effects of the surcharge load in the columns. An example includes the correlation of external horizontal stresses to the resultant internal horizontal stresses due to the random scattering of results along the pile. To mitigate the need for such correlates, a 3D FE model that represents all piles was necessary. This model maps the deformations from the subsoil for different construction phases and the consolidation time.

The ground model, including the working platform, stone column dimensions, and the arrangement of two horizontal geogrid layers (one above and one below the working platform), adheres to the project specifications. All geogrid layers, including those for reinforcement at the top and bottom of the working platform and the encasement around the stone column, were modeled as linear-elastic elements to simulate the geosynthetics' mechanical behavior. While it is acknowledged the geosynthetics' do not behave linear-elastically in reality, the simplification was required for the model. Two types of loads are present at the site: the surcharge load from the embankment and a local traffic load. Surcharge loading is applied as an equivalent surface load at the column's top. In the 3D model, the modeling of traffic load is excluded. This is because within the 3D model, only a small section of the overall model is represented. If the traffic load were to be included, the spread of stresses in the subsoil would not be accurately captured. Thus, for simplicity and in order to retain compatibility with the 2D model, only the surcharge load is modelled in the 3D model study.

The summary of the configuration, loads and construction phases within the Plaxis 2D model (as shown in Figure 2 and Figure 3) is as follows:

- Configuration: The encased gravel columns, modeled with soil clusters with spacing of 1.8 m. Dam geometry, encased column dimensions, and forces from the dam, overburden and traffic according to EBGEO. The replacement wall thickness of these "columns" is determined according to Tan et al. (2008) and Barron (1948). Approximately 1 m thick working platform.
- Loads: traffic load. The working platform is not considered in the load calculations for the encased columns.
- Construction phases: an initial phase to achieve equilibrium of the model, followed by phases with the installation of a working platform and the stone columns. Consolidation phases follow after the traffic loads affect the road embankment are activated.

It was identified that parts of the roundabout overlap with the existing road, Federal Highway 2, which presented no subsoil investigation data nor evidence that stabilization measures were undertaken. Thus, the specific construction phases modelled are defined to address the practically impossibility of the road being built without any stabilisation measures. It is assumed that at least an overload embankment was utilised. In addition, the road has been further consolidated over the years by ongoing traffic.

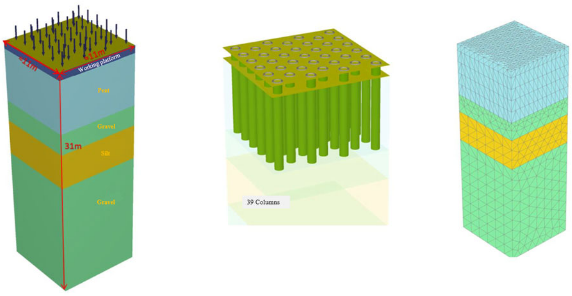

Figure 1. Geometry and mesh of the 3D Plaxis model.

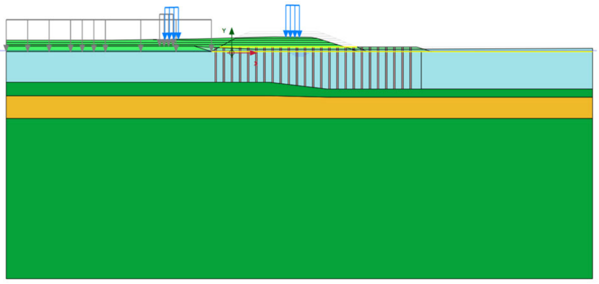

Figure 2. Geometry of the 2D Plaxis model for cross-section QP KV1.

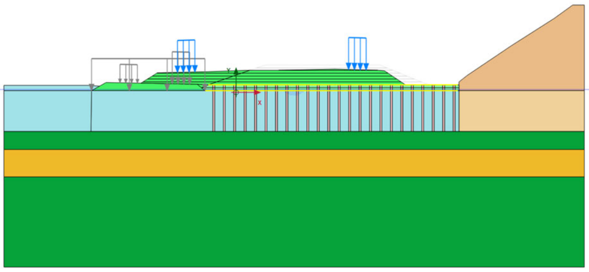

Figure 3. Geometry of the 2D Plaxis model for cross-section QP KV3.

