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PREDICTIVE RISK MODELING OF DIFFERENTIAL BRIDGE SETTLEMENT

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Abstract: Differential settlement between the roadway pavement resting on embankment fill and the bridge abutment built on more rigid foundation often creates a bump when driving from roadway to bridge, and vice versa. This paper studies the problem at a macroscopic level by determining a method to predict the levels of approach settlement to assist designers in developing remediation plans during project development to minimize the lifecycle costs of bridge bump repairs. A macro method considering a combination of maintenance times, maintenance measures, and observed settlement was used to classify the differential settlement scale as minimal, moderate, and severe. A set of project characteristics including approach, abutment type, embankment, foundation, and traffic volume that may influence the formation of differential settlement were identified and used as parameters to develop a model to predict the settlement severity for a given approach. Logistic regression analyses were implemented to identify the relationships between the levels of differential settlement and the input variables for a sample of 600 randomly selected bridges in Kentucky. Geographic region, approach age, average daily traffic, and the use of approach slabs are identified as the four most predominant factors that can significantly affect the formation of differential settlement. Based on the performance of bridge approaches in Kentucky, how those parameters interacted in the prediction model is illustrated in the logistic regressions.

Keywords: Differential settlement, Logistic regression, Prediction model.

1 INTRODUCTION

The difference in elevation between the bridge super structure and the adjacent roadway pavement is commonly defined as differential settlement at bridge ends. The primary manifestation of differential settlement is a bump, which could lead to a series of negative effects, such as damage to vehicles/structure, public perception of the state infrastructure, maintenance cost, traffic delays, and in the most severe cases crash related injuries and death. Considerable amounts of annual maintenance costs to alleviate the bump problems consume a significant amount of the budgets of state Department of Transportations (DOTs) in the United States (Briaud et al. 1997). A survey conducted by Hoppe (1999) reported that bridge approach settlement or bump problems were rated as a significant problem by 44% of the DOTs. Due to the universality and perceived severity of bump

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problems, many studies have identified specific resolution techniques/measures at a microscopic level, such as controlled quality backfill (Ha et al. 2002), rigorous compaction indices or various grain composition of embankment (Parsons et al. 2001), new design or construction methods (White and Sritharan 2005), new abutment backfill (Abu-Hejleh et al. 2008), and new ground-improvement techniques (Zhan et al. 2014), to mitigate this problem by applying these micro techniques/measures on selected sites to assess the severity of differential settlement and evaluate the likelihood of developing a bump. However, few studies predict the differential settlement at bridge ends based on project characteristics. Laguros et al. (1990) have established a linear numerical model to explain the relationships between observed approach settlement and various causative factors by quantitatively defining these factors, but none of the categorical factors were included in this model. This study's objective focuses on differential settlement at bridge ends at a macroscopic level and develops a model for predicting settlement severity by considering important factors based on historic data from a wide range of Kentucky roads and bridges. A sample of 600 approaches in different settlement levels was obtained from inspection history of bridge approaches in Kentucky. The statistical methods were applied to this sample to identify the predominant factors that may significantly influence the formation of differential approach settlement and to figure out how to develop a model for predicting settlement levels by quantifying model inputs.

2 MODEL INPUT IDENTIFICATION

In order to obtain comprehensive and meaningful relationships between approach settlement levels and various contributors, it is necessary to identify as many initial causative factors as possible because no consensuses has been reached on the role of each factor affecting the final approach settlement formation. A series of potential variables were identified and the collection methods are presented. The main model inputs include:

1. Bridge length, width, approach year, and ADT. Some researchers, such as Laguros et al. (1990) and Bakeer et al. (2005), claim that approach age could negatively affect the embankment fill performance in terms of controlling deformation underneath the approach, especially at the expansion joints next to the slab for those bridges with approach slabs. Although traffic volume has been considered as a major factor affecting the performance of the bump severity, the opinions regarding the effects of traffic volume are divergent. Lenke (2006) concluded that bump severity was found to increase with vehicle velocity, vehicle weight, especially heavy truck traffic, and ADT. While Bakeer et al. (2005) pointed out that speed limit and traffic volume almost have no effect on the performance of bridge approaches. These numerical variables can be collected through the online "Bridge Data Miner" of Kentucky Transportation Cabinet (KYTC) once a bridge is selected.
2. Approach type. The bridge approaches were classified into two categories: bridges with approach slabs of Portland cement concrete are termed as rigid, bridges without approach slabs or with approach slabs built with asphaltic concrete cement, are termed as flexible. This predictor can be classified by reviewing bridge design plans.
3. Abutment type. Generally, an abutment can be divided into integral (movable) or non-integral (conventional or stub) types according to its structural characteristics. This factor, to be more accurate, was characterized as closed, spill-through, or perched abutment for a given abutment.

