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Optimal pavement design using the failure probability

Conception optimale de la chaussée à l'aide de la probabilité de défaillance

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ABSTRACT: In this paper, an optimal pavement design with and without geosynthetic reinforcement is discussed and evaluated. The probability of failure is calculated for these two optimal designs and the costs of the structures are compared. For this purpose, an analysis with three main steps was performed. The first step is to develop a deterministic model that includes a computational model of the response variables of interest for a given set of input parameters such as subgrade conditions and live load. In the second step, an uncertainty model was developed in which the California Bearing Ratio of the subgrade, the total number of axle load passes, and the depth of frost penetration were treated as random variables and their values were simulated using Monte Carlo simulation. In the final step, the response variables of the deterministic model were calculated according to the uncertain parameters defined in the uncertainty model. The results of the failure probability analysis allow us to evaluate important elements of the pavement structure that should be changed in order to reduce the probability of failure.

RÉSUMÉ: Dans cet article, une conception optimale de la chaussée avec et sans renforcement géosynthétique est discutée et évaluée. La probabilité de défaillance est calculée pour ces deux conceptions optimales afin de montrer la différence que fait le renforcement. Pour ce faire, une analyse en trois étapes principales a été réalisée. La première étape consiste à développer un modèle déterministe qui comprend un modèle de calcul des variables de réponse d'intérêt pour un ensemble donné de paramètres d'entrée tels que les conditions du sol et la charge réelle. Dans la deuxième étape, un modèle d'incertitude a été développé dans lequel le coefficient de portance californien du sol, le nombre total de passages de la charge à l'essieu et la profondeur de la pénétration du gel ont été traités comme des variables aléatoires et leurs valeurs ont été simulées à l'aide d'une simulation de Monte Carlo. Dans la dernière étape, les variables de réponse du modèle déterministe ont été calculées en fonction des paramètres incertains définis dans le modèle d'incertitude. Les résultats de l'analyse de la probabilité de défaillance nous permettent d'évaluer les éléments importants de la structure de la chaussée qui devraient être modifiés afin de réduire la probabilité de défaillance.

Keywords: Reliability based design; optimization; optimal pavement structure; geosynthetics.

1 INTRODUCTION

Efficient pavement design plays a critical role in the sustainable development and longevity of transportation infrastructure. As the world's population continues to grow and urbanization escalates, the demand for resilient and cost-effective pavements becomes increasingly urgent. In particular, the complexity of today's traffic volumes, environmental pressures and evolving material technologies require a paradigm shift towards the development of optimized pavements that can withstand a wide range of loads while minimizing environmental impact. In recent decades, great progress has been made in the field of pavement construction. These include several innovative methods and materials that promise longer life and lower maintenance costs. Several authors have been working on optimizing the pavement structure designs with and without the use of geosynthetics, with geosynthetics proving to be more favorable at lower CBR values of the subgrade (Jelušič, Varga, et al., 2023; Mamlouk et al., 2000; Nicholls, 1991; Santos & Ferreira, 2012). As mentioned before by new materials, researchers are also testing waste materials such as glass, car tire waste, lignin, and nylon bags to improve the California Bearing Ratio - CBR values of the unbound sub-base course and asphalt binder course (Abukhettala & Fall, 2021; Fatemi & Imaninasab, 2016; Huang et al., 2007; Jelušič, Gücek, et al., 2023; You et al., 2022). The studies all came to the same conclusion that using waste as a building material significantly reduces maintenance costs, construction costs, and reduces CO2 emissions. The studies also showed that asphalt is the main source of CO2 emissions during production, transportation, and installation in the structure. In second place are the unbound sub-base and the unbound base course, as the use of waste material can reduce the thickness of the required layer. To further expand the optimization process and the use of materials, the reliability-based design approach should be considered as it takes a different perspective on the matter and can be critical to understanding the failure mechanisms. In contrast to its prevalent application in various geotechnical constructions, the utilization of reliability-based design optimization remains relatively limited in the context of pavement engineering. Nonetheless, several studies have underscored the significance of failure mechanisms derived from reliability-based design, emphasizing the pivotal role they play in offering critical insights and precise information regarding the operational lifespan of pavements. (Dilip et al., 2013; Jelušič & Žlender, 2022; Sanchez-Silva et al., 2005; Saride et al., 2019). By promoting a deeper understanding of the interplay between uncertain material properties, traffic loads, structural configurations, and environmental factors, this study will pave the way for the implementation of optimal pavement design based on reliability-based design and use of geosynthetics that can meet the diverse needs of modern transportation networks.

