

Soil Structure Interaction of Integral Abutment Bridges

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Abstract

Integral Abutment Bridges (IAB) are defined as simple or multiple span bridges in which the bridge deck is cast monolithically with the abutment walls. Integral abutment bridges are becoming very popular due to its good response under seismic loading, low initial costs, elimination of bearings, and less maintenance. However the main issue related to the analysis of this type of structures is dealing with soil-structure interaction of the abutment walls and the supporting piles. The interaction between the structure and the adjacent soil media is essential in analysis, and gives a better prediction of the structural behavior compared to the analysis of the structure alone. Large varieties of soil constitutive models have been used in studies of soil-structure interaction in this kind of structures by researchers. This paper is an effort to review the implementation of finite elements model which explicitly incorporates the nonlinear soil and linear structural response considering various loading condition and finite element models.

Keywords: Integral Abutment Bridges, Soil-structure Interactions, Finite Element Analysis, Constitutive Models

1. Introduction

Studies conducted on conventional bridges, highlight expansion joints as being critical element affecting the maintenance-free lives of structures and include recommendations that specific studies be conducted on the performance of joints in-service or an alternative solution (Vasant C. Mistry 2002; Edward et.al 1996). The alternative solution would be bridges with minimum numbers of joint or joint-less bridges. The most common minimized number of joints or joint-less bridge in practice is integral bridge or commonly known as integral abutment bridge.

Integral abutment bridges (IAB) are defined as simple or multiple span bridges in which the bridge deck is cast monolithically with the abutment walls. Integral abutment bridges are becoming very popular due to its good response under seismic loading, low initial costs, elimination of bearings, and less maintenance (Arsoy et.al 1999; Faraji 2001; Murat Dicleli et.al 2004; Youssef et.al. Vasant C.Mistry 2002; Arsoy et.al 2004; R.Jayaraman 2001; Jimin et.al 2004; Jimin et.al 2008; Mohd Salleh et.al 2003). It exists as a single span or a multiple span bridge which a movement system composed primarily of abutments supported on flexible piles (Murat Dicleli et.al 2004).

Despite all the advantages of integral bridges (Figure 1), especially the elimination of expansion joint problems, they are not free from problems in service (Arsoy et.al 2004). The main issue related to the analysis of integral abutment bridge is dealing with the soil-structure interaction of the abutment walls and the supporting piles under various loading condition(S Faraji et.al 2001; M Dicleli et.al 2004). The behavior of the structural components including the piles can either be linear or nonlinear depending on the amount of the applied forces. The behavior of the soil on the other hand is nonlinear. This complication generates a nontrivial and interesting problem to handle since the responses of the different elements are interdependent; therefore any attempt to analyze the different parts of the bridge independently will involve considerable assumptions and approximations (Petros et.al; G.LEngland et.al. 2001; RJ Lock 2002).

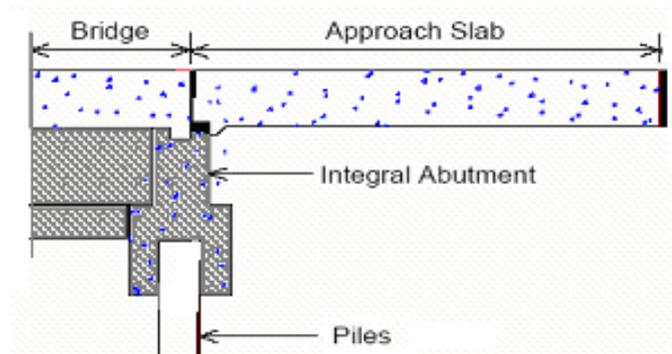


Figure 1: Integral Abutment Bridge Configuration

Therefore, extensive studies on the nature and behaviour of the integral abutment bridges in line with soil-structure interaction are inevitable (M Dicleli 2004). It has been noted by M.Arokiasamy et.al (2005), that there is still no comprehensive model available to analyze the behaviour of integral abutment bridges. Susan Faraji et al. (2001) suggested that the future works on these types of bridges would help to streamline the design process for better performance.

Thus, the primary objectives of this study are to investigate the behaviour of structural elements of the integral abutment bridge under various load cases through implementation of finite elements model which explicitly incorporates the nonlinear soil and linear structural response

considering various loading condition and finite element models. Secondly to conduct finite element analyses to identify the significance of the differences and similarities between the spring constants analysis, linear analysis and nonlinear analysis.

