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Developing a Statistical Model for Building Settlement Prediction

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Abstract

Texas is well known for its complex soil conditions and corresponding building settlement issues. As a result, it is important to introduce to the students of Construction Science and Management (CSM) program the basic building settlement concepts including causes, consequences and treatments. One important topic is how the design of a building (e.g., height, weight and foundation types) affect building settlement on various types of soil. This requires the ability to calculate building settlement. However, theoretical models that are used in the geotechnical engineering area are too complicated to non-engineering students. This paper develops a statistical model to predict the building settlement. An interactive education tool has also been developed based on the statistical model, which is much easier for CSM students to explore the relationship between building & soil characteristics and building final settlement. The model and the tool will be tailored into the Construction Materials and Methods course at the University of Texas at San Antonio as a part of the *soil and foundation* topic.

Introduction

Building settlement is the vertically downward movement of structure due to the compression of underlying soil because of increased load (Bowles 1988). It is very common in all types of buildings and upon the occurrence, it is very risky to the occupants (Zheng et al. 2009). Many countries have applied building codes with guidelines for allowable settlement including International Building Code (International Code Council 2012), Spanish Basic Building Code (Decree 1988), Bangladesh National Building Code (Ministry of Housing and Public Works 2012) and Chinese Code for Design of Building Foundation (Ministry of Housing and Urban-Rural Development 2011).

Texas is well known for its complex soil conditions (United States Department of Agriculture 2013). In particular, the vertisols that are typical in Southern Texas may create serious building settlement issues (Alhassan and Boiko 2013). At the early phase of a project, construction managers should be able to foresee the final settlement based on the information available including design documents and soil conditions, to calculate the risk. Therefore, it is critical for the students of construction science and management (CSM) program to understand the basic concepts of building settlement, and if possible, the calculation methods.

There are a variety of theoretical models for calculating building settlement. Gasping these models requires background knowledge in the area of engineering and mechanics. For non-engineering students, such as CSM students, it is very challenging. To overcome this difficulty, we developed a settlement prediction model for high-rise buildings using regression analysis.

This model can be used to predict final building settlement based on easy-to-understand building information such as number of stories and height of tower. Without further knowledge about building foundation, CSM students should be able to predict the final building settlement by applying this model. To build this model, a dataset was collected from Chinese construction industry which contains data of 33 high-rise buildings.

This model is designed to be applied in a newly developed Construction Materials and Methods course at the University of Texas at San Antonio. This course focuses on introducing a variety of construction materials as well as related construction methods to the CSM students. An important topic in the syllabus is *soil and foundation*. Properties and common construction issues related to soil will be presented which certainly includes the building settlement phenomenon. By applying the developed model, the CSM students are expected to gain a first-hand expected on the building settlement issues and how different designs (especially foundation designs) may mitigate this issue. The remainder of this paper introduces the developed model.

Background

Theoretical models of settlement prediction

Differential settlement can be detrimental to the structure, depending on the type of structure (Bowles 1988). Settlement in a structure can occur due to various factors such as underground erosion, structural collapse of soil, thermal changes, frost heave, vibration and shocks, landslides, creep and mining subsidence, besides the inherent variable soil conditions (Tomlinson and Boorman 1986). Numerous theoretical models have been developed to predict final building settlement based on the variables above, but few can yield satisfactory results. Briaud and Gibbens (1994) initiated a well-known experiment to test the performance of different settlement prediction models. They selected a spot of homogeneous sandy ground (length 18m × width 12m) on the campus of Texas A&M University, and installed five spread footings. A detailed geological survey and field testing was carried out to collect the actual settlement data. Then in the Prediction Symposium sponsored by the Federal Highway Administration, Briaud and Gibbens invited Geotechnical Engineering experts from all around the world to submit their predictions (Briaud and Gibbens 1994). Finally, 31 prediction reports were received from different countries. The results were extremely disappointed: no one can make a prediction whose error is less than 20%. The ratios of the predicted values to the testing value on the Q25 test were between 0.07 and 1.73. And for the Q150 test, the ratios were between 0.12 and 3.34. On average, the settlement was underestimated by 27 % (Briaud and Gibbens 1994). What's worth noting, among the 31 reports, 22 different theoretical models were used. The Finite Element Method (FEM) and methods proposed by Schmertmann (Schmertmann 1970; Schmertmann et al. 1978) and Burland and Burbidge (Burland et al. 1985) were the most used ones. After the Briaud and Gibbens experiment, scholars including Lee and Salgado (2002), Sargand et al.(2003) and Anderson et al. (2007) have performed similar foundation loading experiments. A conclusion has been made by these scholars that current settlement prediction models have apparent flaws.

