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RELIABILITY ASSESSMENT OF SUBGRADE SOIL ALONG THE DAWANAU–KAZAURE RAILWAY LINE

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Abstract: This study investigates the reliability of subgrade soil materials along the Dawanau–Kazaure railway line by analyzing compaction characteristics, including California bearing ratio (CBR), Maximum dry density (MDD), and Optimum moisture content (OMC) derived from field and laboratory data. Statistical information for basic random variables was generated using Minitab 15 software, and limit–state equations were formulated for each compaction characteristic. These limit–state equations are based on regression equations developed from field and laboratory data. The safety of the subgrade material was assessed across a range of coefficient of variation values (from 10% to 100%). The findings revealed that as the coefficient of variation increased, reliability indices generally decreased. For all cases considered, the reliability indices obtained for bearing capacity failure were positive, indicating the subgrade material's overall safety, but did not meet the minimum recommended value of 1.0 set by the Nordic Committee on Building Regulations. Therefore, the subgrade soil requires improvements in its index properties. Specifically, the expected values of the California Bearing Ratio for soaked and unsoaked soil samples were 32.5% and 78%, respectively, with corresponding reliability indices of 0.9275 for soaked CBR and 0.9250 for unsoaked CBR.

Keywords: Subgrade soil reliability, California bearing ratio, Coefficient of variation, Limit–state equations, Railway infrastructure

INTRODUCTION

The construction and maintenance of railway infrastructure are crucial engineering endeavors that demand meticulous attention to detail, especially when it comes to the subgrade – the foundation upon which the tracks are built. The performance and longevity of railway tracks are significantly influenced by the properties of the subgrade soil. Hence, accurate and reliable characterization of subgrade soil properties is essential for ensuring the safety, durability, and cost–effectiveness of railway systems (Kozubal et al., 2022).

Traditionally, subgrade soil properties have been assessed using deterministic methods that rely on point estimates of soil parameters (Ayres, 1997). However, this approach often fails to account for the inherent variability and uncertainties that exist in natural soils. The limitations of the deterministic approach have led to instances of suboptimal designs and unforeseen failures in railway infrastructure.

To address these challenges and enhance the understanding of subgrade soil behavior, engineers and researchers have turned to a more advanced and sophisticated approach known as "Reliability–Based Evaluation" or "Probabilistic Geotechnics." This methodology seeks to quantify the uncertainties associated with subgrade soil properties by incorporating probabilistic methods and data from trial pit investigations. Trial pits represent one of the primary means of gaining direct access to the subsurface layers and are extensively employed in geotechnical investigations for railway projects. These excavations provide a visual representation of the soil profile and enable the collection of in–situ soil samples for subsequent laboratory testing (Gu and Liu, 2021; Zhao et al., 2020). The data obtained from trial pit investigations form the backbone of the reliability–based evaluation process, offering valuable insights into the spatial variability of soil properties.

Numerous studies have explored traditional methods for soil characterization and geotechnical investigation, but a systematic framework for integrating reliability analysis into the evaluation of subgrade soil properties remains lacking (Li and Selig, 1998). Due to the ever–increasing demands on railway infrastructure systems and the need to minimize the risks associated with soil variability, this research gap has been identified (Saha, 2009). This paper aims to explore the concept of reliability–based evaluation of subgrade soil properties using trial pits in the context of railway design and construction.

By considering the inherent uncertainties in soil characteristics, this approach seeks to provide engineers with a more comprehensive understanding of subgrade behavior, enabling the design of safer, more resilient, and economically optimized railway systems (Li et al., 2021; Wu et al., 2022; Phoon and Kulhawy, 2003; Vessia et al., 2020).

This study presents the results of reliability assessments of subgrade soil for a proposed railway line section, spanning from Dawanau to Kazaure in Kano State, Nigeria. The safety level of the subgrade soil was examined using the First–Order Reliability Method. Both field and laboratory data were leveraged to establish the safety level, ensuring that railway subgrade design is both economically viable and reliable for the intended purpose.