2. Description of the Model

A finite element analysis was carried out to understand the behaviour of integral abutment bridges. Figure 2 shows the description of the models used in this study (Thevaneyan 2005). A thorough understanding on the general behaviour of integral abutment bridge is needed to provide a basis for expanding the understanding on the behaviour of integral abutment bridges for further effects. The studies were performed to investigate the inter-related behaviour of deck/girder, abutment, and the piles under various loading conditions considering typical backfill soil properties.

Two models were developed to carry out these studies where the first model follows the description given in figure 2 and in the second model the backfill soil modelled as Winkler Spring. The interactions between the bridge system and the approach system were modelled by finite element method. The analyses were performed using the spring constant, linear and non-linear analysis.

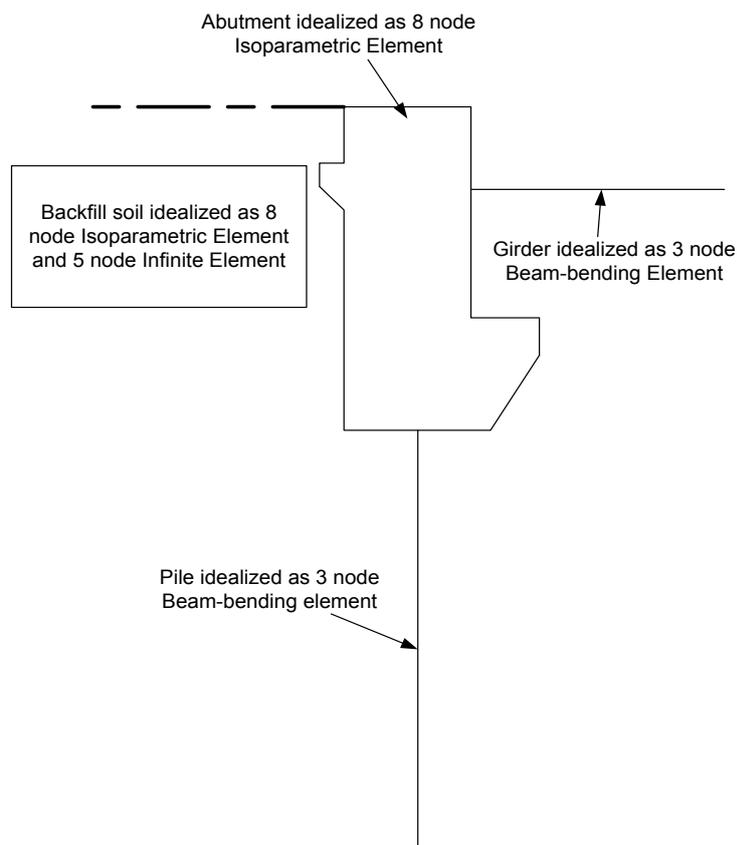


Figure 2 Model used in this study

2.1 Selection of Bridge Dimension

A finite element analysis of a typical integral bridge of 42-m long, 11.5-m wide integral bridge was performed to gain an insight into the interactions between the superstructure, the abutment, the approach fill, the foundation piles, and the foundation soil. The bridge consists of seven equally spaced 'I' 20 pre-stressed concrete girders, a 180-mm thick concrete deck and 100-mm thick asphalt concrete, resting on 3.46-m high 1.3-m thick abutments. The abutments are supported by six 1000-mm diameter bored piles equally spaced. These dimensions and the geometry of the bridge were selected based on a typical bridge drawing with some minor changes in dimension to simplify the analysis.

2.2 Material Model Parameter

Two-dimensional (2-D) plain strain finite elements were used to model the materials comprising the abutment and soil. Two-dimensional beam bar elements were used to model the superstructure and piles. Linear-elastic behaviour was assumed for the abutment, superstructure and piles with a Young's modulus of 27 GN/m². For the soil profile, an actual soil profile from a Malaysian Geotechnical consultant was chosen for the purpose of this study. Four types of soil (see Table 1) were modelled for the purpose of this study. The soil profile is to be considered as a non-linear property.

2.3 Non-Linear Parameters of Soil

It should be noted at the outset that the hyperbolic model has some significant shortcomings with particular regard to modelling the way soil is loaded in the IAB problem. Specifically, cyclic loads are known to be an important aspect of soil behaviour in IAB problems.