3 RESULTS & DISCUSSION

The following results and discussion section presents an analysis of three key aspects: (1) stress redistribution between the stone columns and surrounding soft soil, (2) the structural integrity of the geosynthetic-encased stone columns, and (3) settlement predictions along with validation of the 2D numerical model results.

3.1 *Stress redistribution*

The results of the 3D model are presented in Figure 4. The results in the center of the model are evaluated. The results at the edges do not correspond to reality in this model and must be ignored. In general, the 3D model shows that the encased columns can withstand the load of the overload fill.

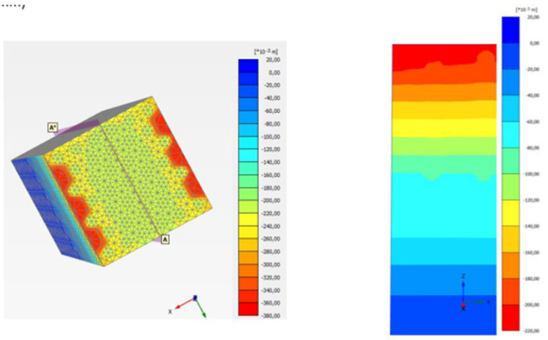

Figure 4. Settlement results for the 3D model (settlement in the cross-section A-A max. 220mm).

According to the 3D FE model, the settlements due to overload fill correspond to 22.0 cm. The 3D model shows that the load is completely redistributed to the columns. This means that the columns bear the entire weight of the embankment fill while the surrounding soft soil is bearing almost no weight. This load is shown in Figure 5 through the stresses in the main stress direction. The load distribution corresponds closely with the theoretical model presented in EBGEO (DGGT, 2010), whereby the load-induced stresses are concentrated above the columns (calculation process in Chapter 10.6.4.2 of EBGEO). For this case, these stresses are then almost entirely diverted through the columns due to their higher stiffness. Thus, when compared to the surrounding soft soil, it is typical for the columns to bear the entire weight of the embankment fill, as successfully modelled.

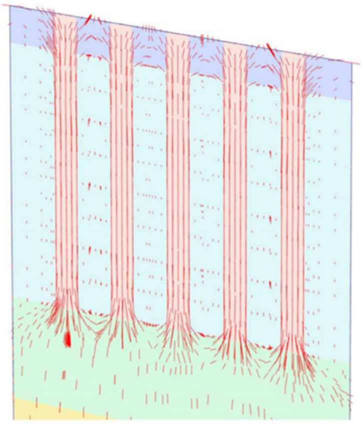

Figure 5. Cross-sectional view of the stress distribution in the 3D model (in the main stress direction).

3.2 *Structural integrity*

As shown in Section 3.1, the 3D FE model serves to accurately capture the stress redistribution effects between the column and the soil, as well as to verify that no failure occurs in the columns or the soil. The structural integrity is verified through the correlation of the encased columns parameters, specifically cohesion, as well as the settlement and the ring tension after surcharge loading.

To check whether the adopted material parameters for modelling overestimates the support effect of the geosynthetic sheathing, an additional simplified 2D model was created that corresponds exactly to the section through the 3D model. This is located where the columns are not sheathed with geogrid elements but are modeled with the equivalent cohesion. The equivalent cohesion accounts for the geosynthetic sheathing and is therefore higher in magnitude. In addition, the columns were modeled analogous to the plane-strain model of the dam with the equivalent wall thickness of 32 cm. The comparison of the mobilised effective vertical stress $\sigma'1$ shows that a similar stress is mobilised at the column in the 3D model as in the 2D model. Thus, the load-bearing effect of the column in the 2D model is comparable to the column in the 3D model and in the plane-strain model. An equivalent cohesion of 90 kPa can therefore be used.

According to EBGEO (DGGT, 2010), the design of geosynthetics based solely on numerical calculations is not permitted. Therefore, the ring forces in the encased columns and the forces acting on the horizontal reinforcement in the embankment foundation area are calculated according to the methods outlined in EBGEO. Creep settlements also cannot be represented using the numerical model. Hence, they are determined using an analytical approach. These settlements must be compensated during the construction period (embankment work). Table 1 shows the final results of the calculations for the load case of overloading embankment and the load case of completion of the roundabout.