MATERIALS AND METHODS

Location and Accessibility:

The study area is located in Dawanau (about 65 km away from the Kano metropolis) and extends towards Kazaure, Jigawa State. It lies between Easting 438906.732 to 435034.140, and Northing 1338525.942 to 1396008.238, with corresponding chainage between 20+500 and 43+500 and covers about 23.50 km stretch (Figure 1). It is accessible through major roads, namely: Kano–Danbatta–Kazaure–Daura Road, Kazaure–Roni–Ingawa and Kazaure–Shuwaki–Lamba road. There are also numerous networks of footpath throughout the area.

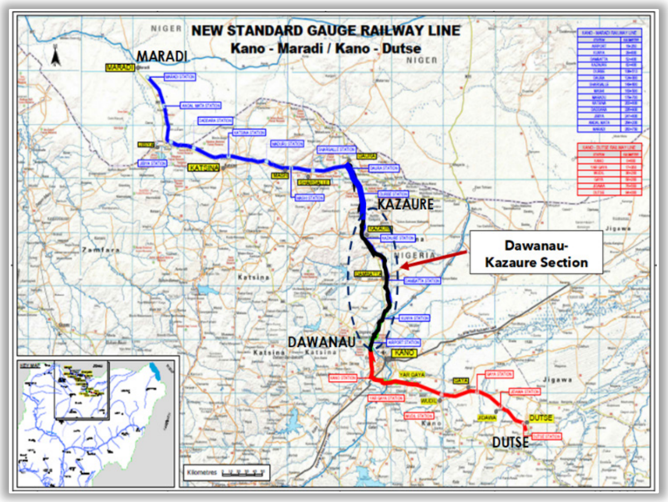

Figure 1. Map Showing Location of the Study Area

The area is typical of Sudan Savanna tropical climatic zone of Nigeria, which is characterized by two distinctive seasons (dry and wet seasons). The dry season begins from October to April and is associated with low humidity, especially during the harmattan period. The wet or rain season commences from May to October, with mean annual rainfall of about 700 – 750 mm per anum. The annual range of temperature is between 27 to 34℃ (Kankara 2014). The vegetation pattern is predominantly thorny shrubs with grasses of less than 2m high. The few tall trees are thorn Acacia, Neem and Baobab which are scattered, and normally shed their leaves completely during the dry seasons. They have an average height of 10 to 15 m. It is denser along river courses due to the presence of moisture which allows the vegetation to flourish.

The study area is a part of the basement complex of Northern Nigeria, which has three main lithologic profiles, including older granite complexes from the late Precambrian to lower Paleozoic eras, also known as pan–African granite, and undifferentiated migmatite complex of Proterozoic to Archean origin. The pan–African thermometric event has altered and damaged all of these rocks. Typically, the rock weathers into reddish micaceous sandstone to clay materials. Underlying the research region are rocks and more recent sediments from the Quaternary–aged Chad formation. Surface layers of fine sand that have been pushed into a number of low dunes cover a large portion of the land. The Chad sediments are concealed by sand dunes and the sandy beds are formed over the impervious clays of the Chad Formation and the main source of water in the dry season. These soils are comparatively recent in origin. They are generally sandy at the top, compact at depth with often hard pans. Aeolian deposits from the Sahara Desert form substantial part of the soils. The mixing of the subsoils in these deposits has given rise to clayey subsoil, which dominates the area.

Trial Pit Excavation and Soil Sampling:

Trial pit, also known as Test pit, is a type of intrusive geotechnical site investigation used to determine the ground conditions and soil profile throughout a site. They are cost effective and allow for a rapid inspection of ground conditions in situ, both horizontally and vertically as the pit advances and side walls exposed. Bulk disturbed samples are taken for detailed laboratory examination and testing.

Along the 23.5 km Dawanau–Kazaure Railway Line section investigated (between chainages 20+500 and 43+500), a total of Forty–Seven (47) Trial Pits were excavated at approximately 500–meter intervals. The Trial Pits were excavated to the dimensions: 1.2m x 1.2m x 3m (Figure 2). Bulk disturbed soil samples were collected for proper identification of the various strata formation of the subgrade subsoil and detailed laboratory analyses. The subsurface lithologic profile encountered across the forty–seven data points along the railway section investigated are mostly greyish to reddish brown concretionary laterite and brownish clayey silty sand. Most of the soil types for this section are classified as either A–4, A–2–4 or A–6 based on American Association of State Highway and Transportation Officials (AASHTO) soil classification system.

Figure 2. A typical excavated trial pit for soil sampling and in situ field observation.

