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Study of the Efficiency of Vertical Drains by an FEM Method in Soil Treatment for Road Projects: Case of the Development and Bitumination Works of the ROCADE Porto-Novo in Benin

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Abstract

This article aims to study the efficiency of coupled vertical drains for the treatment of long-lasting compressible clay soils for the road project platform of the ring road of Porto Novo, capital of Benin. The experimental data allowed us to estimate a consolidation of 29% in 9 months, justifying the drainage of the soil. In order to study the efficiency of drainage, a FEM model was proposed simulating different scenarios. These include a drainless road, pavements equipped with vertical drains with meshes of 0.5 m 0.5 m, 1 m 1 m and 1.5 m 1.5 m respectively and horizontal drains. The results expressed in terms of variations in vertical stresses, effective stresses and shear deformations revealed significant variations in pavement performance depending on the mesh size of the vertical drains. The configuration with a mesh of 0.5 m 0.5 m showed the least deformations, thus indicating a reduction in deformations and better stress distribution. However, the other mesh configurations showed variable results, underlining the importance of choosing the right mesh for the specific project conditions.

Keywords

Pavement, Vertical Drains, Horizontal Drains, Modelling, Plaxis2D, ROCADE de Porto-Novo

1. Introduction

Roads are vital infrastructure for the development of a nation. Its primary role is to open up isolated regions [1] while connecting distant lands and facilitating the free movement of people, goods and services. Often seen as the lifeline of the economy, it effectively transports goods, promotes trade, stimulates tourism and creates economic opportunities [2]. It ensures the transit of goods from production sites to processing centers and then from processing centers to consumption [3].

The unanimous finding is that these vital infrastructures are being prematurely degraded. While some index the sizing methods, others point to the quality of materials and even the lift of support soils, especially when they are subjected to hydrogeological conditions. According to the 1992 GTR [4], the presence of water causes a drop in the platform's lift. Therefore, effective groundwater management is essential to ensure the sustainability and stability of road infrastructure. One of the techniques for controlling these waters is drainage, which can be done by lowering the water table. However, when the soil is thin, this technique is very limited because of the low permeability. Vertical drains [5] are seen as effective drainage systems for improving soil stability in road projects. These drains allow water to be drained from deep layers of soil into appropriate drainage areas, reducing the risk of soil saturation and pavement deterioration [6].

The effectiveness of vertical drains in soil treatment for road projects is crucial to ensuring the long-term sustainability and performance of road infrastructure. Poor design or implementation of vertical drains can lead to problems such as pavement uplift, ground subsidence, and even structural failures, which can result in high maintenance costs and project delays.

Understanding the factors that influence vertical drain efficiency is therefore essential to optimize their design, installation and performance in road projects. A better understanding of these factors will reduce the risks associated with drainage problems and optimize investments in road infrastructure [7].

Despite their importance, feedback shows that there are still gaps in understanding the factors influencing the effectiveness of vertical drains in soil treatment [8]. Some key questions remain unanswered, such as:

- What are the different types of soil for which drains are most effective?
- How do local hydrogeological conditions affect the operation of drains?
- What are the best practices for the design and implementation of drains to optimize their effectiveness?

This study, therefore, aims to answer these questions by identifying and analyzing factors that influence the efficiency of drains in soil treatment for road projects, with a view to improving design and implementation practices in this area.

The overall objective of this article is to examine the various factors that may impact the efficiency of drains in soil treatment for road projects. The ultimate goal is to identify these factors in order to improve current drainage design and implementation practices, thus contributing to the optimization of road infrastructure performance.

The specific objectives of this study are:

- Assess the impact of geotechnical soil conditions on drainage efficiency;
- Analyze different drainage design and installation techniques and their impact on drain efficiency;
- Study drainage monitoring and control methods to ensure that drains function over time.

To achieve these objectives, we propose to use modelling and numerical simulation approaches. These methods will allow the study and analysis of key parameters and the prediction of compressible soil behavior in pavement structures. By combining the results of simulations with experimental data, we will be able to provide recommendations for effective pavement design and management in geotechnical areas affected by compressible soils.

2. Soils Improvement Using Vertical Drains

2.1. History of Vertical Drains

Soil improvement techniques include a set of interventions to positively modify the properties of a soil, either through physical actions such as vibration [9] or by introducing more robust materials [10] in soil or their mixing with existing soil. As civil engineer John X. Wang pointed out, "Vertical drains are essential components in soil treatment for road projects, as they help to regulate groundwater levels and reduce the risk of soil saturation. This is essential to maintaining stable pavements and sustainable roads" [11].

The specific choice and application of these techniques are closely linked to the composition and grain size of the soils to be treated.

Since its introduction in California around 1930, the use of vertical drains to accelerate the consolidation of compressible soil deposits has become a common practice in civil engineering. This method was initially based on an empirical design of sand drainage systems [12] by pushing the soil back. However, thanks to the pioneering work of Barron (1947) [13], who developed abacus for the dimensioning of drainage systems, and the synthesis of Moran *et al.* (1958) [14] and Johnson (1970) [15], which has been the result of decades of sand drain use, this technique has been stabilized and internationally recognized.

At the same time, new techniques for sand drainage have been developed such as open pipe drilling, full or hollow boring, and the use of prefabricated drains [16] [17] made from various materials such as cardboard, plastic, non-woven, sand or rope. Despite the diversity of drainage methods and devices available on the market, as well as the scale of work carried out each year in the world, uncertainties remain about the merits of different approaches and the prediction of soil consolidation rates.

Since the first work of Johnson (1970), problems of vertical drainage consolidation have been addressed in several specialized international conferences, such as the conference of the ASCE (American Society of Engineers) Purdue, the Bangkok International Soft Clay Symposium, and the Sixth Asian Regional Congress on Soil Mechanics and Foundation Work in Singapore. These conferences helped to develop a "body of doctrine" guiding drainage practices, highlighting the importance of accurate assessment of soil consolidation parameters, preference for prefabricated drains, and the need to verify on-site the actual efficiency of drains under specific conditions. RPD can effectively reduce excess pore pressure in loose soil and shorten the consolidation period. The pore pressure in the RDF-reinforced area is less than 20.0 kPa at the end of construction, compared to 52.0 kPa at the beginning of construction [18].

