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STUB TYPE INTEGRAL ABUTMENT – BACKFILL SOIL RELATIONSHIP

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Abstract: Integral bridges have become one of the most common types of joint-less bridge construction, certainly over the last three decades. Simple integral abutments, such as stub-type abutments supported by piling, have been found to perform well and recommended for widespread use. Cost-effective system in terms of construction, maintenance and longevity becomes their principal advantages, derived from the elimination of expansion joints and bearings. Elimination of joints from bridges creates a significant soil-structure interaction behind the abutment. A 2D finite element analysis was performed on a typical integral abutment bridge using OASYS SAFE to investigate the complex interactions that exist between the stub-type integral abutment bridge and the backfill soil. Where possible, these results were validated with existing field data. The results from this analysis are believed to help answer two of the most debated issues with respect to stub-type integral abutment bridge-soil interaction analyses. Firstly, it is clear, and now possible, that a reliably accurate soil constitutive model is used in the analysis/design. The Mohr-Coulomb soil model was found to realistically represent the soil behaviour. Secondly, the research may suggest that cyclic movements / loads may not significantly influence the overall behaviour of integral abutment bridges especially in a small daily temperature changes.

Keywords: *Integral Bridges, stub-type, Mohr-Coulomb; soil model, finite element analysis*

1.0 Introduction

Integral abutment bridges, also known as integral bridges, have become one of the most common and popular joint-less bridges in practice over the last three decades. The principal advantages of integral abutment bridges are derived from the absence of expansion joints and bearings in the deck (the abutments are rigidly connected to the bridge beams and deck with), making them very cost-effective systems in terms of construction, maintenance, and longevity (Arsoy, 2000; Huang *et al.*, 2008; Arockiasamy *et al.*, 2004; Faraji *et al.*, 2001). An integral bridge generally comprises a deck slab, approach slab, abutment, wing walls, piers and foundation/piles. These elements are divided into two categories; substructure, comprising abutment and piles and superstructure generally comprising deck slab/girder, wing wall and approach slab (see Figure 1).

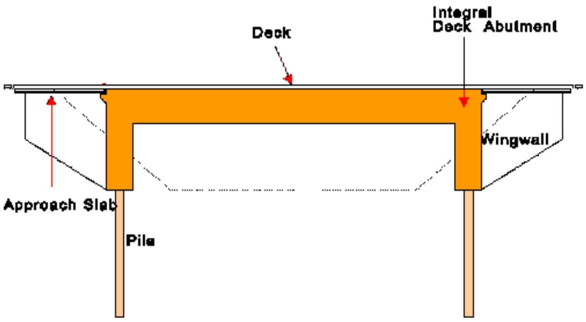


Figure 1: Integral Abutment Bridge and its component

Integral abutment bridges are built are designed to rely on the interaction between the structure and primarily the surrounding soil to accommodate lateral forces caused by thermal expansion and/or contraction. Since there are no expansion joints and bearings in an integral bridge, i.e. the abutment, its characteristics, boundary conditions, design and construction will potentially have a greater influence on the overall behaviour of the integral bridge compared to any other components of the bridge.

The North American Study Tour Report has identified and recommends eight types of abutments; they are ***a***. full height frame, ***b***. embedded wall abutments, ***c***. embedded wall with reinforced earth, ***d***. spread footing on reinforced earth wall, ***e***. stub-type at top of side slope, ***f***. stub-type abutment, ***g***. vertical wall with semi-integral and ***h***. stub-type abutment with semi-integral joint which are suitable for various situations (Cooke, 2003). However, simple integral abutments, such as stub-type abutments ((f) above) supported by piling, have been found to perform well and have been recommended for widespread use (Faraji *et al.*, 2001; Dicleli & Albhaisi 2004c; Huang *et al.*, 2008; Hong *et al.*, 2003; Cooke, 2003). In this work, a stub-type abutment, supported by circular concrete piles, which are commonly used in Malaysia, has been investigated.

2.0 Objective and Scope of Work

The effect of temperature on the behaviour of integrated abutment bridges during their working life are significant due to the absence of expansion joints, which would normally reduce the stresses / movements induced by the thermal loads. The thermally induced lateral movement of the structural components is opposed by the soil behind the abutment; the soil next to the piles; and the internal pier foundation (only for multi-span bridges). The magnitude and the nature of the forces that are developed in the soil are directly related to the magnitude and the nature of the displacement of the structural elements and the strain in the soil. Consequently, this is a challenging soil-structure interaction problem; any prediction of behaviour ideally requires a model for the whole bridge, including the surrounding soil system that will account for the integral bridge responses.

Attempts have been made previously by many researchers to analyse the different parts of the bridge independently; these attempts involved considerable assumptions and approximations. However, little 'whole bridge' modelling has been performed. Thus, the primary aim of this study is to develop a comprehensive finite element model of a 'whole bridge' capable of providing a reliable and realistic representation of the soil-structure interaction. In doing so, it also aims to investigate the complex interactions that exist between the stub-type integral abutment bridge and the backfill soil. Where possible, these results were validated with existing field data.

