Development of Permanent Deformation Models for Granular Materials and Soils

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INTRODUCTION

→ A pavement can exhibit different types of damage that can lead to failure such as permanent deformation, which can be associated to:
- → Asphalt concrete layer
- → Coarse aggregate layers
- → Subgrade soil

→ In Costa Rica, this research project corresponds to the first study focused on permanent deformation for granular materials and soils.

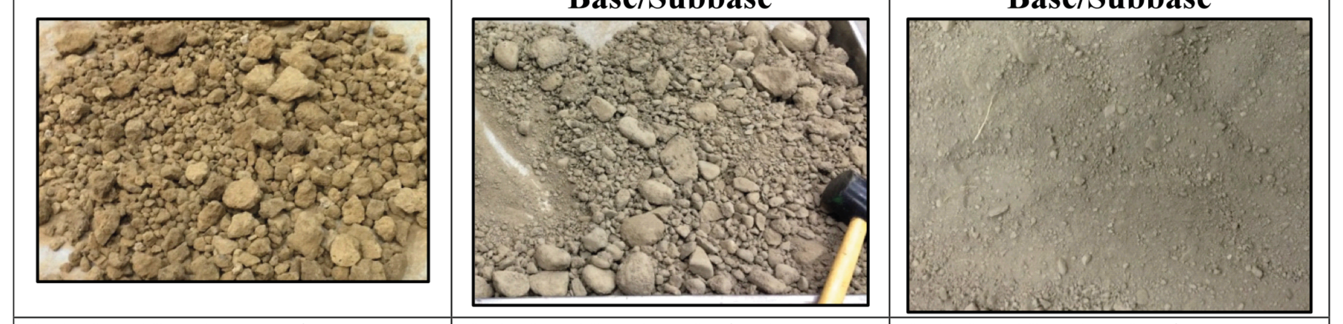
→ Currently there is no international entity that defines an official test protocol to evaluate permanent deformation of unbound materials.
- → Develop a testing protocol and permanent deformation model for Costa Rica

OBJECTIVE

→ Establish a general permanent deformation model for two types of granular materials and one soil. The purpose of the model is to predict the deterioration process that the material will be subjected in the field.

MATERIALS

→ The selected materials are commonly found in the central region of Costa Rica and correspond to typical conditions.



Soil-Material Subgrade	Coarse-Material 1 Base/Subbase	Coarse-Material 2 Base/Subbase
Soil Clasification MH/A-7-5	**Soil Clasification** GP/A-1-a	**Soil Clasification** SW/A-1-a
Atterberg Limits LL: 60 PL: 41 PI: 19	**Atterberg Limits** Non Plastic	**Atterberg Limits** Non Plastic
Dry unit weight: 1072.0 kg/m^3 **Optimum water content:** 51.0%	**Dry unit weight:** 2212.0 kg/m^3 **Optimum water content:** 8.80%	**Dry unit weight:** 2125.0 kg/m^3 **Optimum water content:** 10.3 %

Figure 1 Materials Used for Model Calibration

TESTING METHOD

→ The material for each sample is brought to optimum moisture.

→ Compaction is done based on ASTM D 698-12 and ASTM D 1557-12 for Standard and Modified Effort respectively, seeking to obtain 100% density thru compaction.

→ The triaxial chamber is placed with the specimen in a loading frame (UTM-25) capable of applying dynamic forces and confining stresses.

→ To perform the test, three confining stresses with three deviator stresses varying every 5,000 load cycles were defined.

→ In order to optimize the test time and the amount of material required for testing, a stepwise test procedure was implemented.

