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Assessment of Linear and Nonlinear Subgrade Behavior Using FWD Deflection Ratios: Implications for Pavement Modelling

Eng. Catherine Mugai * Dr. Kepha Abongo, Dr. Brian Jacks Odero

School of Civil, Environmental and Geospatial Engineering, Jomo Kenyatta University of Agriculture & Technology

* E-mail of the corresponding author: mugaicatherine78@gmail.com

Abstract: *Accurate modelling of pavement performance requires understanding the linearity or non-linearity of subgrade soil behaviour. This study assesses subgrade response under falling weight deflectometer (FWD) loading on 24 road sections in Kenya. Deflection ratios (DR) derived from FWD deflections at multiple geophone offsets were used to evaluate linear and nonlinear behaviour. Statistical analysis, including descriptive statistics, Pearson correlation, and ANOVA, were applied to explore relationships between DR and soil properties. Results indicate that fine-grained soils such as elastic silt (MH) and lean clay (CL) exhibit higher DR variability, suggesting nonlinear behaviour, while coarse-grained soils such as silty gravel (GM) and silt with sand (ML) demonstrate more linear response. These findings provide guidance for selecting appropriate pavement modelling techniques based on observed subgrade behaviour.*

Key Words: Falling Weight Deflectometer, Deflection Ratios, Soil Classification, Subgrade

1. Introduction

Pavement performance is highly dependent on subgrade characteristics and their response under load. The Falling Weight Deflectometer (FWD) provides a non-destructive means to assess subgrade deflections and infer material behaviour. Linear assumptions in pavement design may not hold for highly plastic or moisture-sensitive soils, leading to inaccuracies in predicted service life (Tripathi & Singh, 2011; Mugai et al., 2020). Deflection ratios (DR) at successive geophone offsets provide insight into linearity: DRs close to 1 suggest linear elastic response, while deviations indicate non-linear behaviour.

The objective of this study was to assess the linearity or non-linearity of subgrade soils in low-volume roads in Kenya using FWD deflection ratios and to identify implications for pavement modelling.

2. Materials and Methods

2.1 Study Area and Road Sections

Twenty-four road sections spanning diverse soil classes (MH, ML, CL, CH, GM, SC) were selected across Kenya (Table 1). These sites represent common low-volume road conditions.

Table 1: Summary of Road Sections and Dominant Soil Classes

Road No	Location	Soil Class
1	Nakuru/Nyandarua	MH, CH, CL
2	Rift Valley/Kisumu	ML, CL
3	Oyugis	CL, CH
...	...	...
24	Kikuyu	CL, CH, MH

2.2 FWD Testing and Deflection Ratios

FWD testing was conducted at multiple chainages for each road section. Deflections were recorded at nine geophones positioned between 0mm to 2100mm from the centre of the loading plate. Deflection ratios were computed as:

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Deflection Ratio (DRi)= D_i / D_0

Where:

- D_i = deflection measured at any other geophone (i)
- D_0 = reference (surface) deflection

DR > 1 indicates a reduction in deflection with distance, suggestive of non-linear subgrade response.

2.3 Statistical Analysis

Descriptive statistics characterized the mean and variability of DR for each soil type. Pearson correlation was used to assess the relationship between DR and subgrade properties such as plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD). ANOVA tested differences in DR between soil groups.

3. Results

3.1 Descriptive Statistics of Deflection Ratios

Table 2: Mean Deflection Ratios by Soil Class

Soil Class	Mean DR (0–200)	Mean DR (200–300)	Mean DR (300–600)	Std. Dev (0–2100)
MH	1.42	1.28	2.16	0.35
CL	1.34	1.22	1.95	0.28
ML	1.30	1.25	2.10	0.22
GM	1.18	1.15	1.60	0.18

3.2 Correlation with Subgrade Properties

Pearson correlation indicated significant positive correlation between DR (0–600 mm) and PI ($r = 0.63$, $p < 0.05$), suggesting that soils with higher plasticity exhibit more nonlinear behaviour. Negative correlation with MDD ($r = -0.47$, $p < 0.05$) indicates denser soils tend to behave more linearly.