Huang et. al. (2004 and 2008) have highlighted that the main issue related to the analysis of integral bridges is dealing with the behaviour of the structural elements of the bridge under environmental conditions. According to Arsoy (2000) and Faraji *et al*. (2001), the significant soil-structure interaction that takes place behind the abutment and piles has remained largely undetermined. This complication generates an interesting problem to handle since the responses of the different elements of the integral bridge are interdependent.

The interaction between the structural components (i.e. abutment and foundation) and the soil medium has the potential to alter considerably the actual behaviour of the structure. The properties of the soil medium which can influence the behaviour of the structure are: - soil density, internal friction angle, soil-structure friction and backfill angle (Paul *et al.*, 2005). As stated above, due to the absence of expansion joints and/or bearings, the behaviour of an integral abutment bridge depends on the interaction of its structural components with the surrounding soil medium. It is, therefore, vital that an appropriate constitutive model is used to represent these soils.

In general, modelling of the structural elements, i.e. superstructure and foundation piles in isolation are rather simple and straightforward when compared to modelling the structure in combination with the soil medium. While structures are usually satisfactorily modelled as linearly elastic, homogeneous and isotropic materials, modelling of soils is extremely complex. The complex behaviour of soil due to its heterogeneous, anisotropic and nonlinear force–displacement characteristics (Sekhar & Roy, 2001) need to be accounted for in its modelling. The need for appropriate material and structural modelling of integral bridges has also been highlighted by Jaafar *et al.*(2003).

3.0 Soil-structure Interaction

Soil behaviour is complex and highly nonlinear. The performance of integral abutment bridges are known to be affected by the interaction between the backfill soil and the abutment, where relative displacement occurs and the soil stress-strain behaviour is activated due to the lateral earth pressure. The nonlinear behaviour of soil has important consequences with respect to the soil-structure interaction problem (Jardine *et al.,* 1986). However, for analysis purposes, it is generally assumed that the soil behaves in a linear elastic manner. In the analysis of integral abutment bridges, consideration of earth pressures induced by the expansion and contraction of the superstructure is very important. These thermally induced movements of the bridge superstructure mobilize the earth pressures which range from passive to active, behind the abutments and foundation piles (Arsoy *et al.,* 2004).

In general, the earth pressure at a particular point in the soil is a function of the effective stress at that point multiplied by the earth pressure coefficient (K) which changes from the full active pressure coefficient (K_a) to full passive pressure coefficient (K_p). Terzaghi, initially, presented the relationship between earth pressure and the movement of the earth retaining structure (see Figure 2).

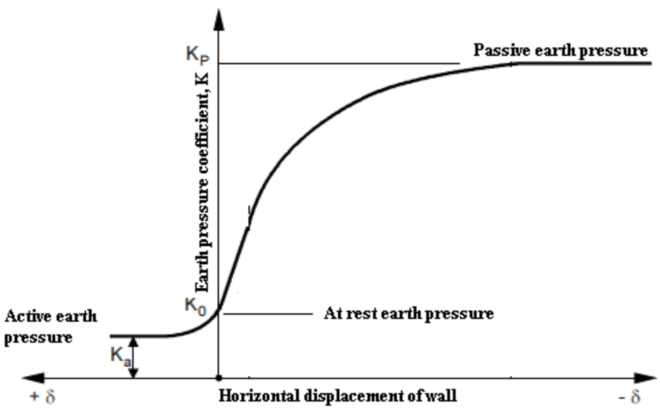


Figure 2: Earth pressure coefficient-horizontal displacement relation (Kerokoski, 2006)

The earth pressure coefficient varies according to the superstructure movement. When the structure expands, the backfill will experience passive pressure (P_P). At rest, the backfill will exhibit at rest pressure (P_o) and when the superstructure contracts, active pressure (P_a) will be induced in the backfill (see Figure 3). It has been determined that the passive earth pressure has the greatest influence on the behaviour of structural elements (Arsoy *et al.*, 2004; Huang *et al.*, 2004; Paul *et al.*, 2005). Therefore, in this study, the corresponding lateral passive earth pressure has primarily been considered.

However, the effect of active and at rest pressure was also considered to further understand the influence of these pressures on the overall behaviour of integral abutment bridges.

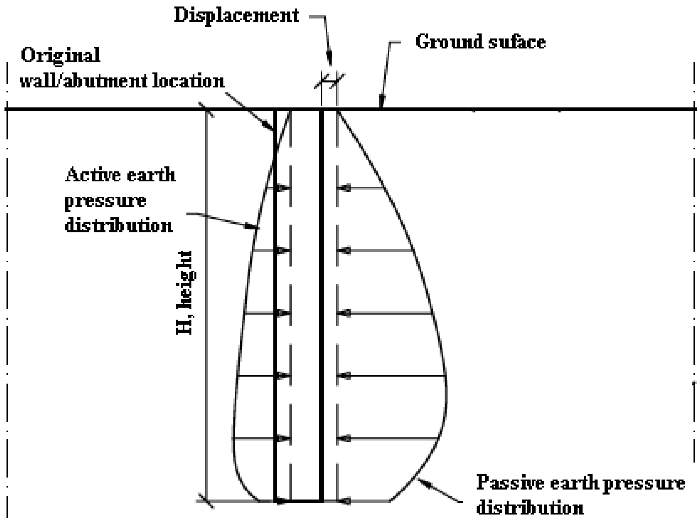


Figure **Error! No text of specified style in document.**: Lateral earth pressure due to structure movement (Kerokoski, 2006)