2 OPTIMIZATION MODEL

The deterministic optimization model (*PVT-OPT*) for the targeted pavement structure (see Figure 1) consists of several elements, including a comprehensive set of input data, an objective function (*COST*) that determines the properties of the pavement structure as determined by the geotechnical analysis and design constraints, and a set of variables is also included. In particular, the inclusion of the Monte Carlo simulation method in the reliability-based design serves to effectively account for and address the inherent uncertainties contained in these variables as we expand the deterministic model into an uncertainty model. To effectively use an evolutionary algorithm to perform the optimization the problem was translated into a mixed integer problem. Firstly, an optimal design based on the AASHTO and local technical specifications - TSC for roads (AASHTO, 1993; Nicholls, 1991; TSC 06.520:2009, 2009) was obtained and further evaluated using the expanded reliability-based design method. The probability of failure was calculated and determined for the proposed optimal designs. The expanded deterministic model was then also used to provide a graphical comparison between different soil conditions, ranging from $CBR_{subgrade}$ 1 % to $CBR_{subgrade}$ 8 % and effects of the geosynthetics and reliability on the price and longevity of the pavement structure. The parameters of interest are the thickness of asphalt surface course d_{as} (m), thickness of asphalt base course d_{ab} (m), thickness of unbound base course d_b (m) thickness of unbound sub-base course and pavement construction costs *COST* (€/m^2). Also, while optimizing using the reliability-based design the failure probability Pf (%). To obtain the optimal values for these parameters, six distinct conditions (see, Table 1) were established according to the AASHTO guides and local technical specifications (TSC).

2.1 Constrains in the optimization model

As already mentioned, Table 1 consists of the cost objective function and the necessary conditions for the optimization model (*PVT-OPT*). The cost objective function includes the individual costs (c_i - unit price) of the different soil and construction works for the construction of a pavement structure. The costs are listed in Table 2. The material properties (Young's modulus) per AASHTO are 320 MPa for granular base, 125 MPa for granular sub-base and depending on the CBR value the subgrade stiffness differs. The six conditions, based on the AASHTO and local TSC specifications, represent the basic design constraints. It should be noted that the denotation *mod* is used to describe the modified CBR value. For example, if the CBR value of the subgrade is on the lower side, unbound sub-base is used to increase this value for the safety and durability of the pavement structure.

Condition 1 states that the thickness index of the pavement structure (D_{total}) must be greater than the required thickness index of the structure (D_{req}). The equations consist of the equivalency factors a_i specified by the AASHTO and the thickness of the asphalt surface course d_{as}, the asphalt base course d_{ab} and the sub-base course d_b.

Condition 2 limits the required asphalt thickness to account for the number of vehicles (ESAL), as per TSC specifications ESAL is the only variable that determines the thickness of the asphalt course.

Condition 3 describes the required thickness of the unbound base course to ensure the load-bearing capacity of the pavement structure, as the quality and thickness is vital in providing a sufficient load bearing capacity when calculating the required thickness index of the pavement structure. The quality of the unbound base course is translated into the equivalent factor a_i as specified by AASHTO and TSC.

Condition 4 specifies the required total thickness of the pavement structure to combat the effect of frost penetration - h_{req}, which consists of h_m which is obtained based on the geographical location and is specified in the TSC and the factor f_{fr} that considers the soil conditions on the construction site based on laboratory tests.