Laboratory Testing:

A comprehensive suite of geotechnical laboratory tests on the soil samples obtained from the trial pits. These tests included grain size analysis, Atterberg limits, moisture content, modified proctor compaction test, specific gravity and California bearing ratio test (soaked and unsoaked) to determine the soil properties (Table 1).

Data Analysis and Pre–processing:

The trial pit data and laboratory test results were organized and compiled in a suitable format. Conduct a statistical analysis of the data to identify the mean, standard deviation, and other statistical parameters for each soil property (Table 1).

Uncertainty Quantification:

Determine the uncertainties associated with soil properties obtained from the trial pits and laboratory tests. This involves quantifying the spatial variability of soil properties, measurement errors, and other sources of uncertainty.

Probabilistic Modeling:

Probabilistic modeling in reliability–based evaluation involves choosing an appropriate probability distribution (e.g., normal, log–normal, or uniform) based on the characteristics of the soil property data and then calibrating the distribution's parameters to fit the observed data. This process allows engineers to incorporate uncertainty into their analyses and make more informed decisions in railway design by accounting for the probabilistic nature of subgrade soil properties.

Reliability Analysis:

A reliability analysis model was developed to integrate the probability distributions of soil properties with the loading conditions and design parameters, utilizing the First–Order Reliability Method (FORM) to compute the probability of failure or the reliability index. Let the limit state function in the space of input variables be given by:

$$g(X_1, X_2, \ldots, X_n) = 0 \qquad (1)$$

Also,

Let the input variables be random variables collected in the vector $X = [X_1, X_2, \ldots, X_n]^T$ with second moment statistics $E(X)$ and $Cov(X, X^T)$. The normalized random variables $Y_1, Y_2, \ldots, Y_n$ are introduced by a suitable one to one linear mapping. $X = L(Y)$ such that $Y = L^{-1}(X)$.

The corresponding space of y is then defined by the transformation:

$$X = L(Y),\ Y = L^{-1}(X) \qquad (2)$$

Applying Equation (1) maps Equation (2) into:

$$h(y_1, y_2, \ldots, y_n) = 0 \qquad (3)$$

Where the function h is defined by:

$$h(y) = g[L(y)] \qquad (4)$$

Equation (2) represents the limit state equation in normalized coordinate. The mean value of y is the origin and the projection of y on the arbitrary straight line through the origin is the random variable with the standard deviation of unity. The geometric reliability index β is then defined as the distance in the normalized coordinate from the origin to the failure surface.

That is:

$$\beta = \min\left\langle \sqrt{\sum y_1^{\,2} + y_2^{\,2} + \ldots + y_n^{\,2}}\ \middle|\ h(y_1, y_2, \ldots, y_n) \right\rangle = 0 \qquad (5)$$

In matrix notation, Equation (5) can be re–written as:

$$\beta = \min\left\langle \sqrt{y^t y}\ \middle|\ h(y) \right\rangle = 0 \qquad (6)$$

where β = reliability index.

The values of the design variables that minimize the reliability index β subject to $h(y_1, y_2, \ldots, y_n) = 0$ are obtained by optimization. Tables 1 and 2 show the results of the laboratory analyses and statistics of the basic random variables respectively.

Sensitivity Analysis:

A sensitivity analysis was carried out by varying the values of coefficient of variation (COV) of the design parameters and output variables between 10% and 100% to identify the most influential soil parameters and loading conditions that affect the reliability of the subgrade soil materials.

RESULTS AND DISCUSSION

The results obtained from the laboratory analysis of soil samples obtained from the different trial pit locations are presented in Table 1. Statistical information for basic random variables obtained are summarized in Table 2.