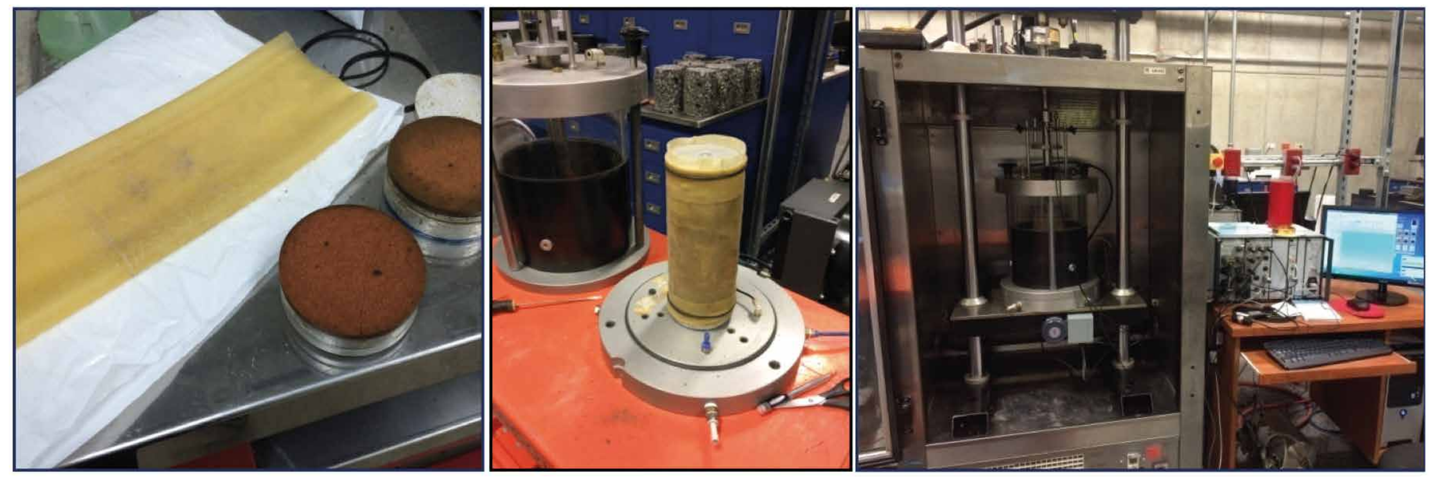


Figure 2 (a) Equipment used to prepare specimens (b) Sample (c) Permanent deformation testing device

TEST RESULTS AND DATA ANALYSIS

→ Figure 3 shows an example of the representative cumulative permanent deformation trends for all the 8 materials, where P4-P10 are the codes assigned to each test specimen.

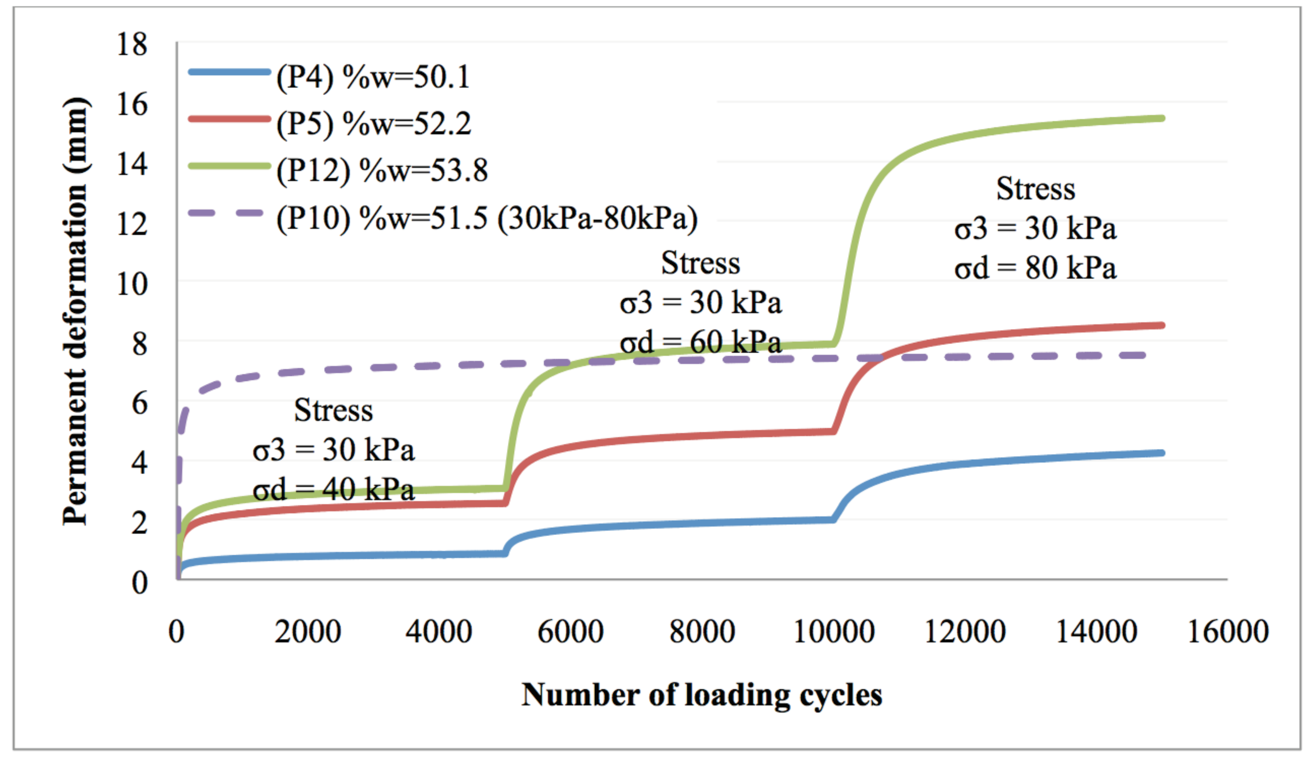


Figure 3 Cumulative permanent deformation for the soil

→ Generalized Least Squares (GLS)