Regression Analysis

Regression analysis is a statistical modeling technique for estimating the relationships among variables (Neter et al. 1996). It focuses on finding the relationship between a dependent variable and one or more independent variables. More specifically, a regression model relates Y to a function of X and β.

$$Y \approx f(X, \beta)$$

The approximation is usually formalized as $E(Y \mid X) = f(X, \beta)$. To perform the regression analysis, the form of the function f must be specified. Sometimes the form of this function is based on knowledge about the relationship between Y and X that does not rely on the data. If no such knowledge is available, a flexible or convenient form for f is chosen.

Regression analysis has been widely applied in the area of construction engineering and management (CEM). Applications include production cycle time forecasting (Siu et al. 2013) productivity prediction (Aziz 2009; Chong et al. 2005) and cost estimation (Du and Bormann 2012; Jafarzadeh et al. 2013). In the geotechnical engineering area, regression analysis has also been applied to estimate soil vertical displacement (Chiru - Danzer and Christopher 2000), soil liquefaction probability (Lai et al. 2006; Liao et al. 1988) and displacement of spread footings (Stuedlein and Holtz 2013). Previous works have provided support to the potential application of regression analysis in settlement prediction.

Methodology

A three-step roadmap was followed to develop the statistical model for final building settlement prediction.

- Step 1: Data collection. Building settlement data was collected from multiple job sites in China. This study focused on the settlement prediction of high-rise buildings and therefore 33 high-rise building construction projects in China were investigated. Documentation studies and job site survey were performed to get necessary information. Prior to any statistical analysis, the collected data was also processed initially to deal with the missing values.

- Step 2: Statistical modeling. Two requirements were considered in the development of this model: 1) Accuracy: it should be accurate enough for prediction and 2) Economy: it should be economic enough for practical applications. A regression model was built to predict final settlement of 33 high-rise buildings in China. What's worth noting, a strict statistical modeling procedure was followed to ensure the validity of the model.

- Step 3: Validation. The prediction results were finally compared against the actual observation values. In addition, empirical methods such as FEM (Potts et al. 2001) was also compared to demonstrate the predictivity of the statistical model.

The Statistical Model

Description of Data Set

The dataset used contains 33 samples collected from actual high-rise building construction projects in China, which range from year 2002 to 2008. The response variable (Y) is "Building final settlement (cm)". The explanatory variables (X's) are determined upon the project manager's experience and relevant building codes. Data is obtained from technical documents or based on job site observation. Table 1 summaries the descriptive statistics of the collected data:

Table 1: Descriptive statistics of explanatory and response variables

	Name	*Unit*	*N*	*Min*	*Max*	*Mean*	*Std. De*
Y	Building final settlement	cm	27	0.02	24	4.9726	6.0890
X1	Number of tower stories (aboveground)	#	27	12	41	23.9259	8.2319
X2	Number of tower stories (underground)	#	27	1	3	1.7407	0.7642
X3	Number of annex stories (aboveground)	#	27	0	7	1.5556	1.9677
X4	Number of annex stories (underground)	#	27	0	3	0.6296	0.9260
X5	Height of tower	m	27	38.3	136.1	78.7711	27.0779
X6	Type of building structure	Non-frame:0; frame:1	27	0	1	0.4815	0.5092
X7	Seismic resistance power	6, 7, 8, 9	27	6	9	6.9630	0.8077
X8	Type of ground soil	2, 3	27	2	3	2.4074	0.5007
X9	Coefficient of shear of ground soil	#	25*	0.001	0.1	0.0323	0.0227
X10	Weight of tower	MN	27	102	2464	467.4333	511.4301
X11	Basal area of tower	m^2	27	405	4406	1362.9259	993.1786
X12	Type of foundation	Non-pile:0; pile:1	27	0	1	0.5556	0.5064
X13	Ground bearing capacity	KN	27	87480	2E+06	577984.4444	452928.9732

*: because of the documentation, there are two cases miss X9. In this project, likewise method is employed to deal with the missing values.