An important rheological aspect of cyclic soil loading is the accumulation of plastic (non-recoverable) strains due to the inherent hysteretic behaviour of soil (Noorzaei et al. 1993). The hyperbolic model only approximately replicates hysteretic behaviour. Therefore, from the beginning of this study it was known that certain aspects of the anticipated soil behaviour would not be well modelled. However, it was felt that this would not detract from the overall qualitative and quantitative correctness of the results of this study.

Unlike many engineering materials the constitutive law of soil is complex and nonlinear in nature. There are several nonlinear models such as bi-linear, K-G model, hyperbolic, hypolastic and hyperlastic model are reported in the literature (Noorzaei et.al 1993). The non-linearity of the soil mass has been represented by using the Duncan and Chang approach. The non-linear parameters of the soil being used in this study are; c , Cohesion; ϕ , Friction angle (degrees); R_f , Failure ratio; E_i , Young's modulus (Initial); p_a , atmospheric pressure; σ_1 , maximum principal stresses, E_{tan} , Initial tangent modulus and n , Young's modulus exponent. An experimental laboratory test using Triaxial Compression Tests produced results as shown in Table 1, which were used in this study.

Table 1: Material Parameters used in this Study

Element	Material	Material Properties							
		Linear Property		Non-linear Property					
		E (kN/m ²)	ν	n	Pa	E _{tan}	R _f	c	Ø
<i>Girder</i>	<i>Concrete</i>	27000000	0.35						
<i>Abutment</i>	<i>Concrete</i>	27000000	0.35						
<i>Pile</i>	<i>Concrete</i>	27000000	0.35						
<i>Soil</i>	<i>Clay</i>	25000	0.3	0.98	101	290	0.846	10	4
	<i>Silt</i>	45000	0.3	0.995	101	200	0.88	22	19
	<i>Silt + Sand</i>	50000	0.35	0.9	101	200	0.875	21	19
	<i>Silt + Gravel</i>	65000	0.35	0.81	101	230	0.885	25	16

2.4 Loading

Integral bridges are subjected to dead and live loads (primary loads), and additional secondary loads due to creep, shrinkage, thermal gradients, and differential settlements. An adequate design needs to consider both vertical loads [due to dead and live loads] and secondary loads. Burke (1993) promotes standardization of abutment-superstructure continuity connections such that the abutments need only to be designed for vertical loads for a wide range of applications. It has been stated by Porter et.al (1992), that simple abutments are better than the complex ones. The loading for this study has been determined according to BD 37/01.

3. Validation of Model

This study was conducted using numerical analysis with MS FORTRAN program. An existing 2D nonlinear finite element program written using MS FORTRAN was used with some modifications. Zeinkiewicz and his co-worker initially developed this program in 1972. Assoc. Prof. Dr. Jamaloddin Noorzaei (UPM) has further modified this program since then in 1991 by including several finite, infinite and interface elements. This program was validated for its accuracy with simple theoretical examples of analysis of a thick cylinder subjected to internal pressure and displacement and rotation using beam bar element were carried out. The figures 3 and 4 below show the comparison of the theoretical results to FEM analysis.

The analysis in this project focused on the vertical displacement of the girder, the horizontal displacement of the pile and the stress distribution on the abutment.