4. Embankment fill material and height. The deformation of the backfill material has been perceived and proven to be one of the crucial factors to cause bridge approach settlement. Helwany et al. (2007) concluded that the causes of vertical and horizontal deformation of the backfill material result from volumetric changes in the soil, lack of compaction, post-construction consolidation settlement, and bearing capacity failure of the embankment soil. It is difficult to retrieve the fill material type based on the current storing system in KYTC due to a large time span. Therefore, the embankment height was merely considered as the variable that reflects the contribution of the embankment fill.
5. Foundation soil type (consistency) and thickness. It is inappropriate to grossly categorize the foundation soil type as silt, clay, sand, or rock because foundation soil is usually a mixture of several types of soil. However, the consistency of the foundation soil could be identified as soft, stiff, very stiff, or hard rather than soil type based on its engineering properties according to testing such as by the standard penetration test. The foundation soil depth usually refers to the elevation difference between original ground and hard rock.
6. Transportation districts. The practice regrading when and how to initiate corrective measures varies from district to district, as well as personnel allocation and maintenance frequency. Additionally, this variable may also include inherent information related to geographic formations within the district, typical contractors/equipment used, etc.

The differential settlement scale was classified by rating the severity of a bump. Two differential settlement tolerances are usually applied for consideration of when to initiate the maintenance work. One is derived from the actual surveying of the differential settlement at bridge ends in the form of inches. The other rating system used to describe the riding quality is the International Roughness Index (IRI). These two rating systems originated from micro level perspectives, while this paper evaluated the riding quality of an approach from macro level perspectives. The macro level methods here refer to techniques that determine the differential settlement scale mainly by maintenance frequency. The settlement levels can be determined by a combination of maintenance frequency, maintenance measures, and sometimes observed settlement. According to the evaluation methods in the macro level perspectives, the differential settlement levels could be classified as minimal, moderate, and severe, which corresponds to the approach performance status good, fair, and poor. Table 1 and Table 2 represent the systems for determining the settlement levels in microscopic level and macroscopic level, respectively.

Table 1. Micro Method in Determining Differential Settlement Levels

Rating	Description	Micro Method	
		Actual Settlement (in.)	IRI (mm/m)
Very good	No bump	0	0~4
Good	Slight bump	~1 inch	5~8
Fair	Moderate bump – Readily recognizable	~2 inch	9~12
Poor	Significant bump – Repair needed	~3 inch	13~16
Very poor	Large bump – Safety hazard	> 3 inch	> 17

Table 2. Macro Method in Determining Differential Settlement Levels

Rating	Description	Marco Method
Good	No bump or minimal/slight bump	No or less than 1.5 inches approach settlement was detected and no maintenance work is needed to correct differential settlement.
Fair	Moderate bump	Settlement ranging from 1.5 to 3 inches was detected and repair work including wedging repair, local patching, and mud jack may be needed. Problem may repeat in periodical inspection reports.
Poor	Severe bump	Settlement more than 3inches was detected and problem lasts for a long time. Transitions have to be resurfaced or approach slabs need to be replaced.

3 DATA COLLECTION AND ANALYSES

One determinant factor for a statistical analysis is the quality of the sample, which depends on the random drawing of the sample and the size of the sample. Approaches used for analyses in this paper consisted of the database Pontis, an internal network server used for storing inspection history of approaches of most of the bridges in Kentucky, from the Kentucky Transportation Cabinet (KYTC). Simple random sampling (SRS) without replacement was used for sorting bridges in 12 districts from Pontis to construct a sample with sufficient population. Six hundred bridges from the inspection history in various project characteristics were selected. Archived bridge plans were used to classify an approach slab as rigid or flexible for selected bridges and other necessary information. The SRS method was used by Statistical Package for the Social Sciences (SPSS) to ensure the unbiased property of the sample. If bridges without inspection history were selected, these bridges would be deleted, and the selection process would be iterated to obtain the anticipated sample size with completed inspection history. This selection process also guarantees that the sample includes approaches from every transportation district.