Model 0: The base model

In order to check the potential prediction power of linear regression model, we conducted a preliminary analysis. As illustrated in Figure 1, most explanatory variables have linear or nonlinear relationships with Y except X2, X6 and X8.

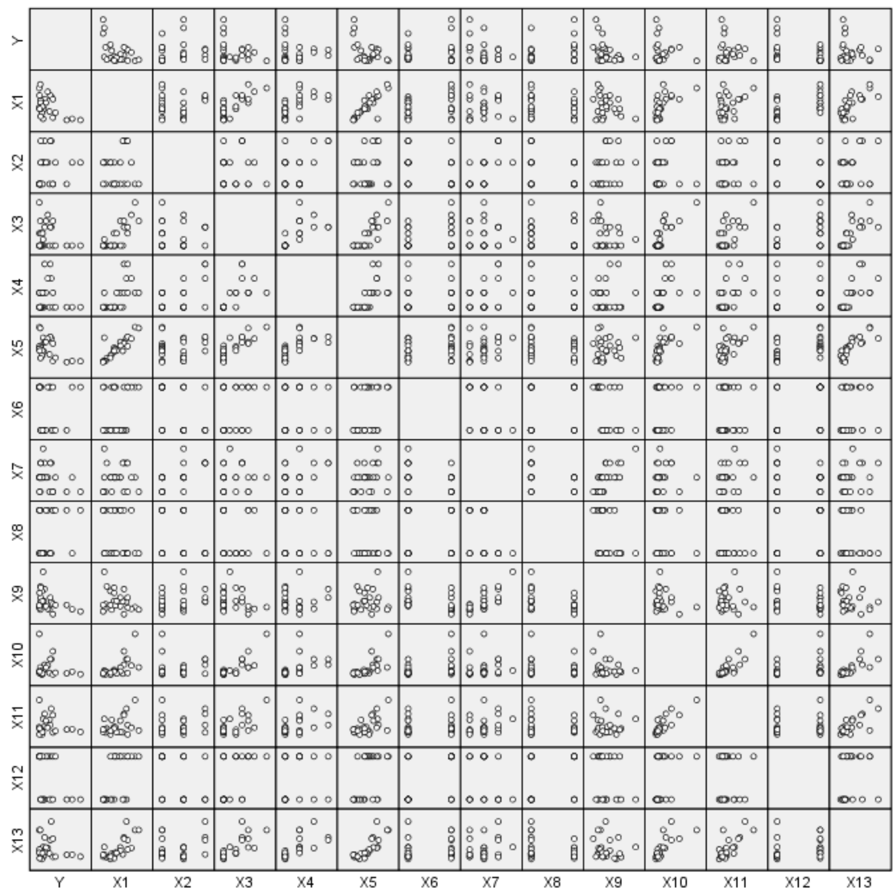


Figure 1. Scatter-plot matrix of the dataset

In order to better understand current data, it is proposed the use of "Enter" method to build a preliminary model. In this preliminary model, all 13 explanatory variables are forbidden to enter into a linear regression model, without any modification:

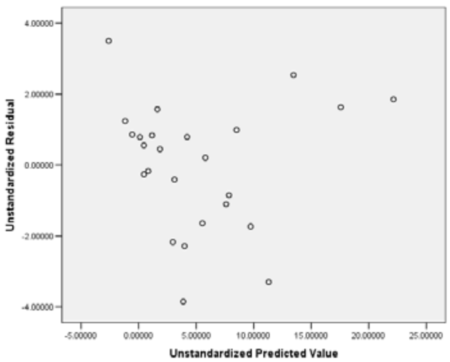
$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + ... + \beta_{13} X_{i13} + \varepsilon_i \quad \text{...} \quad \textit{Model 0}$$

By fitting this model, it is found that linear regression could perform very well in predicting Y based on the current dataset (R^2=0.919 and adj.R^2=0.823). However, it is noticed that the collinearity of this model is serious and some explanatory variables are less useful to the prediction model. As a result, it is decided to select a better model. The new model was expected to have less explanatory variables and several transform might be applied.