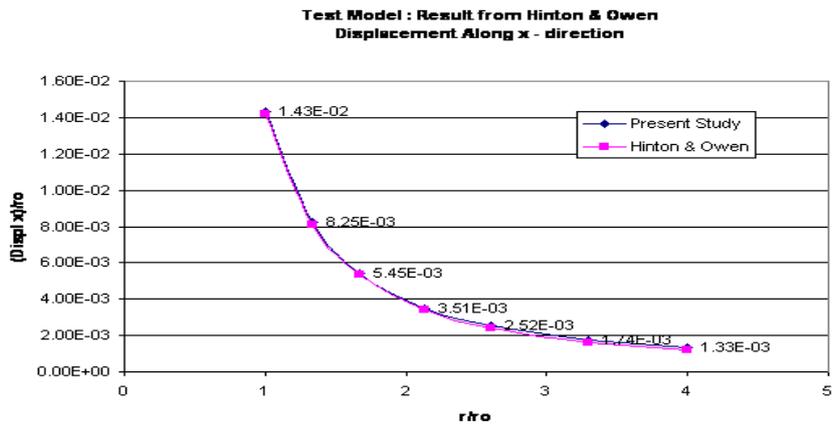


Figure 3: Test Model 1

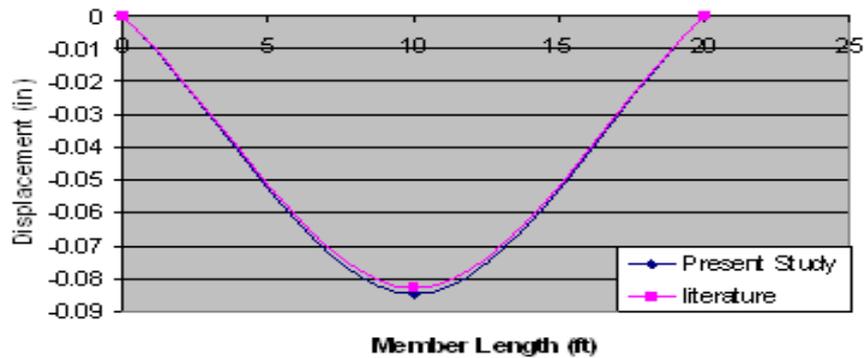


Figure 4: Test Model 2

4. Results and Analysis

Finite element analysis is a popular means to predict and analyze the behavior of a variety of structural and non-structural elements (Robert J. Melosh, 1990). Finite element methods have been adopted for this study since it should provide results to a high degree of accuracy. Finite element methods are also cost effective compared to full scale instrumentation and laboratory experiments. Three fold analyses namely spring constant analysis, linear analysis and nonlinear analysis were carried out in this study.

4.1 Spring Constant Analysis

The behaviour of the girder when using different values of spring constants does not vary significantly when compared to the different load cases as shown in Figure 5. Change in the depth of the pile also does not influence the deflection of the girder. The behaviour of the pile for the different values of spring constant does vary, but not significantly as in the different loading conditions (Figure 6).

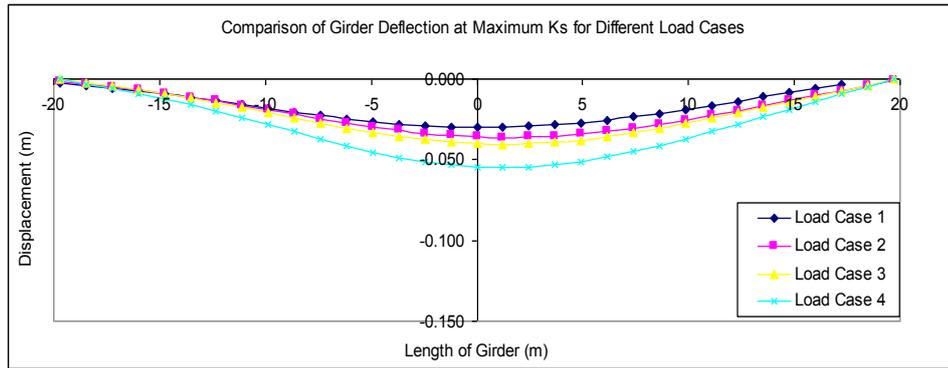


Figure 5: Superstructure displacement for various load cases in Winkler Spring Model