The first type of drain used consists of sand drains that can contribute to reducing settlement and are a better option for depth by working properly during primary consolidation of the soil to be improved but limited because of their duration life weak favored by their obstruction [19]. Then there are the prefabricated vertical drains which are suitable in case of a depth limited by their equipment [20].

A PVD is defined as any material (or product) consisting of a synthetic filter envelope surrounding a plastic core that has the following characteristics:

- Ability to drain water from the ground to the core of the drain;
- Filter role: prevents the migration of fines from the soil to be improved;

The water collected in the drain is carried along the drain, via the core, to a draining level.

Pre-fabricated Vertical Drains (PVD) are preferred for their quick execution, best drainage properties [21].

2.2. Principle and Advantages of Vertical Drains

There are a variety of improvement techniques and their use depends largely on the size of the soil in place. While dynamic consolidation causes compaction of granular soils, vibroflottation is mainly applied to non-coherent granular soils, resulting in a temporary phenomenon of liquefaction of the soil surrounding the vibrator.

Rigid inclusions are suitable for all types of work on compressible soils of any kind. The ballasted column technique is an extension of vibroflottation to soils with silt or clay layers whose elements cannot be rearranged by vibration.

Drains facilitate the evacuation of interstitial overpressures in compressible soils to reduce the consolidation time from several decades to a few months or weeks depending on the spacing of the drains and the thickness of the drained layer a new load on cohesive floors (clays, silts...) saturated generates first of all an interstitial overpressure. It is during the dissipation of this interstitial overpressure that the solid skeleton of the soil can in turn be charged. The natural process of dissipation of these interstitial overpressures in clay soils is very slow because of their weakly permeable character and over several years. Vertical drains are set up in order to accelerate this phenomenon by facilitating the flow of water under overpressure to allow the loading of the soil grains themselves [22]. The use of vertical drains that are set up in a regular mesh, with a spacing not often exceeding 3 m, causes horizontal drainage over a smaller distance, compared to the thickness of the compressible layer, but with a horizontal permeability greater than the vertical permeability (**Figure 1**). This results in a high degree of acceleration of horizontal consolidation and, as a result, a considerable reduction in the time needed for consolidation [23].

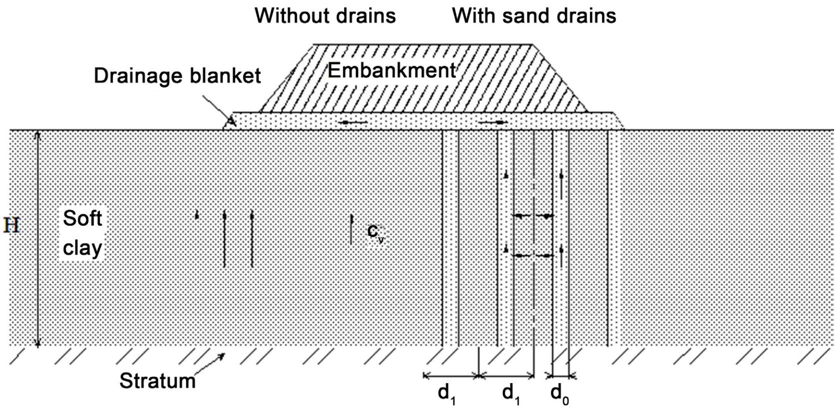

Figure 1. Principle of operation of vertical drains [24].

Figure 2 shows a cut of a precast vertical drain: geodrain.

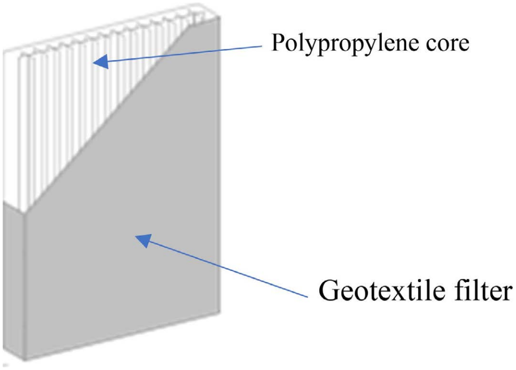

Figure 2. Cut of a precast vertical drain: geodrain [24].

2.3. Sizing of Vertical Drains: Consolidation Acceleration

Two theories have been developed.

2.3.1. Barron's Theory (1948): Elementary Cell

Barron puts forward the hypothesis of horizontal drainage (unidimensional consolidation), an applied load assimilated to constant vertical stress and a uniform vertical deformation.

$$\frac{\partial u}{\partial t} = C_h \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right] \tag{1}$$

u: excess interstitial pressure.

C_h: Horizontal consolidation coefficient.

Equivalent diameter: D_e (drain regular mesh) (**Figure 3**).

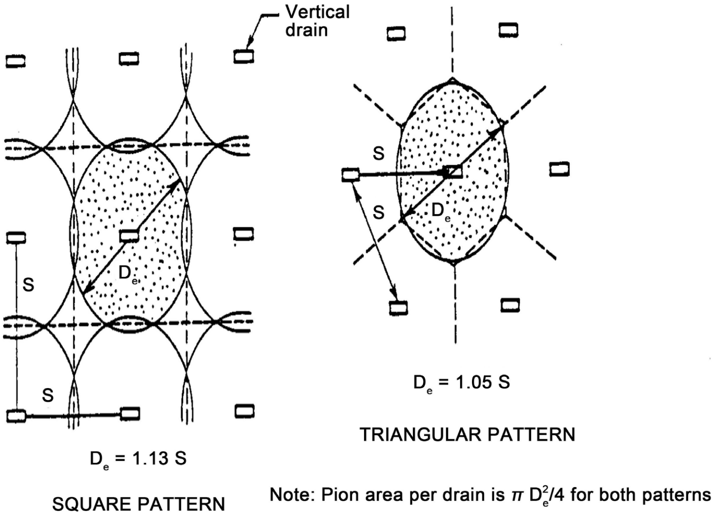

Figure 3. Relationship between the spacing of drains (*S*) and the diameter of the influence zone (D_e) [21].