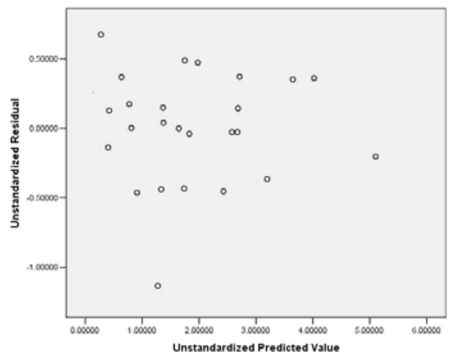
Model 1: Box-Cox transformation

Box-Cox transformation was applied to refine the model. After test, it was found that the square-root transformation $Y' = \sqrt{Y}$ ($\hat{\lambda} = 0.5$) maximize the likelihood function among $\lambda = -2, -1.75, ..., 1.75, 2$. Compared with Model 0, new model effectively reduced the curvature and heteroscedasticity, as shown in Figure 2 (b): Residuals against fitted values of model 1. Therefore, we propose a new first-order model without interaction terms, which is model 1:

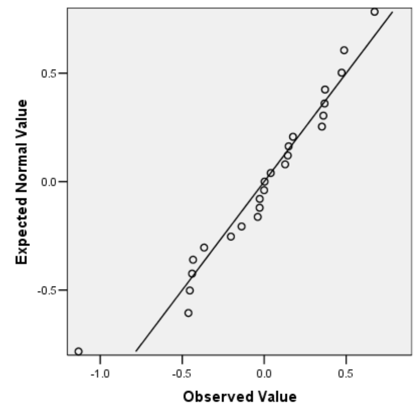
$$Y'_i = \sqrt{Y_i} = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + ... + \beta_{13} X_{i13} + \varepsilon_i \quad .... \textit{Model 1}$$



(a) Residuals-fitted, model 0



(b) Residuals-fitted, model 1



(c) Q-Q plot, model 1

Figure 2. Residual Plot of model 0 and model 1, Q-Q plot of model 1

Model 2: Stepwise procedures

To continue with the model refinement, stepwise procedures are highly preferred rather than all-subset selection due to the large number of subsets ($2^{P-1} = 8192$). Three procedures were followed: Forward Selection, Backward Elimination, Forward Stepwise Regression and compare models by typical selection criteria. The result is listed below.

Procedure	Significance α	p	Variable
Forward	0.10	3	X_5, X_{13}
Stepwise	0.10	3	X_5, X_{13}
Stepwise	0.15	7	$X_1, X_2, X_4, X_7, X_9, X_{13}$
Forward	0.15	8	$X_1, X_2, X_4, X_5, X_7, X_9, X_{13}$
Backward	0.10	8	$X_1, X_2, X_3, X_4, X_9, X_{11}, X_{13}$

Since the results of forward selection, backward elimination, and forward stepwise regression are different, selection criteria were compared to select the best model:

Procedure	p	R^2	Adj.R^2	C_p	AIC	BIC	PRESS
Forward	3	0.4588	0.4096	42.500	2.031	5.688	28.321
Stepwise	3	0.4588	0.4096	42.500	2.031	5.688	28.321
Stepwise	7	0.8575	0.8100	5.190	-21.334	-11.583	11.085
Forward	8	0.8675	0.8129	6.059	-23.146	-13.395	9.865
Backward	8	0.8754	0.8241	5.157	-24.690	-14.939	8.571

It is apparent that the model selected by backward elimination procedure appear to be the most appropriate one since it has largest R^2 , R_a^2 and smallest AIC , BIC and $PRESS$. It is determined as model 2:

$$Y_i' = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_4 X_{i4} + \beta_7 X_{i7} + \beta_9 X_{i9} + \beta_{13} X_{i13} + \varepsilon_i \quad .... \textit{Model 2}$$

One data in figure 2 (b) is far away from the rest points. And in Q-Q plot (figure 2 (c)), the same point is on the left-bottom which weakens the normality. This suggests the existence of an outlier. Therefore, outlier diagnoses are needed. To test for Y outliers and their influence on the model, it is calculated several typical measuring criteria, and it suggest 22nd sample as an outlier ($\alpha = 0.10$).22nd sample's outlier measuring criteria are shown in the following table:

Potential Outlier	Studentized ti	Cook's D_i	$DFFITS_i$	$DFBETAS_k$>1
Y22	-3.436	0.194	-1.593	1.160 (k=3)

By examining measures of influence, it is concluded that removing this outlier from the sample will not significantly affect the fitted regression; however, it will change the coefficient of β_3 much. So it must be carefully discussed whether current model should be fixed or improved further.