Where ε_i is the plastic strain (dimensionless), N is number of load cycles, σ_d is the deviator stress in kilopascals, σ_3 is the confining stress in kilopascals, %w is moisture content, β_i are calibration parameters, and e_i are unobserved factors that are not captured by the model.

$$\varepsilon_i = \beta_1 \cdot N_i^{\beta_2} \cdot \sigma_{d,i}^{\beta_3} \cdot \sigma_{3,i}^{\beta_4} \cdot \%w_i^{\beta_5} \cdot e_i$$

Table 2 GLS Results for the three materials

Variable	Subgrade			Granular Material 1			Granular Material 2		
	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value
N	0.0500	46.9	<0.001	0.120	144	<0.001	0.100	208	<0.001
σ_d	2.19	752	<0.001	0.860	317	<0.001	0.890	717	<0.001
σ_3	0.260	52.3	<0.001	0.580	161	<0.001	-0.0440	-28.3	<0.001
%w	18.0	764	<0.001	3.56	270	<0.001	0.310	14.6	<0.001
Constant	-35.1	-853	<0.001	-6.26	-569	<0.001	-2.84	-127	<0.001
R^2	0.888			0.831			0.872		

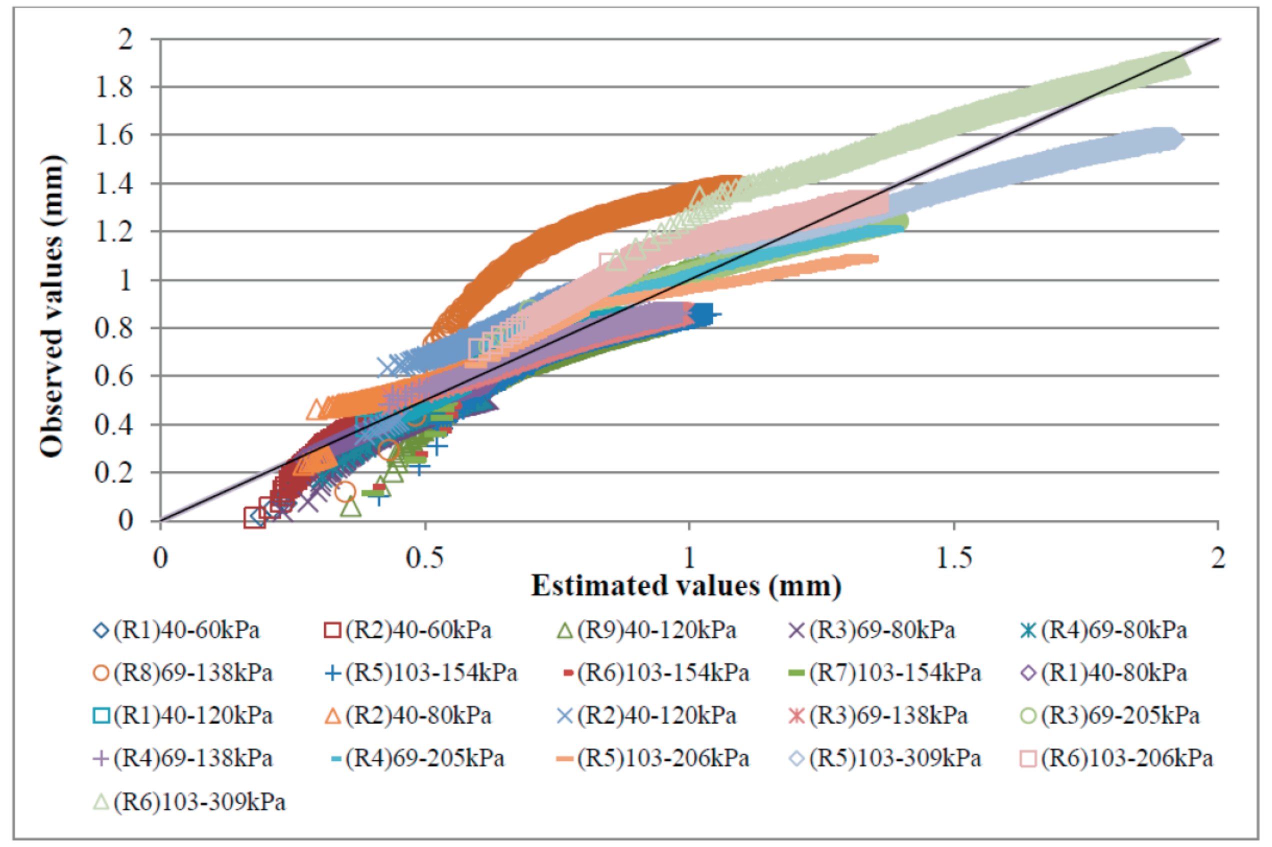


Figure 4 Observed values against estimated values for granular material 2

→ Panel Data

$\varepsilon it=Xit\beta i\cdot\varepsilon i(t-1)\rho i1\cdot\varepsilon i(t-2)\rho i2\cdot eit\cdot ui$, for i = 1,...,N; t=1,...,T