Condition 5 specifies the minimum thickness of the unbound sub-base course to achieve a certain CBR value, also known as CBR_{mod}, which following TSC should be at least 15 %. This is done to artificially create better conditions for unbound base course, as the price of unbound sub-base course is cheaper and therefore ideal to increase the CBR value of the subgrade. The thickness required to obtain a given CBR_{mod} value is also reduced by the factor $\gamma_{geo,sb}$ when geosynthetic reinforcement is used. The value of the mentioned factor has been determined by laboratory and field tests and is considered to be 2.0 when geosynthetics are used.

Condition 6 sets minimum asphalt thickness requirements necessary for machine-based road construction.

Condition 7 is applied when designing based on probability of failure and considers all the above conditions. With the use of Monte Carlo simulation, 100,000 random numbers of the random variables reported in table 3 were created and the 100,000 random samples were than analyzed using condition 7 to estimate the failure probability of a pavement structure.

2.2 Results of the optimization model PVT-OPT

The evolutionary algorithm is used to optimize the design, effectively using the six previously mentioned conditions. Later the deterministic model is expanded with another condition, condition 7 (see Table 1) that includes the failure probability of the pavement structure. The previously obtained results were than analyzed and a probability of failure for a pavement structure with no reinforcement and with geosynthetic reinforcement was determined (see Table 3). The findings exhibit a mutual failure probability of 19.5 % of which 15.7 % is provided by the pavement thickness index (Condition 1) and 3.8 % is due to inadequate frost resistance thickness (Condition 4), as those are also the main conditions that are checked for failure. The input data for the reliability-based design analysis and optimization can be found in Table 4. Notably, it is imperative to highlight that pavement structure with no reinforcement is thicker for 29.5 % which also translates into a cost difference of 7.37 €/m^2 which for a standard road with a width of 7 m and a length of 1,000 m (the cost calculations therefore refer to 1 km of a given pavement) add to over 51.590 € in total costs (see, Table 3). Evidently, these observations show that a pavement structure with geosynthetic reinforcement is favorable in such conditions ($CBR_{subgrade}$ = 3.5 %, h_m = 80 m, f_{fr} = 0.7 and $N = 2.5 \cdot 10^6$). Further the study calculates the relationship between cost and failure probability of the pavement structure for different soil properties to showcase the usefulness of geosynthetic reinforcement in providing an economically and sustainable pavement design (see, Figure 2).

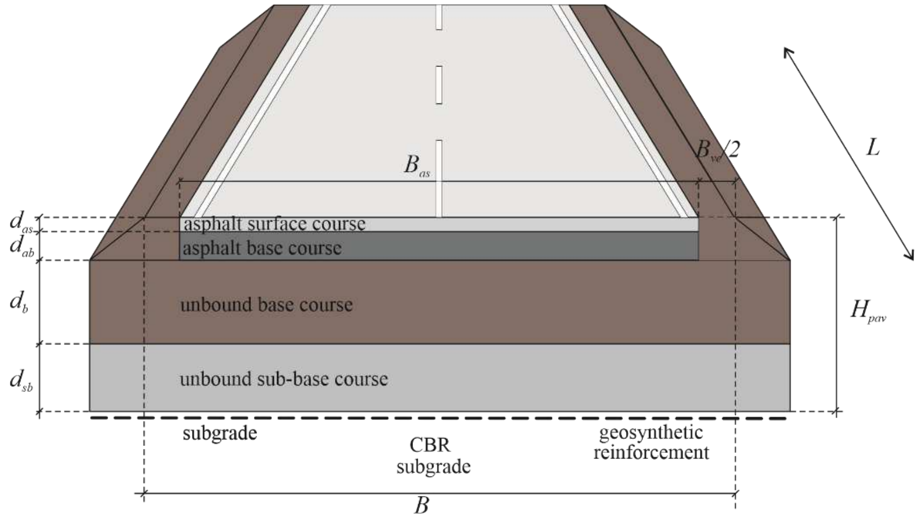

Figure 1. Cross section of the pavement design with the geometrical parameters shown.

Table 1. Optimization model PVT-OPT with all the required conditions.