Model 3: The final model

After the outlier is removed from the sample, the P-value of hypothesis test $H_0 : \beta_3 = 0$ increased from 0.0742 to 0.2451, which exactly reflects the meaning of $DFBETAS$. This has suggested for authors to search for a better model. Once again, stepwise procedures are preferred with selection criteria details.

Procedure	Significance α	p	Variable
Forward	0.10	4	X_5, X_8, X_{13}
Stepwise	0.10	4	X_5, X_8, X_{13}
Backward	0.10	9	$X_1, X_2, X_4, X_6, X_8, X_9, X_{12}, X_{13}$

The value of selection criteria related to Model 2 is also obtained for comparison.

Procedure	p	R^2	Adj.R^2	C_p	AIC	BIC	PRESS
Forward	4	0.5627	0.5002	95.058	-3.436	1.439	23.286
Stepwise	4	0.5627	0.5002	95.058	-3.436	1.439	23.286
Backward	9	0.9510	0.9265	5.551	-48.167	-37.197	4.170
Model 2	8	0.9219	0.8898	11.007	-38.509	-28.758	5.658

It is obvious that the new model selected by backward elimination appears to be the most appropriate one since all selection criteria prefer it. Therefore, the final model was built:

$$Y_i' = \sqrt{Y_i} = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_4 X_{i4} + \beta_6 X_{i6} + \beta_8 X_{i8} + \beta_9 X_{i9} + \beta_{12} X_{i12} + \beta_{13} X_{i13} + \varepsilon_i \text{ ....Model 3}$$

After fitting, the final regression results were obtained. Where R^2=0.951, adj.R^2=0.925.

Variable	Estimate	Std.Err	t	P	VIF
Intercept	1.98797	0.07037	28.25	<.0001	0
x1	-1.58821	0.12524	-12.68	<.0001	3.18137
x2	0.36107	0.09707	3.72	0.0021	1.84536
x4	0.443	0.12809	3.46	0.0035	3.25806

x6	0.22999	0.08925	2.58	0.021	1.54525
x8	0.23329	0.08788	2.65	0.018	1.47074
x9	-0.80421	0.0932	-8.63	<.0001	1.74883
x12	-0.26254	0.11189	-2.35	0.0331	2.53948
x13	0.71251	0.16699	4.27	0.0007	5.62814

The developed model was applied to predict the final building settlement of 25 high-rise buildings in China. The predictions were compared against the actual settlement data and prediction results of a FEM-based model (Potts et al. 2001). As shown in Figure 3, the regression model yields better results than FEM model. Considering that FEM is very popular in the geotechnical engineering area to deal with the settlement prediction problems, the authors suggestthat regression models outperform theoretical models.

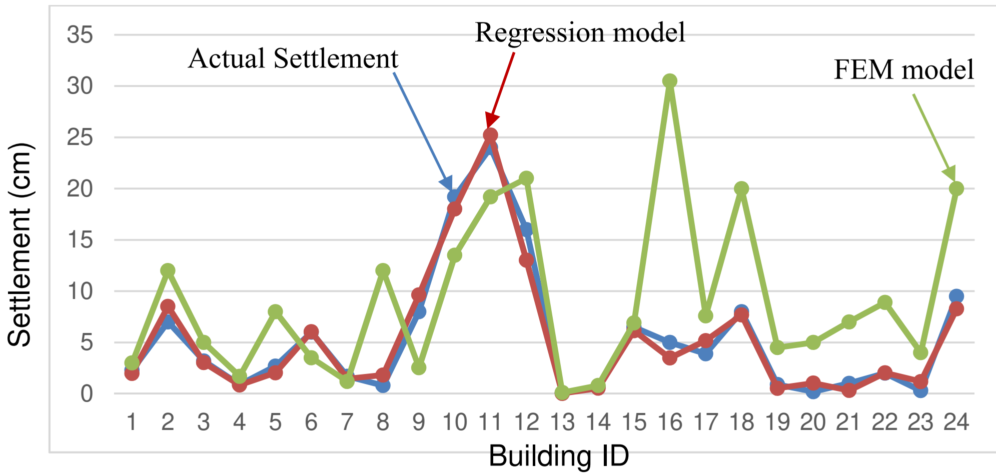


Figure 3. Comparison of prediction accuracy

Model Implementation in a construction material and method course

The Department of Construction Science at of Texas at San Antonio is developing a new Construction Materials and Methods course for the College of Architecture (CoA), as an attempt to extend the scope of an existing construction materials course. The objective of this new course is to provide an introductory overview of the various materials used in construction, as well as common construction methods and building details. Fundamental principles of structural, physical and long-term performance of the various materials will be the main content of this course. Students will also learn about common and specific construction issues that relate to construction materials and methods.