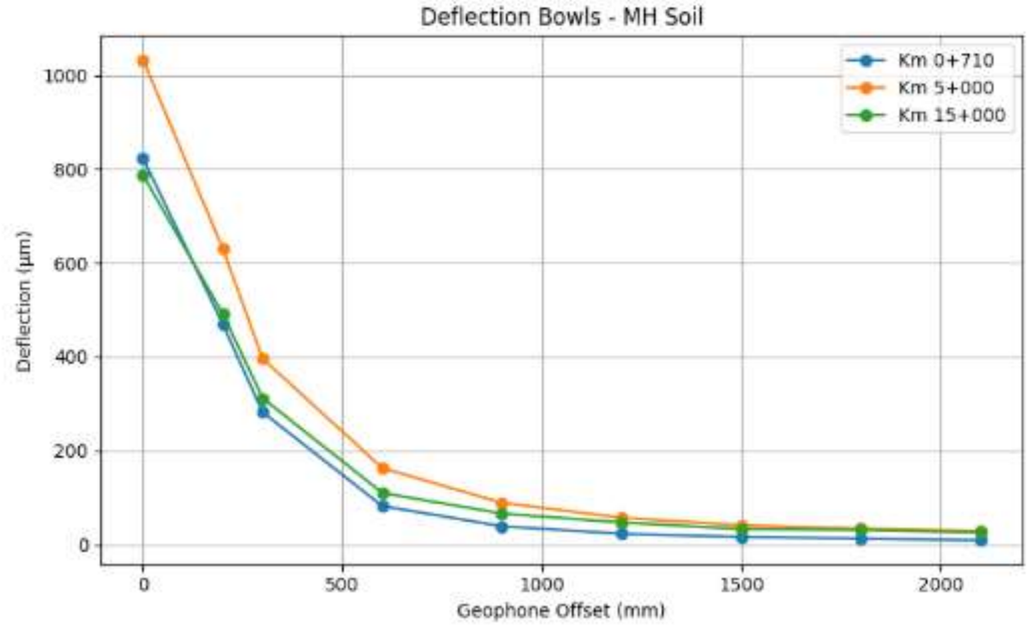
3.3 ANOVA Results

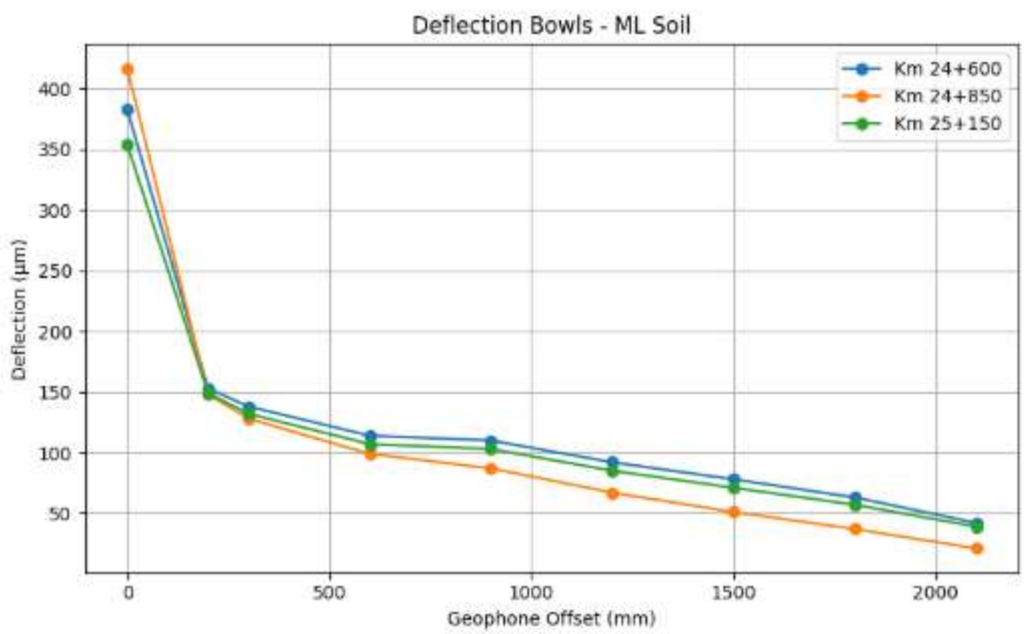
ANOVA results showed statistically significant differences in DR among soil types ($F (5, 118) = 6.82$, $p < 0.01$). Post-hoc tests indicated MH and CL were significantly different from ML and GM soils, confirming the influence of soil type on subgrade linearity.

3.4 Deflection Patterns

Figure 1 shows representative deflection bowls for MH and ML soils. MH soils display higher mid-span deflections relative to peripheral geophones, indicative of nonlinear response. ML soils show more uniform deflections, suggesting linear elastic behaviour.

Figure 1: Representative Deflection Bowls for MH and ML Soils





3.5 Implications for Pavement Modelling

Subgrades exhibiting DR > 1.5 at 0–600 mm should be modelled using nonlinear material models in mechanistic pavement design software. Linear models may underestimate stress and strain in high PI soils, potentially leading to premature failures.

4. Discussion

The study confirms that FWD deflection ratios are effective indicators of subgrade linearity. Soils with higher plasticity (MH, CH) show significant non-linear behaviour, consistent with findings by Tripathi & Singh (2011), Mugai et al. (2020)

and Mugai et al. (2025). The correlation analysis provides a quantitative relationship between soil properties and observed behaviour, allowing engineers to select appropriate modelling assumptions. Future studies could explore nonlinear finite element models validated against FWD-derived DR to improve pavement design accuracy.

5. Conclusion

1. FWD deflection ratios effectively differentiate linear and nonlinear subgrade behaviour.
2. Fine-grained soils (MH, CL) are more nonlinear, while coarse-grained soils (ML, GM) behave linearly.
3. Subgrade soil properties such as PI and MDD significantly influence DR.
4. Pavement models should consider nonlinear material behaviour for high PI soils to avoid overestimation of pavement performance.

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