Table 1: Results of laboratory analysis of trial pit soil samples

Trial Pit No.	EMC (%)	LL (%)	PL (%)	PI (%)	MDD (g/cm3)	OMC (%)	Specific gravity	CBR (%) Unsoaked	CBR (%) Soaked
1.	4	25	16	9	1.92	10.20	2.62	56	11
2.	8	30	20	10	1.88	17.10	2.73	87	36
3.	6	31	21	10	1.86	16.30	2.70	80	32
4.	4	27	18	9	1.90	10.50	2.63	48	12
5.	6	26	19	7	2.12	9.20	2.71	76	29
6.	5	36	18	18	1.89	10.20	2.62	53	16
7.	4	30	21	9	1.93	12.70	2.69	82	29
8.	6	28	16	12	1.98	11.10	2.64	56	17
9.	5	26	17	9	1.96	10.80	2.60	46	13
10.	6	28	18	10	1.92	12.30	2.65	61	22
11.	14	34	16	18	1.78	16.70	2.70	58	23
12.	10	27	19	8	1.93	9.90	2.68	78	25
13.	7	22	17	9	1.96	10.03	2.60	41	8
14.	7	28	18	10	1.91	10.4	2.61	53	13
15.	4	32	20	12	1.89	12.8	2.69	70	25
16.	15	33	17	16	1.95	14.8	2.72	72	27
17.	6	30	20	10	1.96	9.9	2.63	47	10
18.	12	32	21	11	2.04	9.30	2.68	79	27
19.	10	35	23	12	1.83	14.9	2.73	62	23
20.	7	27	17	10	1.99	10.3	2.66	75	26

Table 1: Results of laboratory analysis of trial pit soil samples (continuing)

Trial Pit No.	EMC (%)	LL (%)	PL (%)	PI (%)	MDD (g/cm3)	OMC (%)	Specific gravity	CBR (%) Unsoaked	CBR (%) Soaked
21.	5	31	19	12	1.97	11.1	2.65	86	25
22.	11	32	20	12	1.94	12.3	2.69	80	33
23.	6	30	21	9	2.02	7.6	2.67	51	14
24.	5	29	20	9	1.98	9.2	2.60	49	10
25.	7	28	18	10	1.90	10.5	2.62	52	10
26.	4	32	22	10	1.93	11.6	2.61	45	8
27.	7	28	20	8	1.91	10.40	2.60	42	11
28.	10	29	21	8	1.92	10.80	2.63	53	13
29.	5	27	18	9	1.89	10.60	2.61	45	12
30.	5	26	18	8	1.95	10.40	2.62	37	12
31.	7	30	20	10	1.86	10.80	2.62	42	10
32.	6	31	21	10	1.90	9.90	2.63	39	8
33.	6	30	19	11	1.84	10.10	2.60	43	11
34.	5	30	21	9	1.88	10.70	2.63	48	11
35.	4	28	20	8	1.90	9.90	2.60	45	10
36.	5	32	22	10	1.92	10.30	2.62	47	9
37.	4	29	21	8	2.10	7.20	2.72	85	31
38.	8	28	19	9	1.89	11.10	2.61	50	11
39.	6	30	21	9	1.94	9.80	2.63	46	10
40.	6	31	22	9	1.84	11.1	2.61	47	11
41.	5	28	20	8	1.71	13.1	2.63	42	12
42.	7	29	19	10	1.88	10.1	2.65	49	13
43.	5	34	22	12	1.86	9.4	2.62	43	12
44.	6	30	20	10	1.90	10.3	2.60	38	10
45.	6	32	22	10	1.87	9.7	2.62	41	10
46.	7	28	20	8	1.89	10.0	2.62	37	11
47.	10	30	19	11	1.92	9.9	2.60	40.0	13

Table 2: Statistics of the basic random variables

S/N	Variable	Unit	Type of Probability Distribution	Mean	Standard Deviation	Coefficient of Variation
1	EMC	%	Lognormal	6.681	2.563	0.384
2	LL	%	Lognormal	29.809	2.890	0.084
3	PL	%	Lognormal	19.702	1.793	0.091
4	PI	%	Lognormal	10.106	2.305	0.228
5	MDD	g/cm^3	Lognormal	1.917	0.07042	0.037
6	OMC	%	Lognormal	11.01	2.07	0.188
7	Gs	–	Normal	2.643	0.0403	0.0152
8	CBR (Unsoaked)	%	Lognormal	55.362	15.4	0.278
9	CBR (Soaked)	%	Lognormal	16.57	8.216	0.494

The results of the sensitivity analysis carried out over a range of coefficient of variation between 10% – 100% are displayed in Plots 1 to 8 respectively.

The results of the reliability–based design of subgrade soil analyzed at predefined reliability indices are presented in Table 3.