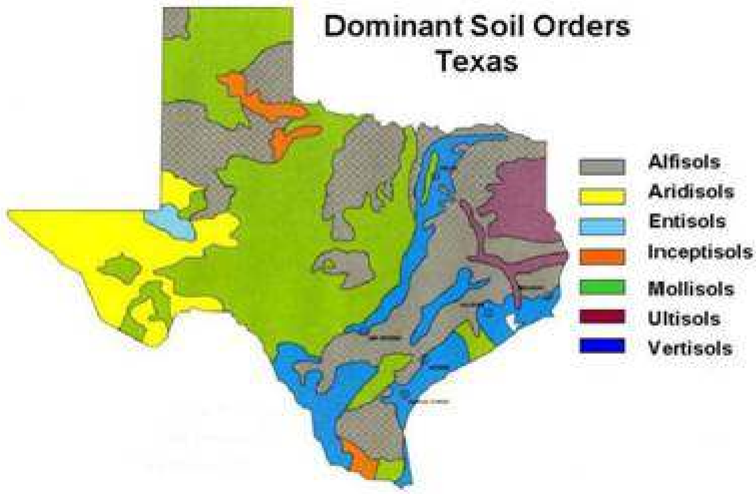


Figure 4. Soil orders in Texas (USDA 2013)

One of the covered topics of this course is *soil and foundation*. Texas is well known for its complex soil conditions. In particular, vertisols are common in the Blackland Prairie in the central part of the state from Bonham south to San Antonio, as shown in Figure 4 (United States Department of Agriculture 2013). Vertisolic soil can create serious building settlement because it swells markedly when moist and shrinks when dry (Alhassan and Boiko 2013). Therefore, building settlement is very common in certain areas of Texas. The developed Construction Material and Method puts particular attention to help CSM students understand the building settlement issues including causes, consequences and treatments. Two unique approaches will be applied:

(1) **Introduction to soil and building foundations.** Settlement highly depends on the properties of soils and the designs of building foundations. Although not a design-concentrated class, this class will explore the relationships between multiple soil types and building foundation methods. First, characteristic soils in and their properties will be introduced such as liquid limit, plastic limit, linear shrinkage, plasticity index, swelling pressure, and bulk density. Then, typical building foundations will be presented with a focus on shallow foundations such as spread footing and slab-on-grade foundation (SOG). Last, the performance and applicability of different foundation methods will be discussed on the soil type basis.

(2) **Hypothetical Building settlement experiments.** Diggelman and McGeen (2003) proposed a research component in a construction material and method course. Their concern was that not all the issues related to construction materials can be taught in the class, and therefore students should be introduced to research tools and skills that they can use to find and evaluate information for themselves. Following their approach, there will be a laboratory exercise where students are requested to predict the building final settlement based on design and soil parameters as addressed in table 1. In the exercise, students will also be asked to perform the following experiments to explore the changes to the predicted final settlement if certain design and soil parameters are altered:

Experiments	*Building design parameters*	*Soil parameters*	*Predicted building settlement*
1	Type of foundation (type 1)	Type of ground soil (type 2)	
2	Type of foundation (type 1)	Type of ground soil (type 3)	
3	Type of foundation (type 2)	Type of ground soil (type 2)	
4	Type of foundation (type 2)	Type of ground soil (type 3)	
5	Type of building structure (0)	Type of ground soil (type 2)	
6	Type of building structure (0)	Type of ground soil (type 3)	
7	Type of building structure (1)	Type of ground soil (type 2)	
8	Type of building structure (1)	Type of ground soil (type 3)	
9	Type of foundation (type 1)	Ground bearing capacity (high)	
10	Type of foundation (type 1)	Ground bearing capacity (low)	
11	Type of foundation (type 2)	Ground bearing capacity (high)	
12	Type of foundation (type 2)	Ground bearing capacity (low)	
13	…		