- The coefficient of horizontal consolidation C_h is determined by:

$$C_h = \frac{k_h E_{oed}}{\gamma_w} \text{ with } \begin{cases} 1 \leq \dfrac{C_h}{C_v} \leq 5 \\ E_{oed} \text{ oedometrique module of soil} \\ k_h \text{ Phorizontal soil permeability of the disturbed area} \\ \gamma_w \text{ the density weight of water} \end{cases} \tag{2}$$

- facteur temps T_h:

$$T_h = \frac{C_h t}{D_e^2} \text{ with } \begin{cases} t \text{ the consolidation time in month} \\ D_e \text{ is the equivalent diameter} \end{cases} \tag{3}$$

The coefficient *n* is determined from the Barron abacus (**Figure 4**):

$$U_h = f\left(T_h, n\right) \text{ with } n = \frac{D_e}{d} \tag{4}$$

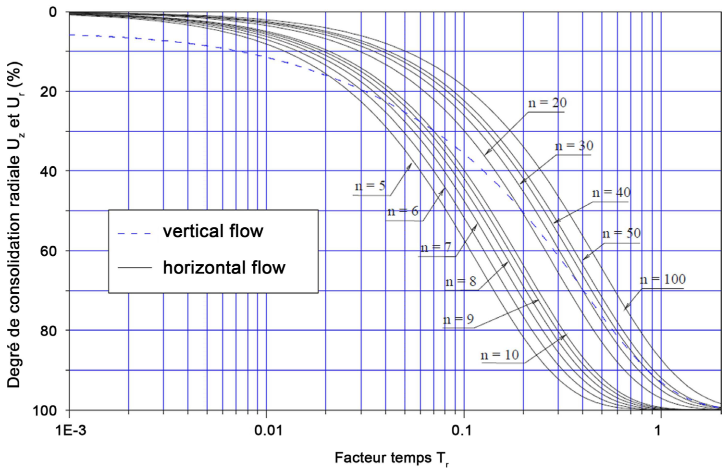

Figure 4. Consolidation abacus of Barron [13].

U_h is degree of horizontal consolidation.

d is drain diameter.

2.3.2. Theory of Carillo (1942) [13]

The Carillo theory concerns 3D consolidation (C_h and C_v). It consists of a set of the combined Terzaghi and Barron solutions: (3 abaques). Knowing the horizontal and vertical consolidation coefficients Ch and C_v from laboratory tests and knowing the consolidation time t, the coefficient T_v is determined, from which the value of the vertical degree of consolidation U_v is estimated using the Terzagui diagram shown in Figure 5.

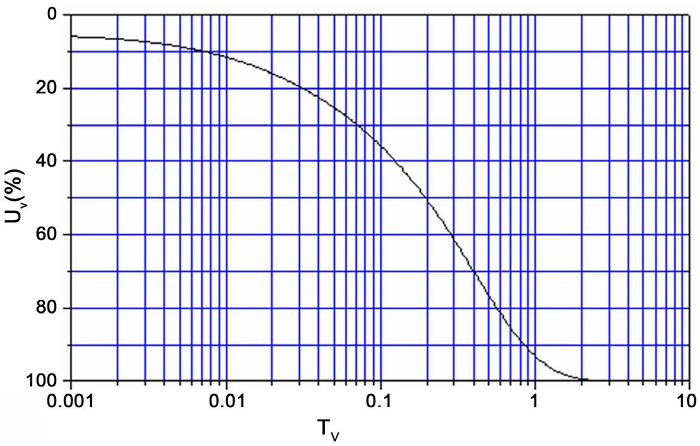

Figure 5. Terzaghi abacus [13].

Knowing U_v and the degree of consolidation required U, U_h can be easily deduced from the Carillo formula:

$$1-U=\left[1-U_h\right]\left[1-U_h\right] \tag{5}$$

For an efficient calculation, the spacing will be optimized:

$$U_h=f\left(T_h,n\right) \text{ avec } n=\frac{D_e}{d} \tag{6}$$

the procedure is as follows:

- Start by setting a value n_1 for n and deduct T_h from the Barron abacus.
- Then determine the equivalent diameter D_e from the formula:

$$T_h=\frac{C_h t}{D_e^2} \text{ avec } \begin{cases} t \text{ the consolidation time in months} \\ D_e \text{ is the equivalent diameter} \end{cases} \tag{7}$$

and $D_e=\left(\frac{C_h t}{T_h}\right)^{1/2}$.

- Then deduce n using its relationship with D_e: $n=\frac{D_e}{d}$.
- Let n_2 be this determined value, if n_1 and n_2 are very different, a new value of n is adopted and the calculations are repeated until a convergence of these

values is obtained; this method is iterative.

- Finally consider the value D_e corresponding to the value of n retained after convergence and deduce the spacing of drains S from the relationship between the spacing between drains (S) and the diameter of the influence zone (D_e).

- For squarred mesh, $D_e = 0.13S$.
- For triangualar mesh $D_e = 1.05S$.

3. Materials and Methods

3.1. Description of the Environment

Our study is on part of the ROCADE project, the bypass of the city of Porto Novo, political capital of Benin. The Porto-Novo Bypass project is a major road infrastructure that bypasses the city of Porto-Novo to reduce rush hour traffic, located on the southern coast of Benin near the border with Nigeria. The planned development crosses a marshy area with a very compressible soil between PK 0 + 850 and PK 1 + 275 of the Bypass. It will be built next to an existing platform. The plan view of the study area is shown in **Figure 6**.

Figure 6. Plan view of the study area.

The control of the hydrogeological context of the study environment allows to study the capacity of drains to lower the water table, reduce soil saturation and improve the stability of road infrastructure. The town of Porto-Novo is located near the coast, which means that it is influenced by coastal hydrology related phenomena such as tides, fluctuations in the groundwater level in response to tidal movements, and the possibility of saline intrusion into coastal aquifers. The city is crossed by several rivers and streams that can influence natural drainage and groundwater movements.

In addition, the climate of Porto-Novo is tropical with two dry seasons and two rainy seasons. During the rainy season, the region experiences heavy rainfall and unstable weather conditions, which affect soil stability and road infrastructure sustainability.