Where u_i represents the unobservable effects that differ between samples but not in time, e_{it} refers to purely random error, and; β_i are the calibration parameters. X_{it} is composed by N, σ_d (kPa), σ_3 (kPa), and %w. $\varepsilon_{i(t-1)}$ and $\varepsilon_{i(t-2)}$ corresponds to permanent deformation of a previous cycle, and; ρ_i is the calibration parameter associated to $\varepsilon_{i(t-i)}$.

Table 3 Regression results for fixed and random effects AR(2) models

Variable	AR(2) Fixed Effects Model				AR(2) Random Effects Model			
	Coeff.	Std.Err.	t-Stat	p-value	Coeff.	Std.Err.	t-Stat	p-value
N	0.00986	4.16×10^{-5}	237	<0.001	0.00988	4.16×10^{-5}	237	< 0.001
σ_d	0.00651	0.00193	3.37	0.001	0.00724	0.00193	3.75	< 0.001
σ_3	-0.108	0.00762	-14.2	< 0.001	-0.101	0.00761	-13.3	< 0.001
%w	-31.8	1.14	-27.9	< 0.001	0.0428	0.0195	2.20	0.028
$\varepsilon_{(t-1)}$	0.841	0.00141	598	< 0.001	0.843	0.00141	599	< 0.001
$\varepsilon_{(t-2)}$	0.0286	0.00123	23.4	< 0.001	0.0273	0.00123	22.2	< 0.001
LogConstant	38.3	1.37	28.0	< 0.001	0.0874	0.0294	2.97	0.003
$\sigma\ u_i$	-	11.7	-	-	-	0.0590	-	-
$\sigma\ e_{it}$	-	0.00675	-	-	-	0.00676	-	-
p-value	< 0.001				< 0.001			
F-Statistic	2.89×10^6				2.67×10^6			
R^2	0.976				0.972			

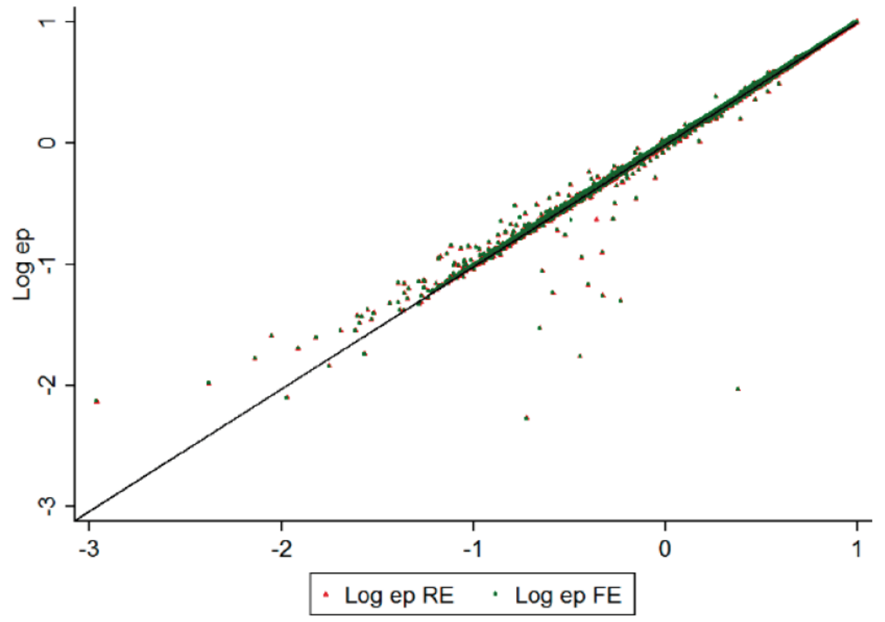


Figure 5 Observed vs. Estimated Permanent Deformation Based on Panel AR(2) Models

SUMMARY AND CONCLUSIONS

→ Significant changes due to low moisture variations were observed mainly in cohesive materials.

→ Even though materials might have similar classifications, they can exhibit significantly different behaviors.

→ Based on the developed permanent deformation predictive models, it was found that Panel Time Series Analysis was more accurate than the multiple linear regression (OLS), which is the method used to traditionally estimate the permanent deformation models.

→ The Random Effects model predicts the data more efficiently and can be estimated in a probabilistic manner since the intercept term is assumed to follow a normal distribution.