What's worth noting, students of this new Construction Material and Method course will be diverse, including all majors from the CoA such as architecture and construction science. It is not realistic to require all the students of this course to handle the theoretical models that are used in the geotechnical engineering area. Instead, an Excel spreadsheet tool was developed based on the previous statistical model, as shown in Figure 5. Students will only need to select or type in certain building design parameters (e.g., number of stories) and soil conditions (e.g., types of soil), and then the predicted building settlement value will show automatically. This tool simplifies the settlement calculation remarkably, making the above experiments possible. The final goal is the interactive experiments to explore the influences of these design and soil conditions on the building settlement. For example, in a typical experiment, students may be asked to alter the foundation type while holding all the other parameters fixed. The predicted building settlement values can be compared to evaluate the performance of different foundation designs. In another experiment, students may change the type of soil while holding the foundation type fixed. In this way, influence of soil type on building settlement can be visualized. We expected this type of interactive experiments to become an effective education approach in teaching complex engineering topics.

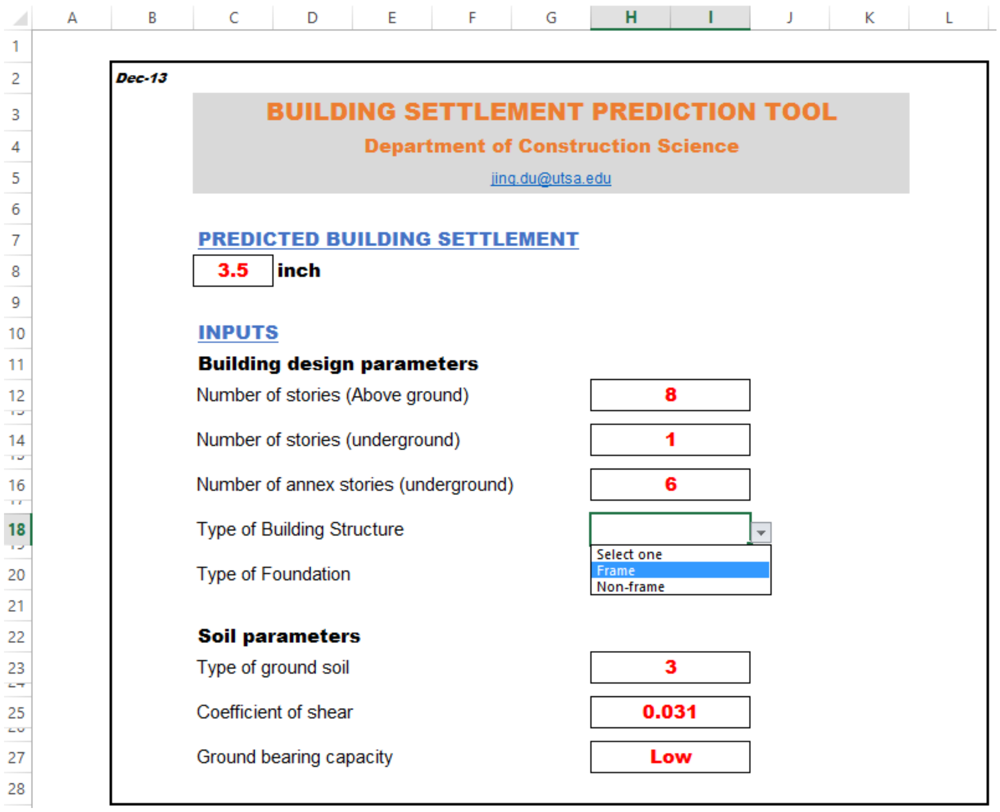


Figure 5. Snapshot of the developed tool

Conclusion

In certain areas of Texas the building settlement issue is serious due to the unique properties of soil. CSM students in these areas need to grasp better knowledge about building settlement issues to prepare for their career. One important step is the ability to calculate building final settlement given certain design and soil parameters. However, most settlement prediction models that are being applied in the geotechnical engineering area are too complicated for non-engineering students. This paper developed a regression model for the settlement prediction based on 33 high-rise building data in China. The result can be easily embedded in an Excel Spreadsheet tool. This tool will be applied in a new constriction material and method class at of Texas at San Antonio to allow students to perform a set of interactive experiments. CSM students should be able to directly apply the developed model without further knowledge in the geotechnical engineering and mechanics area. The developed model and the interactive tool are expected to facilitate the teaching of building settlement issues.

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