The region's water table is medium to shallow in some areas, making soils prone to saturation and waterlogging, especially during the rainy season.

3.2. Pavement Structure

In the course of our study, the different layers will be composed of several materials selected with specific thicknesses. The physical and mechanical properties of these materials will be determined from geotechnical studies carried out in the project area. These geotechnical studies will provide a precise characterization of locally available materials, providing essential data such as compressive strength, permeability, plasticity, and other relevant parameters. This information will provide a solid basis for the design and construction of the different layers of the project, ensuring their suitability to site-specific conditions.

The pavement studied has a flexible structure. Among the different types of pavements, the flexible pavement is a solution widely adopted in many road projects. Designed to provide a flexible and resistant running surface, the soft pavement is composed of several layers of laminate, each layer having a specific role in the distribution of loads, fatigue resistance and long-term preservation of road quality.

In the particular case of the Bypass project, it consists of a BB bituminous concrete bearing layer, a base layer and a foundation layer made of untreated GNT gravel all resting on clay soil.

The environment is characterized by complex geological formations including alluvial sediment layers, volcanic rocks and limestone formations. These geological formations can have an impact on the permeability and drainage capacity of soils.

The types of soils encountered in the study area vary. Examples include clay, sandy and silty soils. The composition and geotechnical properties of soils can have a significant impact on the stability and performance of infrastructure.

3.3. Modelization under Plaxis

Numerical modeling uses various techniques such as finite elements and finite differences to analyze the stability, deformation and impact of several parameters at all points in the model effectively. In this chapter, we will present the PLAXIS 2D finite element code [25] version 8.2 that will be used in our study, focusing on the description of some behavior models available in this code.

The PLAXIS user interface consists of four sub-programs:

- **Input program**
- To perform a finite element analysis with PLAXIS, the user will need to create a numerical model and specify material properties and boundary conditions. This is done using the data entry program (Input).
- To generate a finite element model, the user must create a two-dimensional geometric model consisting of points, lines and other components. The gen-

eration of an appropriate mesh, properties and conditions at the element-by-element boundary is automatically performed by PLAXIS' mesh generator from the previously entered geometric model. The last part of the data entry includes generating interstitial pressures and effective constraints to define the initial state.

- **Calculations program**

PLAXIS allows different types of finite element calculations. The calculation program only deals with deformation analysis and allows to perform a plastic calculation (Plastic Calculation), consolidation analysis (Consolidation Analysis), calculation of safety coefficients (Phi/C Reduction) or dynamic calculation (Dynamic Calculation).

- **Output program**

The main results of a finite element calculation are the shifts at nodes and constraints at stress points. In addition, when a finite element model includes structural elements, forces are calculated in these elements.

- **Curves program**

The curves program (Curves) can be used to draw load-or time-displacement curves, stress-strain curves, stress paths or deformation for selected points in geometry. These curves represent the evolution during the different phases of calculation, and this gives an overview of the global and local behaviour of the soil [26].

3.4. Modelization Parameters

The values of these parameters used in modelling the different layers are presented in Table 1.

- For the surface layer (Bitumen)

Table 1. Geotechnical properties of bituminous concrete.

Linear elastic	Unit	Asphalt concrete
Type		Drained
γ_{unsat}	[kN/m³]	24.00
γ_{sat}	[kN/m³]	24.00
k_x	[m/day]	0.001
k_y	[m/day]	0.001
e_{init}	[-]	0.500
c_k	[-]	1E15
E_{ref}	[kN/m²]	1210000.00
v	[-]	0.350
G_{ref}	[kN/m²]	448148.148
E_{oed}	[kN/m²]	1941975.309
E_{incr}	[kN/m²/m]	0.00
y_{ref}	[m]	0.000
R_{inter}	[-]	1.000
Interface permeability		Neutral

- **For the base and foundation layers (GNT), the values in Table 2 will be used**

Table 2. Geotechnical properties of NTG.

Mohr-Coulomb	Unit	NTG A	NTG B	NTG C
Type		Drained	Drained	Drained
γ_{unsat}	[kN/m^3]	21.00	21.00	21.00
γ_{sat}	[kN/m^3]	21.00	21.00	21.00
k_x	[m/day]	1.000	1.000	1.000
k_y	[m/day]	1.000	1.000	1.000
e_{init}	[-]	0.500	0.500	0.500
c_k	[-]	1E15	1E15	1E15
E_{ref}	[kN/m^2]	540000.000	180000.000	60000.000
v	[-]	0.350	0.350	0.350
G_{ref}	[kN/m^2]	200000.000	66666.667	22222.222
E_{oed}	[kN/m^2]	866666.667	288888.889	96296.296
c_{ref}	[kN/m^2]	1.00	1.00	1.00
E_{inc}	[kN/m^2/m]	0.00	0.00	0.00
y_{ref}	[m]	0.000	0.000	0.000
$c_{increment}$	[kN/m^2/m]	0.00	0.00	0.00
$T_{str.}$	[kN/m^2]	0.00	0.00	0.00
$R_{inter.}$	[-]	1.00	1.00	1.00
Interface permeability		Neutral	Neutral	Neutral

- **For the base layer (Clay), the values in Table 3 shall be taken into account**

Table 3. Geotechnical properties of clays.

Soft-Soil	**Unit**	**Clay 1**	**Clay 2**	**Clay 2**	**Clay 3**
Type		Drained	Drained	Drained	Drained
γ_{unsat}	[kN/m^3]	12.57	11.17	10.00	12.30
γ_{sat}	[kN/m^3]	14.30	16.17	12.50	14.00
k_x	[m/day]	0.012	0.012	0.012	0.012
k_y	[m/day]	0.012	0.012	0.012	0.012
e_{init}	[-]	0.50	0.50	0.50	0.50
c_k	[-]	1E15	1E15	1E15	1E15
c	[kN/m^2]	15.17	21.90	18.90	25.30
K_0^{nc}	[-]	0.56	0.99	0.79	0.74
R_{inter}	[-]	0.60	0.60	0.60	0.60
Interface permeability		Neutral	Neutral	Neutral	Neutral

The applied load represents the traffic loads that will be borne by the road during its lifetime, including vehicle weight, traffic effects, environmental conditions and other external loads. This study identifies all traffic loads at a vertical load evenly distributed over a length of 0.25 m on either side of the track axis. The values of the loads are summarized in Table 4.