Table 1. Calculation results from EBGEO for the surcharge embankment load case on the encased columns.

	Only constant force (LF1, BS-T)	Total force (LF2, BS-P)
Force distribution factor, E	1	1
Maximum characteristic ring tensile force (kN/m)	36.5	39.4
Design value of the ring tensile force (kN/m)	43.9	55.8
Settlements in the peat layer (cm)	12.0	13.0

BS-T: temporary load case
BS-P: permanent load case

Note: while no activation expansion of the geogrid was taken into account, settlements of up to 20 cm due to activation expansion are expected during construction.

3.3 *Settlements*

The embankment fill for the area of the existing road, represented by the surcharge load, is completed in layers (duration: 20 days) and consolidated over a relatively short time period (Table 2). This results in settlements under the embankment fill itself and possibly small entrainment settlements of the newly constructed road from the previous construction phases.

A summary of the results is presented for each construction phase. Of interest to the current paper, are the results for construction phases from the construction of the embankment to the construction of the superstructure. Construction phases including the construction of the embankment and subsequent consolidation phase are dedicated to the construction of the second half of the embankment fill, which overlaps with federal highway 2, and its consolidation. In these phases, the settlements caused by the construction and consolidation of this second half are of interest and may have to be compensated for during the construction period. In addition, the settlements for the newly constructed road are of interest.

A summary of the results for the two critical cross-sections, QP KV1 and QP KV3, is presented in Table 2.

Table 2. Consolidation and settlement results for the transverse profiles.

	QP KV1	QP KV3
Consolidation time remaining after completion of the filling work (embankment filling)	2,0 days	1,0 day
Max. Settlement in the area of the new embankment fill	13.8 cm	8.8 cm
Max. Carry-over settlements in the area of the road constructed in construction phase D	1.5 cm	1.8 cm

The settlements for the newly constructed road at the end of the consolidation of the embankment fill results in 1.5-1.8 cm at the edge of the road, which can be classified as a tolerable settlement.

The newly constructed embankment fill settles by a maximum of 13.8 cm. As the consolidation time is very short, these settlements can be compensated for during construction.

In the final step during the use of the entire roundabout, the traffic load is also applied to the road constructed in construction phases and consolidated. The phase results are presented in Table 3.

Table 3. Consolidation and settlement results for the traffic load phase.

	QP KV1	QP KV3
Consolidation time Traffic load	1.1 day	1.0 day
Max. Settlements due to traffic load	4.9 cm	4.2 cm

The settlements due to the traffic load are relatively high for both cross-sections. The settlements were be reduced by a preload, which would have to be applied for a short duration. In addition, the calculation neglects the construction site traffic, which will also anticipate settlements. Therefore, it was recommended that the consolidation of the entire roundabout be recorded using a monitoring program. As the consolidation times are relatively short, the calculation assumptions can be checked during construction and during the lay-by period.

The embankment fill calculated within another cross-section on the other side of the roundabout, which was constructed in previous construction phases, does not continue to settle as a result of the traffic load.

A final summary of the stabilisation measures required based on the 2D Plaxis model results is provided in Table 4.

Table 4. Summary of the stabilisation measures.

Measure	Characteristics
Surcharge embankment from the geotextile	H = 2.8-3.1 m with respect to hse = 1.1 m
Horizontal reinforcement	Rb,d ≥ 41.3 kN/m; Rb,c ≥ 80 kN/m J ≥ 5500 kN/m and max. ε = 0.15%
Encased gravel columns	ac = 1.8 m (triangular grid) rc = 0.4 m EA = J = 4500 kN/m Rb,d ≥ 51 kN/m

Rb,d; Rb,c – Design value with respect to the characteristic value for the tensile strength
J – Tensile stiffness of the geogrid
ε - Elongation
ac – Column spacing (centre distance)
rc = Radius of the column

While the creep settlements are reduced by means of the encased columns, there is still up to 12 cm of creep settlement over a period of 5 years expected. Where there are no encased stone columns, the estimated creep settlements are as much as 24 cm. However, as the calculations are based on many conservative assumptions due to the lack of laboratory tests, it is quite possible that the creep settlements will be lower. In any case, it is advisable to monitor the settlements of the roundabout with an appropriate monitoring program. Alternatively, to significantly reduce creep settlement, the peat could be pre-loaded to such an extent that it is in an over-consolidated state even with traffic loads.