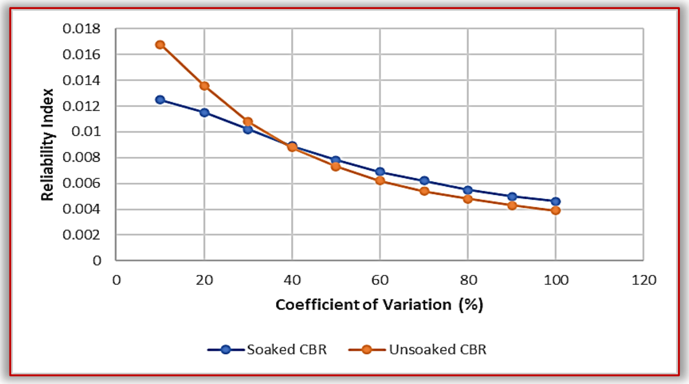

Figure 3. Relationship between Reliability Indices and Coefficient of Variation for Soaked and Unsoaked CBR.

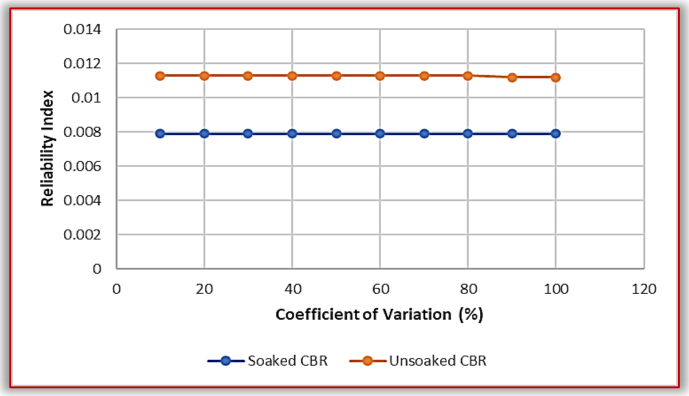

Figure 4. Relationship between Reliability Indices and Coefficient of Variation for Moisture Content.

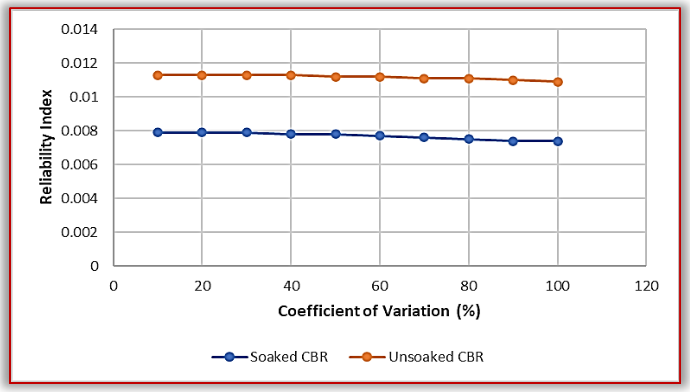

Figure 5. Relationship between Reliability Indices and Coefficient of Variation for Liquid Limit.

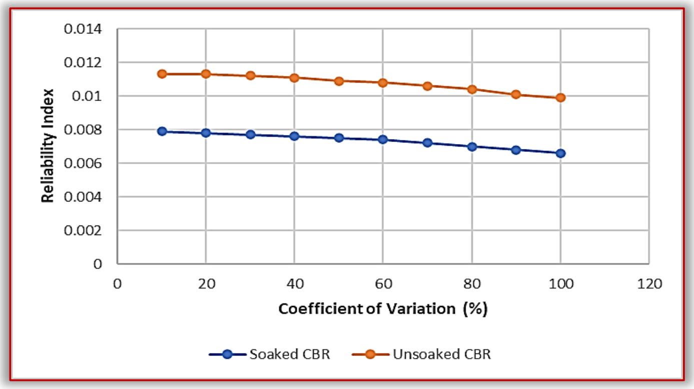

Figure 6. Relationship between Reliability Indices and Coefficient of Variation for Plastic Limit.