Table 4. Applied loads.

Load no.	First node	q_x [kN/m/m]	q_y [kN/m/m]	Last node	q_x [kN/m/m]	q_y [kN/m/m]
1	861	0.000	−0.662	983	0.000	−0.662
2	1141	0.000		1305	0.000	

In our case study we used the drain function defined in PLAXIS version 8.2. Figure 7 shows the in-situ execution of PVD in real image.

Figure 7. PVD execution.

3.5. Study Methodology

- Analysis of parameters without drains

In this initial phase, the objective is to evaluate the deformation of the soil before the installation of vertical drains. This involves modelling the soil, applying loads and conditions to the boundary. Adding the layer and interstitial pressures. This data provides a thorough understanding of the study model before treatment. Scenario 0 is explained in Table 5.

Table 5. Explanation of scenario 0 for the no-drain analysis.

Scenario	Simulation description	Simulation procedure	Output parameters to monitor
Scenario 0	Road as it is, water table 1.5 m below the model With the following details: - Width of the roadway: 7.5 m - Support soil: swelling clay - Structural composition: - Four layers of clay - TNG Foundation Layer - TNG base layer - Asphalt concrete tread - Axle load: 13 tonnes	1) Modelling of the pavement with precise structural details 2) Definition of material and geotechnical properties 3) Application of axle load 4) Simulation in Plaxis considering the water table at 1.5 m	- Model mesh deformation - Horizontal deformation - Vertical deformations - - Constraints

- Parameters analysis with drains

After the drainless parameters are evaluated, vertical and horizontal drains are installed in specific areas identified as having drainage or soil stability problems. This phase of the study is designed to observe changes in geotechnical characteristics of soils after drains are installed. The same parameters as those initially assessed are measured again to assess the impact of drains on soil behaviour. Scenarios 1, 2 and 3 are explained in **Table 6**.

Table 6. Explanation of scenario (1, 2, 3), for drains analysis.

Scenario	Simulation description	Simulation procedure	Output parameters to monitor
Scenario 1	Insertion of vertical drains, 0.5m mesh * 0.5 m and horizontal drains With the same details as Scenario 0	1) Insertion of vertical and horizontal drains into the model 2) Modelling of the mesh 3) Simulation in Plaxis considering drains	- Model mesh distortion - Horizontal deformation - Vertical deformations - Constraints
Scenario 2	Insertion of vertical drains, 1 m mesh * 1 m and horizontal drains With the same details as Scenario 0	1) Insertion of vertical and horizontal drains into the model 2) Modelling of the mesh 3) Simulation in Plaxis considering drains	- Model mesh deformation - Horizontal deformation - Vertical deformations - Constraints
Scenario 3	Use 1.5 m × 1.5 m mesh for vertical drains, install horizontal drains with same details as scenario 1	1) Readjustment of mesh to 1.5 m × 1.5 m resolution 2) Simulation in Plaxis using the new mesh	- Model mesh deformation - Horizontal deformation - Vertical deformations - Constraints

3.6. Geometric Models

Figures 8-10 illustrate the different geometries of the mesh for vertical drains, respectively 0.5 m 0.5 m; 1 m 1 m and 1.5 m 1.5 m. For different scenarios: scenario 0 (without drain), scenario 1 (with a drain of 0.5 m 0.5 m), and scenario 2 (with a 1 m × 1 m drain), including variations in the placement of drains.

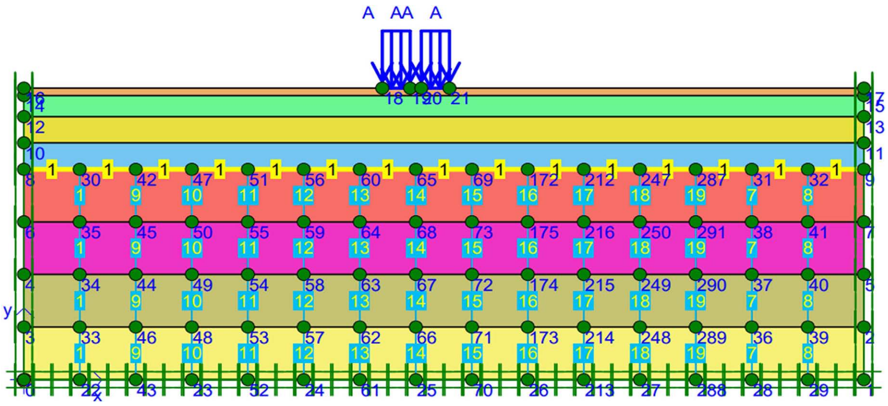

Figure 8. Geometry for the model with 0.5 m × 0.5 m mesh for vertical drains and addition of horizontal drains.

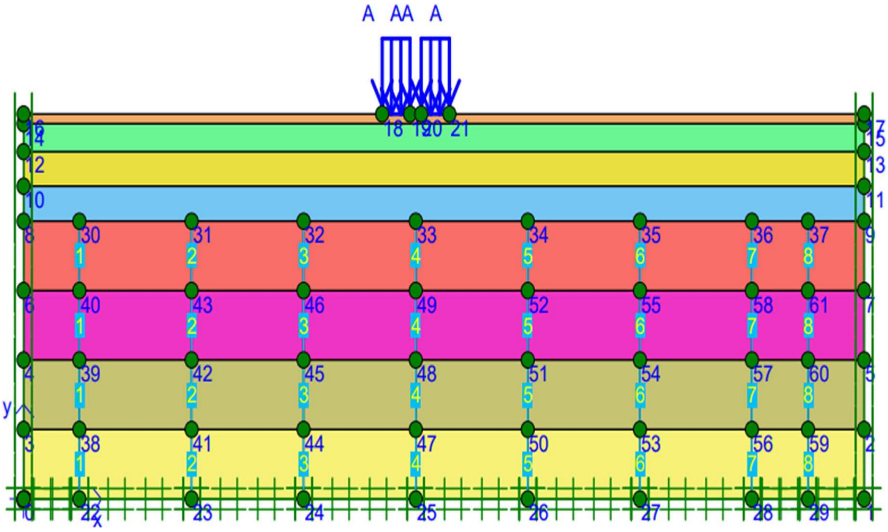

Figure 9. Geometry for model with 1 m × 1 m mesh for vertical drains and addition of horizontal drains.