In summary, the settlement predictions from the 3D model validate the 2D results, enhancing reliability in assessing consolidation behavior and verifying design assumptions.

4 CONCLUSION

In conclusion, the study demonstrates that preloading with surcharge and geosynthetic-encased stone columns significantly reduces primary settlements and consolidation time for the construction of roundabouts on poor soil. The 3D FE model developed in this study effectively captures the stress redistribution between columns and surrounding soil, addressing the limitations of 2D modeling. The results validate the 2D model's predictions, enhancing the reliability of assessing consolidation behaviour and verifying detailed design phase assumptions. Although the settlement results are considered high, and therefore conservative, the model developed contributes to the replication of real-world conditions. While the creep settlements are reduced by the encased pillars, continuous monitoring and potential pre-loading of the peat are recommended to further mitigate settlement issues. Overall, the findings provide valuable insights into the geotechnical modeling and analysis of surcharge loading combined with geosynthetic-encased stone columns, contributing to the successful detailed design phase prior to the construction of the new federal state road B2 near Eschenlohe in Bavaria, Germany.

5 REFERENCES

Alexiew, D., Brokemper, D. and Lothspeich, S., 2005. Geotextile encased columns (GEC): load capacity, geotextile selection and pre-design graphs. In: Proceedings of the Geo-Frontiers Conference. Austin, Texas, USA. Reston, VA: ASCE, pp. 497–510.

Almeida, M.S.S. and Marques, M., 2013. Design and performance of embankments on very soft soils. London: Taylor and Francis.

Almeida, M.S.S., Riccio, M., Hosseinpour, I. and Alexiew, D., 2018. Geosynthetic encased columns for soft soil improvement. London: Taylor and Francis.

Deutsche Gesellschaft für Geotechnik e.V. (DGGT), 2010. Empfehlungen für den Entwurf und die Berechnung von Erdkörpern mit Bewehrungen aus Geokunststoffen (EBGEO). 2nd ed.

Gniel, J. and Bouazza, A., 2010. Construction of geogrid encased stone columns: A new proposal based on laboratory testing. Geotextiles and Geomembranes, 28(1), pp. 108–118.

Greenwood, D.A., 1970. Mechanical improvement of soils below ground surface. In: Proceedings of Ground Engineering Conference, Institution of Civil Engineers. London, England, pp. 11–22.

Mitchell, J.K. and Huber, T.R., 1985. Performance of stone column foundation. Geotechnical Engineering, ASCE, 111(2), pp. 205–223.

Murugesan, S. and Rajagopal, K., 2010. Studies on the behavior of single and group of geosynthetic encased stone columns. Geotechnical and Geoenvironmental Engineering, ASCE, 136(1), pp. 129–139.

Poorooshasb, H.B. and Meyerhof, G.G., 1997. Analysis of behavior of stone columns and lime columns. Computers and Geotechnics, 20(1), pp. 47–70.

Raithel, M., 1999. Zum Trag- und Verformungsverhalten von geokunststoffummantelten Sandsäulen. Schriftenreihe Geotechnik, Heft 6. Kassel: Universität Gesamthochschule Kassel.

Raithel, M., Kirchner, A., Schade, C. and Leusink, E., 2005. Foundation of constructions on very soft soils with geotextile encased columns—state of the art. In: Innovations in Grouting and Soil Improvement. New Orleans, Louisiana, USA. Reston, VA: ASCE, pp. 1–11.

Raithel, M., Küster, V. and Lindmark, A., 2002. Geotextile-encased columns (GEC) for foundation of a dyke on very soft soils. In: Proceedings of the 7th International Conference on Geosynthetics. Nice, France. Lisse: Balkema, pp. 1025–1028.