Cost objective function for the PVT-OPT model	
$COST = C_{exc,re} + C_{gc} + C_{fill,b} + C_{as,subs} + C_{fill,sb} + C_{as} + C_{ab} + C_{geo}$	
$C_{exc,re} = c_{exc,re} \cdot h_{total} \cdot (B_{ve} + B_{as})$	$C_{gc} = c_{gc} \cdot (B_{ve} + B_{as})$
$C_{fill,b} = c_{fill,b} \cdot (B_{ve} + B_{as}) \cdot d_b$	$C_{as,subs} = c_{as,subs} \cdot B_{as}$
$C_{fill,sb} = c_{fill,sb} \cdot (B_{ve} + B_{as}) \cdot d_{sb}$	$C_{as} = c_{as} \cdot B_{as} \cdot d_{as}$
$C_{ab} = c_{ab} \cdot B_{as} \cdot d_{ab}$	$C_{geo} = c_{geo} \cdot (B_{ve} + B_{as})$
$C_{asb} = c_{asb} \cdot B_{as} \cdot d_{asb}$	
Condition 1	
$D_{total} \geq D_{req}$	
$D_{total} = d_{as} \cdot a_{i,as} + d_{ab} \cdot a_{i,ab} + d_b \cdot a_{i,b}$	$d_{b,CBR_{mod}} = ((c_1 - c_2 \cdot CBR) \cdot \ln(T_n) - c_3 + e^{(c_4 \cdot CBR) \cdot c_5})/\gamma_{geo,b}$ $note{:}\, \gamma_{geo,b} = 2$
$d_{asb,0} = a_1 \cdot {T_n}^{a_2}$	$d_{asb,0} = d_{as} + d_{ab}$ $note{:}\, d_{as} = 4\ cm$
$D_{req} = d_{asb,0} \cdot 0.38 + d_{b,CBR_{mod}} \cdot 0.14$	
Condition 2	
$d_{prov} \geq d_{asb,0}$	$d_{prov} = d_{as} + d_{ab}$
Condition 3	
$d_b \geq d_{b,req}$	$d_{b,req} = d_{b,CBR_{mod}}$
note: denotation *mod* stands for modified CBR value which is set to 15 %.	
Condition 4	
$h_{total} \geq h_{req}$	$h_{req} = h_m \cdot f_{fr}$
$h_{total} = d_{as} + d_{ab} + d_b + d_{sb}$	
Condition 5	
$d_{sb} \geq d_{sb,CBR_{mod}}$	$d_{sb,CBR_{mod}} = (b_1 \cdot (\frac{b_2 \cdot (CBR_{mod} - CBR)}{b_3 - CBR} + b_4))/\gamma_{geo,sb}$
Condition 6	
$d_{as} \geq d_{as,min}$	$d_{ab} \geq d_{ab,min}$
Condition 7	
$Pf = \frac{\sum_1^n A(n)}{n}$ $If\ \frac{{D_{total}}^n}{{D_{req}}^n} \geq 1\ or\ \frac{{h_{total}}^n}{{h_{req}}^n} \geq 1\,;than\ A\,(n) = 1; else\ \ A\,(n) = 0$	

Table 2. Unit price and material characteristics for pavement construction.

Symbol	Meaning	Cost per unit
$c_{exc,re}$	Ground excavation	9.0 €/m^3
c_{gc}	Ground compaction	2.5 €/m^2
$c_{as,subs}$	Asphalt substrate	1.5 €/m^2
c_{as}	Asphalt surface course	300.0 €/m^3
$c_{fill,b}$	Base-course fill	36.0 €/m^3
$c_{fill,sb}$	Sub-base fill	24.0 €/m^3
c_{ab}	Asphalt base course	200.0 €/m^3
c_{asb}	Single asphalt course	250.0 €/m^3
c_{geo}	Geosynthetic install.	4.5 €/m^2

Table 3. Optimal results obtained based on the deterministic model and the corresponding failure probability (Pf).

Type	**d_{as} (m)**	**d_{ab} (m)**	**d_b (m)**	**d_{sb} (m)**	**COST (€/m^2)**	***Pf* (%)**
Reinforced:	4	12	27	31	67.42	19.5
Not reinforced:	4	12	27	62	74.06	19.5

Table 4. Prior knowledge of the random variables.