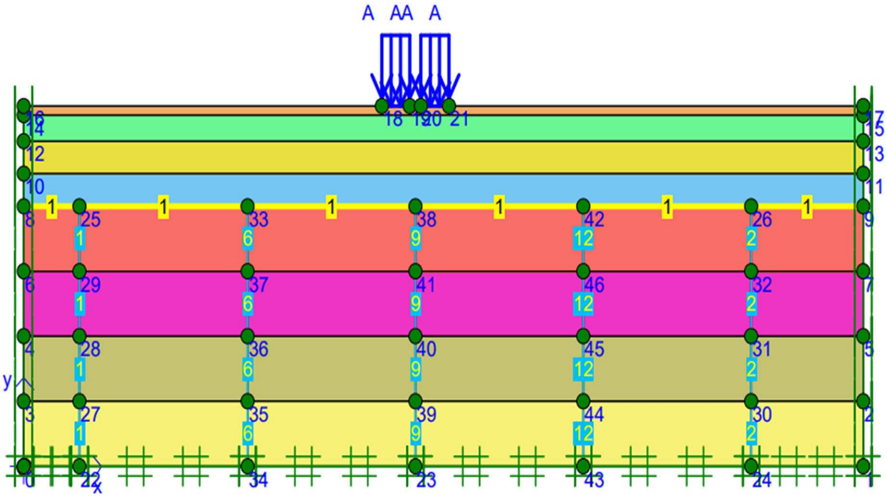

Figure 10. Geometry for model with 1.5 m × 1.5 m mesh for vertical drains and addition of horizontal drains.

4. Results and Discussions

4.1. Results of Simulations under Plaxis

This section is devoted to the exposure and analysis of results obtained during this research, providing a detailed and structured description of data and highlighting key findings and trends.

The results of phase 0 in terms of deformed mesh give a total displacement of 78.17×10^{-3} m.

The results of phase 1 in terms of vertical displacements, vertical effective stresses and vertical strain corresponding to modelling with vertical drains on a 0.5 m 0.5 m mesh are presented respectively in **Figures 11-13**.

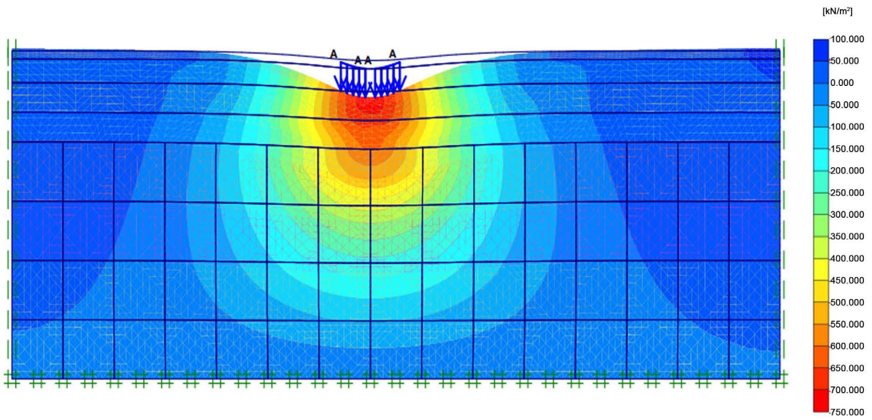

Figure 11. Vertical effective constraints.

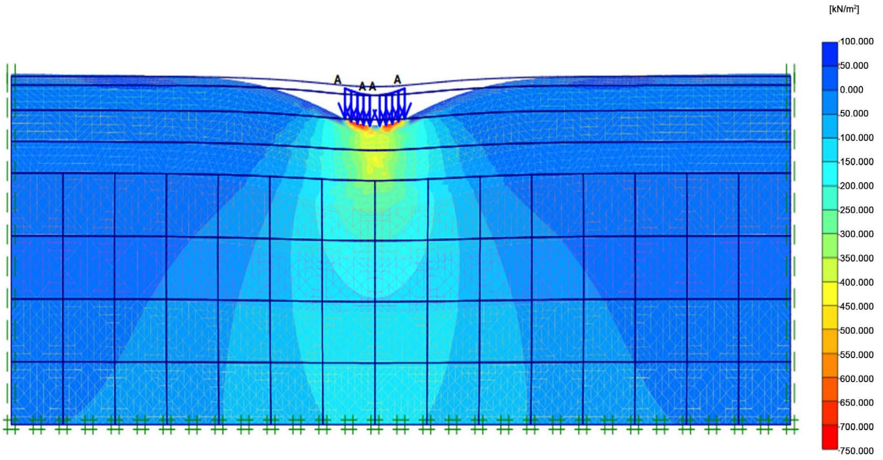

Figure 12. Vertical effective constraints.

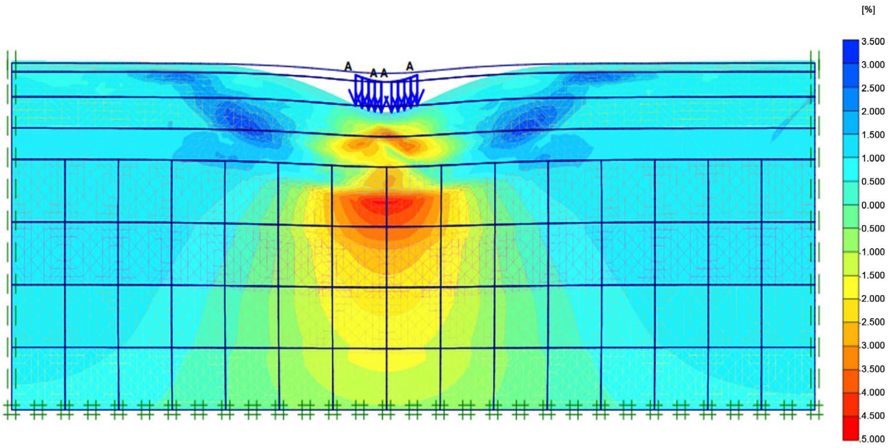

Figure 13. Vertical deformation.