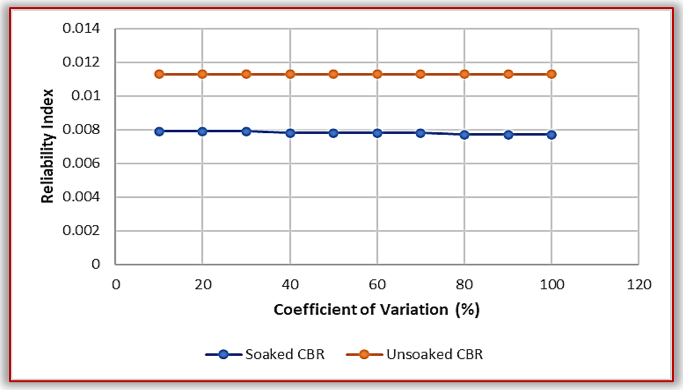

Figure 7. Relationship between Reliability Indices and Coefficient of Variation for Plasticity Index

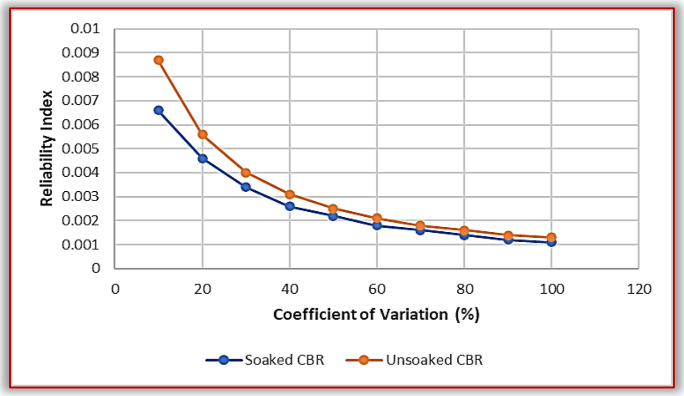

Figure 8. Relationship between Reliability Indices and Coefficient of Variation for Maximum Dry Density

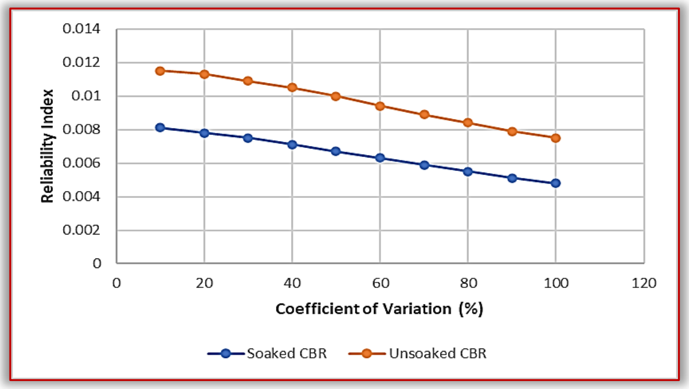

Figure 9. Relationship between Reliability Indices and Coefficient of Variation for Optimum Moisture Content

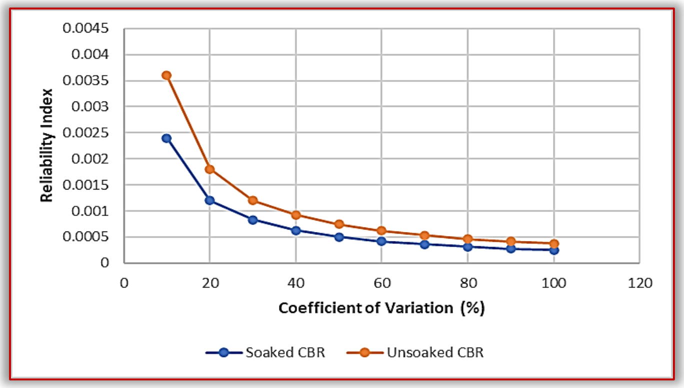

Figure 10. Relationship between Reliability Indices and Coefficient of Variation for Specific Gravity

Table 3: Reliability–Based Design of Subgrade Soil at Pre–defined Reliability Indices

Variables	Soaked CBR (32.5 %) β = 0.9275	Unsoaked CBR (78 %) β = 0.925	Initial Value
EMC	6.6701	6.5646	6.681
LL	24.7616	24.7523	24.53
PL	19.959	19.9691	19.89
PI	9.7065	9.7254	9.745
MDD	1.9267	1.933	1.917
OMC	11.2959	11.3387	11.01
Gs	2.6537	2.6565	2.643

The results of reliability estimate of the subgrade soil along Dawanau–Kazaure proposed railway section based on California Bearing Ratio (CBR) are presented in Figures 3 to 10. The results of the reliability–based design of subgrade soil at target reliability index of 1.0 is presented in Table 3.