The primary goal is to estimate the probability of occurrence of each of the three settlement levels as well as to estimate the odds of severity choice as a function of the covariates and to express the results in terms of odds ratios for severity choice given bridge characteristics. The independent variables of interest both consist of count data and categorical (ordinal and nominal) variables. The outcome (response) variable is ternary: minimal, moderate, or severe, and it is assumed as ordinal under the assumption that the levels of approach settlement have a natural ordering (low to high), but the distances between adjacent levels are not consistent. Logistic regression is a type of a probabilistic statistical classification model that is used for predicting the outcome of a categorical dependent variable based on one or more predictors or features. A code sheet for the variables that were included in data analyses for identifying the relationship between each parameter and the dependent variable (settlement levels) is given in Table 3.

Table 3 Code Sheet for the Variables in Model Structure

Variable	Description	Codes/Values	Name
1	Geographical location	District Number 1=District 1 … 12=District 12	DISTRICT
2	Age of bridge approaches	Years	AGE
3	Bridge length	Ft.	LENGTH

4	Bridge width	Ft.	WIDTH
5	Average daily traffic	Number/day	ADT
6	Abutment type	1=closed 2=spill-through 3=perched	ABUT
7	Approach type	1=flexible 2=rigid	APPT
8	Embankment height	Ft.	EH
9	Foundation soil depth	Ft.	FSD
10	Foundation soil consistency	1=soft 2=stiff 3=very stiff 4=hard	FSC
11	Bridge approach settlement	1=minimal 2=moderate 3=severe	SEVERITY

For categorical variables in logistic regressions, dummy variables are created to represent an attribute with two or more distinct categories/levels. For each categorical variable with K levels, K-1 dummy variables should be assumed because one level would be used as a referent (Table 4). Proportional-odds cumulative logit model is one of the most popular models for ordinal data. This model uses cumulative probabilities up to a threshold, thereby making the whole range of ordinal categories binary at that threshold. The response in this study has three levels which are represented by 1, 2, and 3, and the associated probabilities are $\pi 1$, $\pi 2$, and $\pi 3$. For ten independent variables, the following equations were developed for composing a matrix which can be used to compute the probability that each settlement level may occur.

Table 4 Dummy Variables Definition in the Model for Categorical Variables

Categorical Variable	Original	Dummy
DISTRICT	District1=1; District2=2; District3=3; District4=4; District5=5; District6=6; District7=7; District8=8; District9=9; District10=10; District11=11; District12=12	DIS1=1, otherwise DIS1=0; DIS2=1, otherwise DIS2=0; DIS3=1, otherwise DIS3=0; DIS4=1, otherwise DIS4=0; DIS5=1, otherwise DIS5=0; DIS6=1, otherwise DIS6=0; DIS7=1, otherwise DIS7=0; DIS8=1, otherwise DIS8=0; DIS9=1, otherwise DIS9=0; DIS10=1, otherwise DIS10=0; DIS11=1, otherwise DIS11=0; All DIS=0
ABUT	Perched=1; Closed=2; Spill-through=3	ABUT1=1, otherwise ABUT1=0; ABUT2=1, otherwise ABUT2=0; All ABUT=0
APPT	Flexible=1; Rigid=2	APPT1=1, otherwise APPT1=0; All APPT=0
FSC	Soft=1; Stiff=2; Very stiff=3; Hard=4	FSC1=1, otherwise FSC1=0; FSC2=1, otherwise FSC2=0; FSC3=1, otherwise FSC3=0; All FSC=0

$$Logit\frac{\pi_1}{1-\pi_1} = Logit\frac{\pi_1}{\pi_2+\pi_3} = f(x) = 1.533 + 0.000LENGTH + 0.006WIDTH + 0.017AGE + 1.910E(-5)ADT + 0.005EH + 0.002FSD - 1.124DIS1 + 2.992DIS2 - 0.258DIS3 + 21.369DIS4 +$$

$$1.870DIS5 + 0.753DIS6 + 2.234DIS7 + 2.170DIS8 + 1.699DIS9 - 1.236DIS10 + 0.850DIS11 + 0.000DIS12 + 0.570ABUT1 + 0.706ABUT2 + 0.000ABUT3 + 0.529APPT1 + 0.000APPT2 + 0.316FSC1 + 0.601FSC2 + 0.731FSC3 + 0.000FSC4 \quad (1)$$