The results of phase 2 corresponding to the modelling with vertical drains on a mesh of 1 m 1 m and materializing the plastic areas are presented respectively in **Figure 14**.

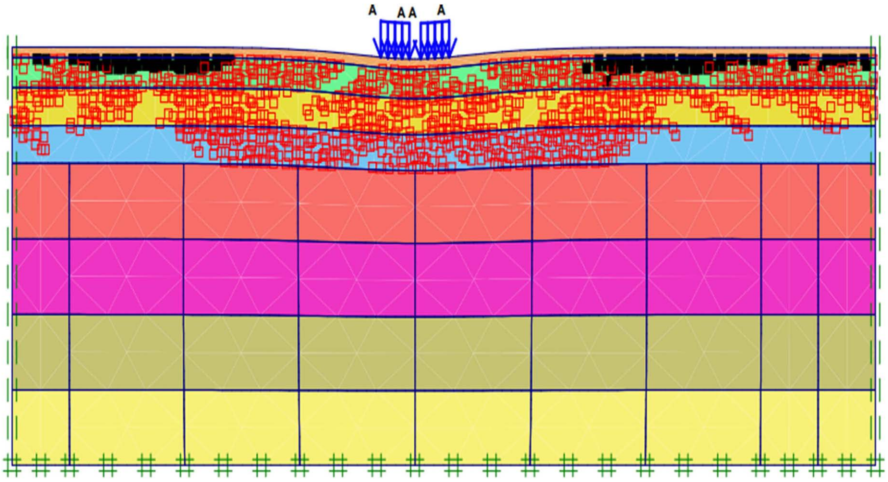

Figure 14. Plastic areas.

The results of phase 3 in terms of shear deformation, vertical effective stress and vertical strain corresponding to the modelling with vertical drains on a 1.5 m 1.5 m mesh are presented respectively in **Figures 15-17**.

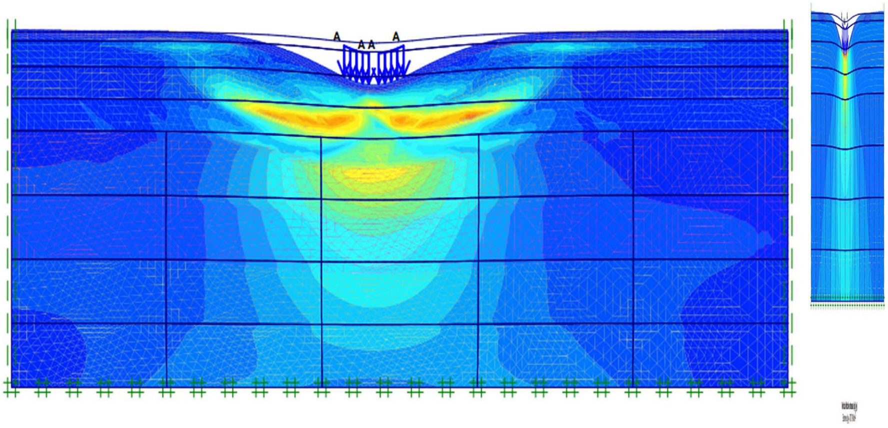

Figure 15. Shear deformation.

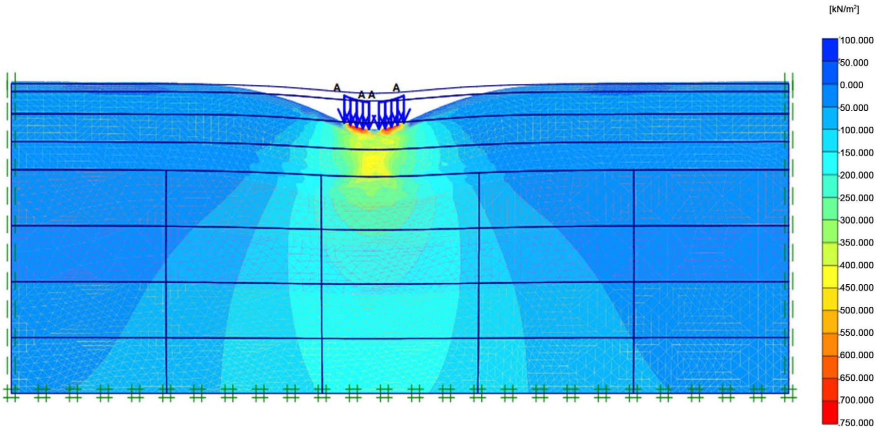

Figure 16. Vertical effective constraints.

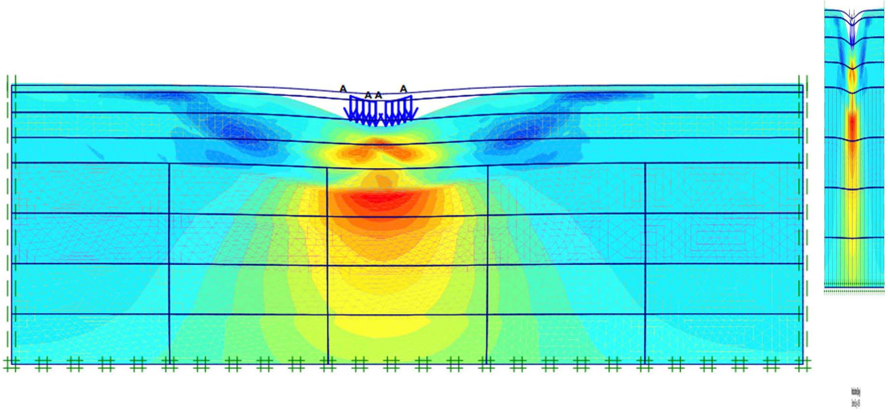

Figure 17. Vertical deformation.

Table 7 summarizes the output data from the different modelling scenarios.

Table 7. Summary of output data from modelling.