Influence of California Bearing Ratio (CBR) on reliability index

Figure 3 displays the results of reliability indices for the California Bearing Ratio (CBR) under both soaked and unsoaked conditions at various coefficient of variation values. It is evident from Figure 3 that the reliability indices exhibit a decrease as the coefficient of variation increases, ranging from 10% to 100%, for both soaked and unsoaked subgrade soil samples. This trend is attributable to the rise in variability in the measured CBR values as the coefficient of variation for CBR (both soaked and unsoaked) increases, leading to a reduction in the reliability index values. The reliability indices range from 0.0046 to 0.0125 for soaked CBR and from 0.0039 to 0.0168 for unsoaked CBR.

These results consistently indicate positive values, signifying the safety of the subgrade soil. However, it is worth noting that the minimum reliability index value of 1.0, as recommended by the Nordic Committee on Building Regulations (NKB, 1978) is not attained within the considered range of coefficient of variation values. This suggests that modifications are required for the subgrade material to enhance its performance, as outlined in Table 3.

Effect of Natural Moisture Content on the Reliability Index

Figure 4 illustrates the influence of natural moisture content (NMC) on the reliability indices of the subgrade soil across a spectrum of coefficient of variation (COV) values, ranging from 10% to 100%.

A notable observation from Figure 4 is the constancy of reliability index values for both soaked and unsoaked soil samples, suggesting that water content has minimal to no discernible impact on the reliability index.

The subgrade soil, in its capacity as subgrade material, maintains consistent reliability index values throughout this moisture content variation range. It is worth highlighting that all reliability index values within the considered range of COV values are positive.

However, it is essential to note that the minimum reliability index threshold of 1.0, as stipulated in the NKB Report (1978), is not attained. Consequently, the subgrade soils necessitate improvement to enhance their performance and meet the specified reliability standards.

Influence of Liquid Limit on the Reliability Index

The results of the reliability indices at varying values of the coefficient of variation ranging from 10% to 100% are presented in Figure 5. It can be seen from Figure 5 that for both soaked and unsoaked California Bearing Ratio (CBR), the reliability index value is constant for the range of values of the coefficient of variation considered.

The constant value is due to the fact that liquid limit has little or no effect on the reliability indices of the subgrade soils evaluated. However, the minimum value of the reliability index of 1.0 recommenced by the NKB Report (1978), is not met and the subgrade soils therefore need to be improved.

Effect of Plastic Limit on the Reliability index

Figure 6 demonstrates the influence of the Plastic Limit on the Reliability Index for both soaked and unsoaked California Bearing Ratio (CBR).

As depicted in Figure 6, it is evident that the reliability index values remain constant across a range of coefficient of variation values spanning from 10% to 100%, regardless of whether the CBR measurements were taken under soaked or unsoaked conditions. This constancy in reliability index values underscores the limited or negligible impact of the plastic limit on the reliability of the investigated subgrade soils.

Although all reliability index values are positive, indicative of the subgrade soils' general safety, they fall short of the recommended minimum threshold of 1.0. Consequently, the subgrade soils require improvement measures to meet the prescribed reliability standards.

Effect of Plasticity Index on the Reliability Index

The results of the reliability index for coefficient of variation ranging from 10% to 100% for both soaked and unsoaked California Bearing Ratio (CBR) are presented in Figure 7. From Figure 7, it can be observed that the reliability indices maintain constant values within the considered range of coefficient of variation, regardless of whether the CBR measurements were conducted under soaked or unsoaked conditions.

This consistency in reliability index values is attributed to the limited or negligible impact of plasticity index on the reliability indices. While all reliability index values are positive, denoting the overall safety of the subgrade soils, they fall short of the recommended minimum threshold of 1.0 for both soaked and unsoaked CBR, indicating the need for improvement measures to meet the specified reliability standards.

Effect of Maximum Dry Density on the Reliability Index

Figure 8 illustrates the outcomes of reliability indices across a range of coefficient of variation values from 10% to 100% for both soaked and unsoaked California Bearing Ratio (CBR).

As evident from Figure 8, the reliability indices exhibit a consistent decrease as the coefficient of variation increases. This trend is expected because higher coefficient of variation values introduces greater variability in the CBR measurements of soaked and unsoaked soil samples, leading to a reduction in reliability index values.