Random variables	**Mean min.**	**Mean max.**	**CoV [%]**	**Standard deviation min.**	**Standard deviation max.**
N (-)	$2 \cdot 10^6$	$2.5 \cdot 10^6$	2-10	$2 \cdot 10^5$	$5 \cdot 10^5$
CBR (%)	1/3/5	3/5/8	10-15	0.1/0.3/0.5	0.45/0.75/1.2
h_m	0.7	0.8	10-20	0.07	0.16

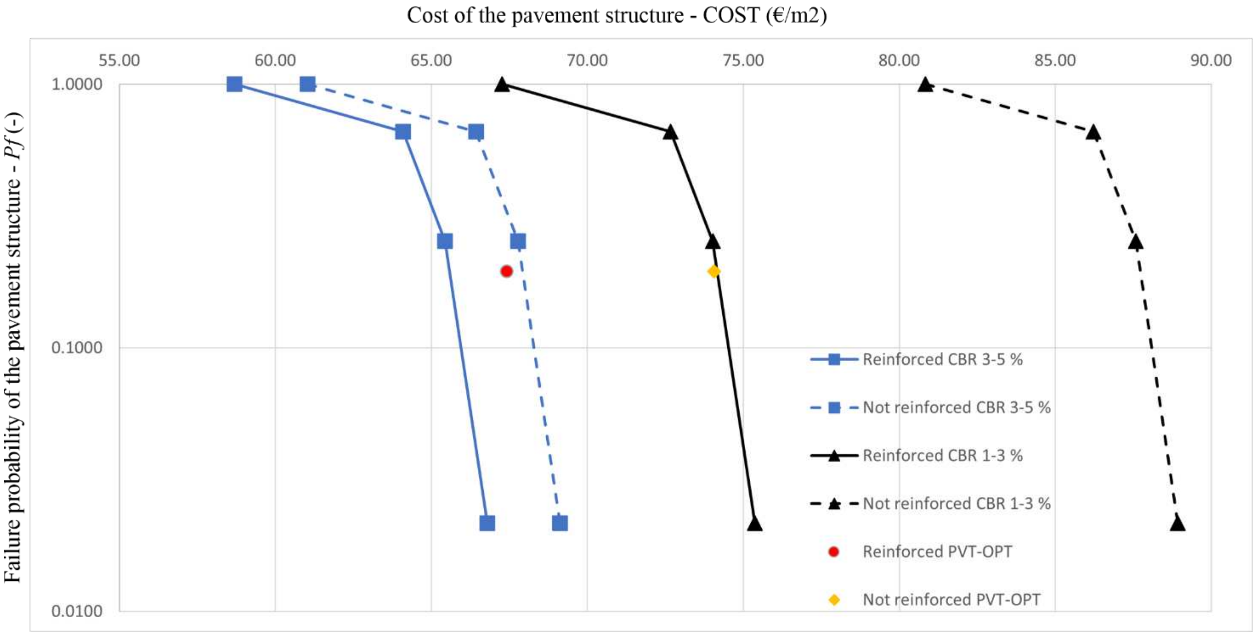

Figure 2. Relationship between COST and failure probability Pf for the optimal pavement designs.

3 CONCLUSIONS

The results of this study highlight the critical role of the thickness of the unbound base course in determining the longevity of an optimal pavement structure. Insufficient thickness of the unbound base course will result in its inability to withstand the combined effects of traffic loads and environmental stresses over a 20-year period with a probability of 15.7 %. In particular, the effects of frost depth on pavement structures with unbound sub-base courses are mitigated because these sub-base courses contribute an additional thickness to the overall structure. In addition, Figure 2 shows the correlation between the probability of failure and the cost of reinforced and unreinforced pavement structures and highlights the favorable performance of structures with geosynthetic reinforcement. Especially for soils with low modulus of elasticity and the resulting CBR values, the cost difference between traditional construction methods and those using geosynthetics is significant. Therefore, the use of geosynthetics is recommended to improve cost efficiency and environmental performance due to the reduced thickness required. Ultimately, this approach contributes to a lower probability of structural failure, highlighting its economic, environmental and performance benefits in pavement design and construction.

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