Modelization scenario	Extreme total displacement (m)	Extreme effective vertical constraints (kN/m^2)	Extreme shear deformations	Extreme vertical displacements (m)
Road without drains	78.17×10^{-3}	−710.88	6.56	-
Road with drains (0.5 m * 0.5 m)	61.77×10^{-3}	−607.79	5.21	−77.48 * 10^−3
Road with vertical drains (1 m*1 m)	62.15×10^{-3}	−617.98	5.23	−63.31 * 10^−3
Road with vertical drains (1.5 m*1.5 m)	62.48×10^{-3}	−616.41	5.70	-

Results show a trend of reduction in extreme total displacement with increasing mesh size for drain scenarios. However, the extreme vertical effective stresses and extreme shear deformations appear to vary in a non-linear manner depending on the mesh size. Extreme vertical displacements are also affected by the presence and size of drains. These results suggest the importance of choosing the mesh size and location of vertical drains wisely to optimize the performance of the pavement in terms of stability and deformation (**Figures 18**).

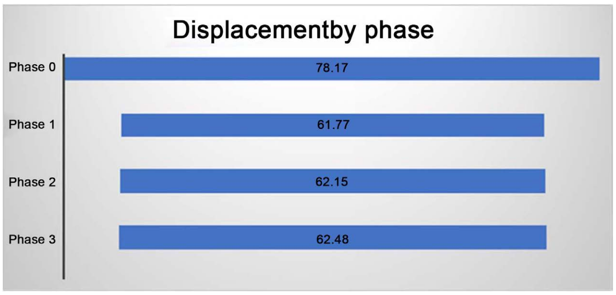

Figure 18. Graph of the displacement according to phases.

When analyzing the results, we see that the minimum of deformations is actually found in phase 1, where the pavement is modelled with a vertical drain mesh of 0.5 m * 0.5 m. This suggests that this particular configuration offers better resistance to deformation than other mesh configurations.

After a thorough analysis of the results obtained, it is clear that the mesh configuration with vertical drains of 0.5 m * 0.5 m in phase 1 is distinguished by its ability to minimize road deformations. This finding suggests that this specific configuration offers increased resistance to deformation compared to other tested configurations. Several factors can explain this promising result. First, a denser mesh allows for more uniform stress distribution, which helps to reduce strain. In addition, the use of vertical drains helps effectively drain water and reduce pore pressures, which plays a crucial role in limiting strain.

Thus, based on these conclusions, it is reasonable to recommend the configuration of phase 1, characterized by a mesh size of 0.5 m * 0.5 m for vertical drains, as well as the incorporation of horizontal drains. This configuration appears to be an optimal choice for ensuring maximum stability and minimum road deformations. These findings highlight the critical importance of proper vertical drain and mesh design in road infrastructure planning to ensure optimal performance in terms of stability and durability.

4.2. Consolidation Calculation

For validation study, we deal with numerical calculation using Carrillo theory.

- Before reinforcement

The permeability coefficients of clay 1 allow to deduce the horizontal and vertical consolidation coefficients using Equation (2): $C_h = 0.288$ m^2/month and $C_v = 0.187$ m^2/month.

Using $T_v = C_{vt}/H_2$ and $T_h = C_{ht}/H_2$, we find respectively using the Terzaghi's Abacus (**Figure 3**), we find $U_v = 0.72$ and $U_h = 0.62$.

The formula of carillo (Equation (5)) allows to find $U = 0.29$.

This means that for 9 months, the consolidation will only be 69%.

The results of 9-month consolidation calculations for the different clay layers are shown in **Table 8**.

Table 8. Consolidation of the different layers of clay.

	Clay 1	Clay 2	Clay 3	Clay 4
T_v	0.46	0.37	0.35	0.3
T_h	0.29	0.33	0.30	0.25
U_v	72%	65%	60%	57%
U_h	62%	59%	51%	50%
U	69%	62%	58%	52%

The results in **Table 8** show low consolidation rates over a period of 9 months.

For this reason, it will be impossible to achieve final clay layer consolidation within an acceptable time [23]. Why vertical drainage improvements are needed.

- After reinforcement.

- For a spacement equal to 1.

$$T_h = \frac{C_h t}{D_e^2} = \frac{0.288 \times 1}{1.13^2} = 0.255 \quad \text{considering a time of 1 month}$$

with $D_e = 1 \times 1.13 = 1.13$,

$$n = \frac{D_e}{d} = \frac{1.13}{0.2} = 5.65\,.$$

The Projection of T_h on n curve (Terzaghi abacus) gives $U_r = 82\%$.

- For a spacement equal to 0.5.

$$T_h = \frac{C_h t}{D_e^2} = \frac{0.288 \times 1}{0.565^2} = 0.9 \quad \text{considering a time of 1 month}$$

with $D_e = 0.5 \times 1.13 = 0.565$,

$$n = \frac{D_e}{d} = \frac{0.565}{0.2} = 2.825\,.$$

The Projection of Th on n curve (Terzaghi abacus) gives $U_r = 94\%$.

5. Conclusions

In this study, we explored in depth the impact of drainage mesh on pavement modelling in the context of road infrastructure engineering. The results obtained show that mesh selection is crucial for reducing deformation and improving pavement stability. These findings highlight the importance of considering geotechnical and hydrological aspects when designing and constructing roads.

One of the key observations in this study is the minimum deformation observed in phase 1, where the road was equipped with drains with a 0.5 m × 0.5 m mesh and horizontal drains. This finding suggests that this particular configuration offers an optimal compromise between control density and drainage efficiency, making it an ideal choice to ensure pavement stability while minimizing the risk of excessive deformation.

These results have important implications for the design and management of road infrastructure, including the optimization of drainage systems to ensure the sustainability and resilience of pavements. Considering the data obtained from this study, engineers and planners can make informed decisions about the choice of drainage mesh to optimize road performance while reducing maintenance costs in the long term.

In addition, this research opens new avenues for improving pavement design and modelling practices by highlighting the importance of considering geotechnical and hydrological factors in the design process.

Promising future research prospects include exploring additional mesh configurations and examining the impact of vertical drain meshes on other performance parameters such as fatigue strength and long-term durability of the pavements. In addition, field studies and laboratory testing are required to validate modelling results and improve understanding of underlying mechanisms. By developing a better understanding of these aspects, we can move towards more efficient design and management practices for road infrastructure.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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