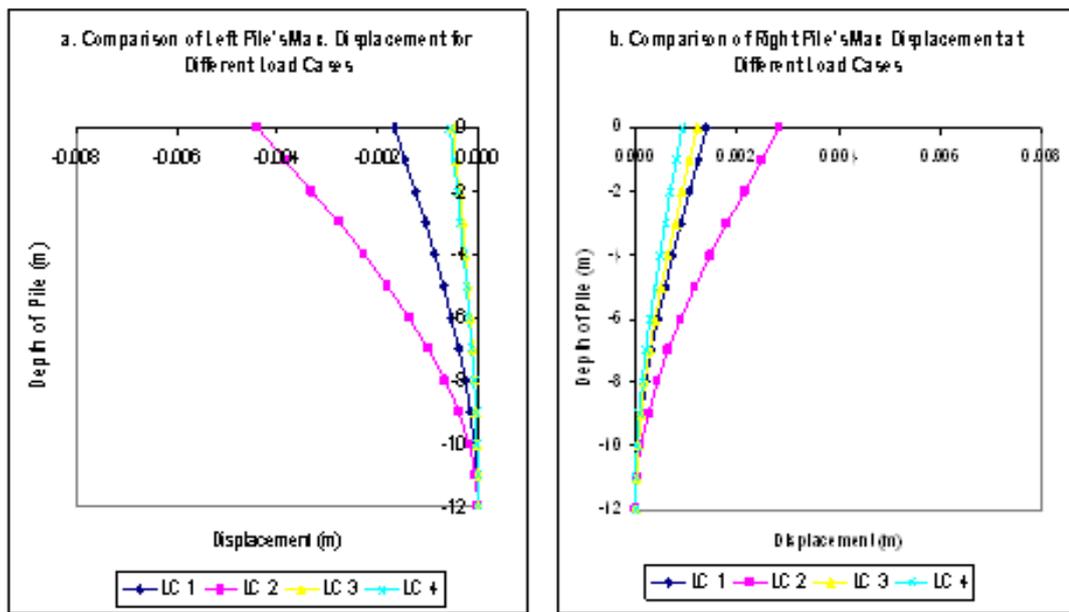


Figure 6: Pile displacements for different Load Cases

To better understand the behaviour of the abutment. Stresses in the x-direction, y-direction and xy-direction were plotted. It was noted that where the change in geometry occurred the concentration of the stresses was higher (Figure 7). This was due to the change in boundary condition as well. The stresses were also found to be higher at the joints, i.e. the joint between the abutment and the girder. There is also a significant concentration of stresses at the joints between the abutment and the pile. This shows that extra care needs to be taken in analysis and design as well as construction of these joints, obviously.

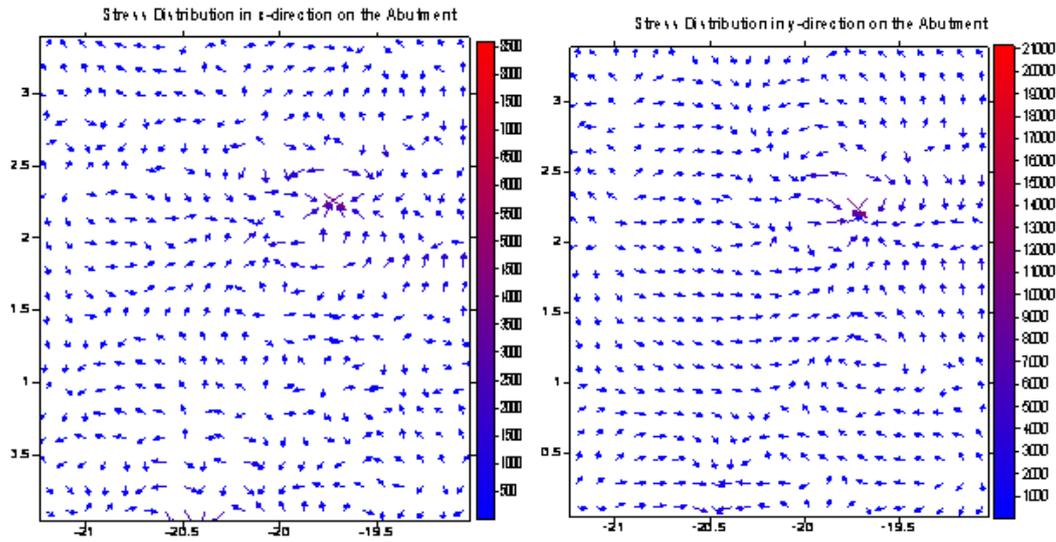


Figure 7: Stress distribution on abutment

The overall behaviour of the structure using the spring constant is very much influenced by the loading and the boundary conditions. However, the analogy of the overall behaviour of integral abutment bridge analyzed using soil spring constants is similar to many previous studies i.e. Arsoy et.al 1999, Faraji et.al 2001. Figure 8 shows the analogy of the structural behaviour for an integral abutment bridge.