$$Logit \frac{\pi_1+\pi_2}{1-(\pi_1+\pi_2)} = Logit \frac{\pi_1+\pi_2}{\pi_3} = g(x) = 4.380 + 0.000LENGTH + 0.006WIDTH + 0.017AGE + 1.910E(-5)ADT + 0.005EH + 0.002FSD - 1.124DIS1 + 2.992DIS2 - 0.258DIS3 + 21.369DIS4 + 1.870DIS5 + 0.753DIS6 + 2.234DIS7 + 2.170DIS8 + 1.699DIS9 - 1.236DIS10 + 0.850DIS11 + 0.000DIS12 + 0.570ABUT1 + 0.706ABUT2 + 0.000ABUT3 + 0.529APPT1 + 0.000APPT2 + 0.316FSC1 + 0.601FSC2 + 0.731FSC3 + 0.000FSC4 \quad (2)$$

$$\pi_1 + \pi_2 + \pi_3 = 1 \quad (3)$$

Therefore,

$$\pi_1 = \frac{exp[f(x)]}{1+exp[f(x)]} \quad (4)$$

$$\pi_2 = \frac{exp[g(x)]}{1+exp[g(x)]} - \pi_1 \quad (5)$$

$$\pi_3 = 1 - \pi_1 - \pi_2 \quad (6)$$

The important information of the logistic regression model between settlement levels and predictors is displayed in Table 5. If this model is used to predict the settlement level for a given approach, it can be 60.5% certain to conclude the correct answer. The analysis of the test of parallel lines indicates that the proportional odds assumption is not violated and the method of ordinal logistic regression for identifying the relationship between the settlement severity and the predictors is valid. If the proportional odds assumption was violated, a less restrictive model, such as the multinomial logistic regression, would be implemented.

Table 5 Logistic Regression Model

Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	984.788	.000	0	.
LENGTH	987.497	2.709	2	.258
WIDTH	988.640	3.852	2	.146
AGE	999.009	14.220	2	.001
ADT	994.452	9.664	2	.008
EH	984.984	.196	2	.907
FSD	986.155	1.367	2	.505
DISTRICT	1169.284	184.496	22	.000
ABUT	988.706	3.917	4	.417
APPT	991.444	6.655	2	.036
FSC	987.878	3.089	6	.798

DISTRICT, AGE, ADT, and APPT are statistically significant from the results of the ordinal logistic regression, while the other variables are not. The interpretations of the relationships between these four predominant parameters and the settlement levels are summarized as following:

- District: If a bridge was moved to district one from district twelve, the log-odds of being into a higher settlement level, such as from minimal to moderate or from moderate to severe, would be expected to decrease by 1.124 while holding all other variables in the model constant. The estimated logistic regression coefficients for other districts can be interpreted in the same way.
- AGE: If an approach was to increase AGE by one year, the log-odds of being into a higher settlement level would be expected to increase by 0.017 while holding all other variables in the model constant.
- ADT: If the ADT for an approach was to increase by one unit, the log odds of being into a higher settlement level would be expected to increase by 1.910E-5 while holding all other variables in the model constant.
- APPT: If an approach was changed to flexible from rigid, the log-odds of being into a higher settlement level would be expected to increase by 0.529 while holding all other variables in the model constant.

Additional details of the statistical analysis is described in Zhang et al. (2016).

4 CONCLUSIONS

A study based on statistical methods was carried out to identify the predominant factors that may significantly influence the formation of approach settlement and to figure out how to develop a model for predicting approach settlement levels by quantifying model inputs. A sample was randomly generated with 600 bridges from the internal network server Pontis which is used for storing the inspection history of most of the approaches in Kentucky. The results of the logistic regressions reveal that transportation district, approach age, ADT, and approach type are statistically significant for the relationship between the settlement severity and its causative predictors. From the interpretations of the parameter estimates for the predominant predictors and the variation trends of the relationship between the predicted probability of minimal and each of statistically significant predictor, the following conclusions can be concluded:

- Besides conventional rating systems to evaluate the performance of approaches as transitions, a macro method based on bridge approach inspection and maintenance history determining the differential settlement scale is introduced and used to classify the settlement levels. This method matches well with the micro rating systems, and more readily and conveniently capable of being statistically analyzed if observed/measured settlement is not available.
- There is a positive correlation between approach age and settlement levels, which implies that the probability of a higher settlement level will increase as the age of an approach increases while holding all other predictors constant.
- As average daily traffic for an approach increases, the probability of being in a higher settlement level will increase.
- Flexible approaches tend to have a higher probability of a higher settlement level than rigid approaches.

The model presented in this work is currently being implemented with the Kentucky Transportation Cabinet through a software program that is expected to roll out in the Spring of 2017.

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