While all reliability index values are positive, signifying the overall safety of the subgrade materials, they fall short of meeting the recommended minimum threshold of 1.0, indicating that there is no assurance of satisfactory performance in service.

Therefore, improvement measures are necessary for the subgrade materials to meet the required standards.

Effect of Optimum Moisture Content on the Reliability Index

The results of the reliability indices for values of coefficient of variation ranging from 10% to 100% are presented in Figure 9. It can be seen from Figure 9, that the reliability indices decrease as the values of the coefficient of variation decreases for the both soaked and unsoaked soil samples. This is because the variability of the optimum moisture content of the soil is expected to increase and this results to decrease in the values of the reliability indices.

Also, the value of the reliability indices are all positive and this connotes the safety of the subgrade soil. However, the recommended minimum value of the reliability index of 1.0 is not achieved, showing that the subgrade soils require improvement.

Effect of Specific Gravity on the Reliability Index

The results of reliability indices for a range of coefficient of variation values from 10% to 100% are depicted in Figure 10. As observed in Figure 10, both for soaked and unsoaked California Bearing Ratio (CBR), the reliability indices exhibit a consistent decrease as the coefficient of variation values increase. This decline in reliability index values, ranging from 0.0024 to 0.000249 for soaked soil samples and from 0.0036 to 0.000373 for unsoaked soil samples, can be attributed to an escalation in the variability of the specific gravity of the soil samples. Despite the decreasing trend, all reliability index values remain positive, indicating the overall safety of the subgrade soil.

However, it is important to note that these values fall short of the recommended minimum reliability index threshold of 1.0, underscoring the need for improvement measures for the subgrade soil, as outlined in the NKB Report (1978).

Reliability–Based Design of Subgrade Materials at Target Reliability Index of 1.0.

The essence of reliability–based design is to ensure that structures perform optimally in service. The results of the reliability–based design of subgrade material at minimum target reliability index value of 1.0 are presented in Table 3. The values of the design parameters for both soaked and unsoaked California Bearing Ratio corresponding to their expected values are presented in Table 3.

The expected values of the California bearing Ratio for both soaked and unsoaked soil samples are 32.5% and 78% and their corresponding reliability indices are 0.9275 and 0.925 respectively. This improvement in the index properties of the soil will lead to improved performance.

Limit State Performance Function

The limit state equation with respect to bearing capacity failure for soaked CBR is given by:

$$G(X) = \text{Expected CBR} - (402.8) - 0.031\,EMC + 0.164\,LL + 0.331\,PL - 0.252\,PI + 38\,MDD + 1.242\,OMC + 122.9\,Gs.$$

The limit state equation with respect to bearing capacity failure for unsoaked CBR is given by:

$$G(X) = \text{Expected CBR} - 0.184\,PI - (-740 - 0.475\,EMC + 0.226\,LL + 0.545\,PL - 0.184\,PI + 89.6\,MDD + 2.05\,OMC + 223\,Gs.$$

where: CBR is california bearing ratio, PI is plasticity index, EMC is equilibrium moisture content, LL is liquid limit, PL is plastic limit, MDD is maximum dry density, OMC is optimum moisture content and Gs is specific gravity.

CONCLUSIONS

From the study, the following conclusions are drawn:

- The reliability indices consistently decreased as the coefficient of variation values of the soil parameters increased, regardless of whether the soil samples are soaked or unsoaked.
- Factors such as water content, liquid limit, plastic limit, and plasticity index had minimal to negligible effects on the reliability indices of the subgrade material.
- An increase in the coefficients of variation for maximum dry density, optimum moisture content, and specific gravity of the subgrade soil reduced the reliability indices.
- The considered index properties yielded positive reliability index values, indicating the general safety of the subgrade soil. However, it is important to note that these values fell short of the recommended minimum reliability index threshold of 1.0, underscoring the need for improvement to ensure optimal performance.
- For achieving satisfactory performance of the subgrade soil, the expected values of California Bearing Ratio are determined to be 32.5% and 78%, respectively.
- The MATLAB–Based First Order Reliability Method Program had proved to be a rapid and suitable tool for generating design points and corresponding reliability indices, making it well–suited for highway and structural applications.

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