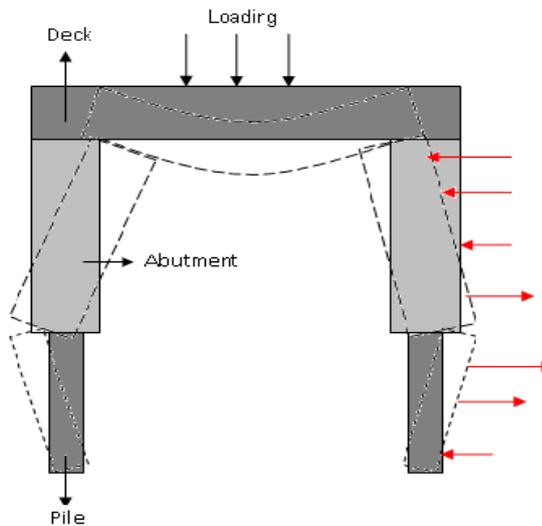


Figure 8: Analogy of Integral Abutment Bridge behaviour (Arsoy, 1999)

4.2 Linear and Nonlinear Analyses

Linear and nonlinear analyses were done similar to the spring constant analogy. This is an attempt to further understand the behaviour of integral abutment bridge. The finite element model, composed of an eight-node quadrilateral element, three-node beam bending element and an infinite

element were used. The model consists of 626 elements with 1815 nodes. Soil and abutment were modelled as eight-node elements and pile and girder were modelled as beam bending elements. The very outer part of the soil was modelled as a five-node infinite element.

The behaviour of the girder in both linear and nonlinear analyses for different loading conditions varies significantly compared to spring constant analysis. Figure 9 shows the comparison of superstructures displacement for load case 4 for three analyses models. Nonlinear analysis model recorded highest displacement approximately four times displacements of Winkler Spring analysis model.

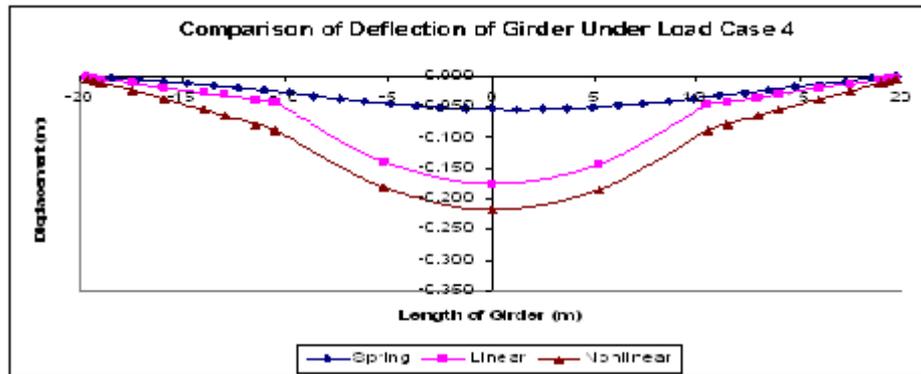


Figure 9: Deflection of girder for load case 4s in different analyses models

The behaviour of the pile for different loading conditions also varies significantly compared to the spring analogy. The displacement of the pile in the linear and nonlinear analysis is very much different compared to the of spring analogy. The overall behaviour of the structure is influenced by the loading, soil parameter and the boundary conditions.

Table 2: Pile displacement for 3 different conditions

Load Case	Pile Displacement (mm) (Left)		
	Spring	Linear	Nonlinear
1	-0.37	-1.32	-9.7
2	-0.43	-2.40	-11.9
3	-2.1	-3.12	-13.0
4	-3.4	-5.62	-15.7

4.3 Parametric Studies

A parametric study on the influence of the depth of pile on the deflection of the girder shows that the deflection of the girder does not change significantly with an increase in the depth of the pile. In fact, the deflection of the girder under different depths of pile is almost of the same. Figure 10 shows the results obtained for this parametric study.

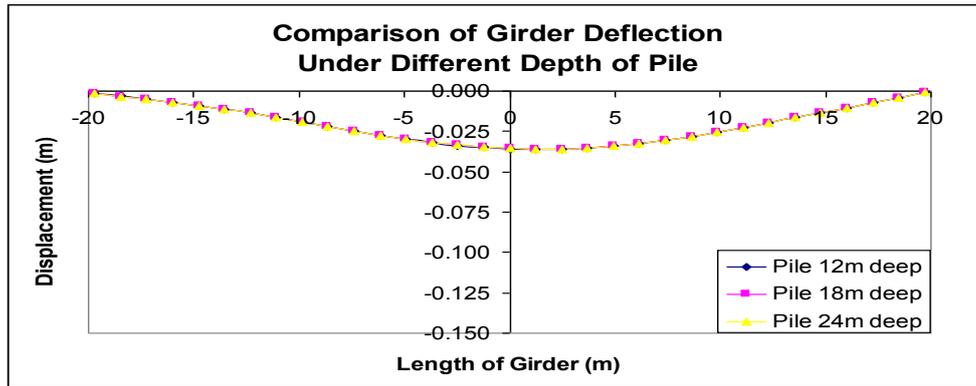


Figure 10: Comparison of Girder Deflection for Different Depth of Pile

5. Summary

Based on the findings of a literature review and finite element analyses conducted using 2D model for spring constant analogy, linear and nonlinear categories for four load cases, the following major conclusions are drawn:

- Since there are no expansion joints and bearings in an integral bridge, the abutment, its characteristics, boundary conditions, design and construction would have a greater influence on the overall behaviour of the integral bridge compared to any other components. Therefore, a thorough study needs to be carried out on the behaviour of this component.
- There is no significant effect of stresses to the abutment due to vertical load. The behaviour of abutment may be greatly affected by thermal load and soil pressure; this has to be verified by further studies. The reaction of the soil behind the abutment wall and next to the foundation piles has been the biggest uncertainty in the analysis and design of an integral abutment bridge [Faraji et.al. (2001)].
- In current analysis and design practice the correlation between the temperature variation and the magnitude of earth pressure is generally neglected [Murat Dicleli, 2000]. This leads to the need for further studies to establish the correlation between these two influencing factors.
- The depth of the pile has no significant influence over the behaviour of the girder. However from the literature it is known that the depth of the pile influences the behaviour of the abutment which has a direct effect on the behaviour of girder. Further studies are required to verify the actual relation between the depth of the piles and the behaviour of the girder.
- Nonlinear analysis differs significantly in magnitude compared to linear analysis. Nasim K. Shattarat et.al. (2007) stated that linear analysis methods may be conveniently used to prioritize cases under which nonlinear analysis should be conducted. Therefore, study using nonlinear analysis should be extended for a realistic prediction of structural behaviour of integral abutment bridges.

5.1 Present Study

Presently, study on extended soil-structure interaction in Integral Abutment Bridges being attempted by the researcher using General Structural Analysis (GSA) Version 8.5 and Oasys SAFE is being conducted by first author.

Three models (Thevaneyan, 2011) were developed to study the behaviour of a single span Integral Abutment Bridge. These models were analyzed for various load cases for preliminary studies under linear static analysis. The result of these preliminary analyses agrees well with the reported work. Further studies need to be carried out considering soil nonlinearity and gapping effect of the soil structure interaction to establish a comprehensive finite element model to analyses the behavior of single span integral abutment bridges. It is noted that most of present work is based on linear elastic models. Nonlinear analysis, especially on material nonlinearity is one area where extensive study is needed for better understanding of the integral abutment bridges' behavior. To achieve this objective, numerical model needs to be established and calibrated for the basic bridge, and a parametric study need to be conducted to expand the results of the numerical model to general cases under different variables.

Correlation of earth pressure and the effect of temperature variations and transfer of stresses between the different parts of the structure under the application of these loading conditions are other concerns (Murat Dicleli, 2000). Since, most of the research work done in the USA or the UK is specific to their own environmental conditions, a study will be attempted to study the effect of Asian environmental conditions on the behavior of an integral abutment bridge by researcher.

6. Concluding Remarks

Based on the findings of a literature review and finite element analyses, the following major conclusions are drawn:

- Integral abutment bridges perform well with fewer maintenance problems than conventional bridges. Without joints in the bridge deck, the usual damage to the girders and piers caused by water and contaminants from the roadway.
- Backfill soil's nonlinear parameters have greater influence over the behavior of the abutment and the pile.
- There is no significant effect of stresses to the abutment due to vertical load.
- The results of the pile horizontal displacement compared well to the model presented by Arsoy (1999 and 2000)
- The depth of the pile has no significant influence over the behavior of the girder. However from literatures it is known that the depth of the pile influences the behavior of the abutment.
- Nonlinear analysis differs significantly in the magnitude compared to the linear analysis. However the orientation of the behavior is same.

Acknowledgements

Major part of this work was carried out during post graduate study at University PUTRA Malaysia by the first author under the supervision of Assoc. Prof. Dr. Jamalodin Noorzaei.

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