3.1 Constitutive model

Bloodworth *et al*. (2012) stated that the understanding of the factors that increase the lateral earth pressures relative to the structural movements remain primitive, although, integral abutment bridges are now frequently used around the world. Reliable modelling of the abutment-backfill system is critical and the assumptions made for the nonlinear stiffness of the soil have a significant effect on the response and performance of the structural components (Faraji *et al*., 2001). Therefore, lateral earth pressures need to be reasonably accurately predicted to prevent any additional and unforeseen forces in the structure. It is anticipated that a reasonably accurate lateral earth pressure can be achieved by representation of the real behaviour of soil properties using an appropriate soil constitutive model. Soil constitutive models are simplified idealizations of soil characteristics and an essential feature for practical applications (Sekhar & Roy 2001).

Interestingly, a survey conducted in the USA shows that some agencies do not consider soil pressure for abutments of certain sizes; other agencies do not consider the earth pressure at all in their design (Hong *et al.,* 2003; Hassiotis & Xong, 2007). This is, therefore, an area of interest of this study and to assess the significance of earth pressure, a realistic representation of lateral earth pressure theory needs to be used.

In this study Mohr-Coulomb and Duncan-Chang hyperbolic soil constitutive models were used. This selection was based on the attributes considered in the literature and the capability of the software package. The Duncan-Chang hyperbolic soil model or the Mohr-Coulomb soil model, are incorporated within the OASYS SAFE finite element software, and are hereafter referred to as SAFE DC Model and SAFE MC Model, respectively.

4.0 Methodology and Description of the Model

A high degree of accuracy and cost effectiveness compared to full scale instrumentation and laboratory experiments has made finite element methods (FEM) to be appropriate for this study (Dicleli, 2000; Faraji *et al.*, 2001; Desai & Abel, 1987). Besides that, thermal analysis and parametric studies are difficult to perform experimentally. Full-scale instrumentation of a structure to study the thermal effect is also time-consuming and expensive.

Further, the general principles and use of finite element methods are also well documented (Desai & Abel, 1987; Zienkiewicz & Taylor, Brauer, 1988). Although FEM is a powerful tool to study the mechanics of materials and structures, care must be taken to allow for any inaccuracies arising from unrepresentative or erroneous input data and numerical limitations while interpreting the results (Desai & Abel, 1987; Brauer 1988). Therefore, it is desirable to calibrate the finite element model qualitatively and quantitatively with real data. Where possible, the results of this investigation were validated with existing field data. Initially, a 2D finite element analysis was performed on a typical integral abutment bridge using OASYS SAFE to investigate the complex interactions that exist between the stub-type integral abutment bridge and the backfill soil. The OASYS SAFE model was developed from the OASYS GSA model.

The bridge was modelled as a 2D plain strain problem in OASYS SAFE, with symmetry around the centreline of the bridge. The finite element mesh used in the analyses is shown in Figure 4. As can be seen in Figure 4, the mesh is finer around the abutment, pile foundation and near the boundaries. A thin layer element interface was also considered between the backfill and the pile/abutments.

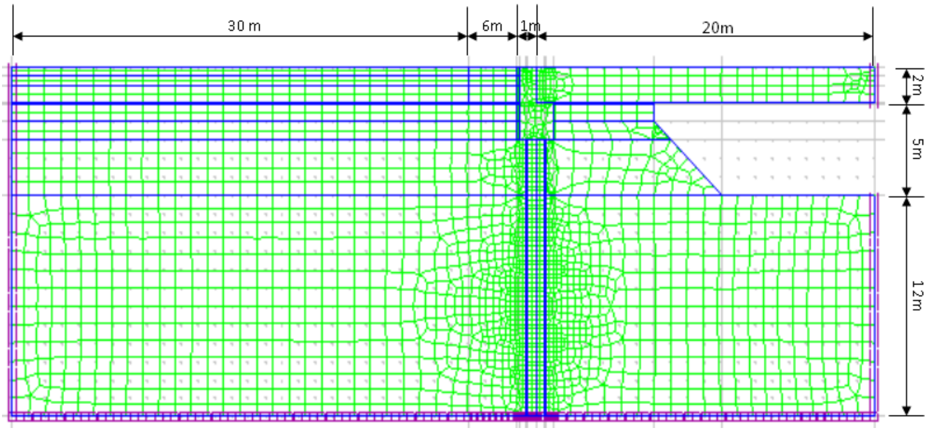


Figure 4: Finite Element Model of Integral Abutment Bridge

4.1 Selection of Bridge Dimension

The bridge geometry used for this study matched an existing bridge built in the State of Perak, Malaysia in 2004 (Thevaneyan, 2005). It is a typical bridge with a 42m span and an 11.5m wide deck. The bridge consists of seven equally spaced 'I' 20 pre-stressed concrete girders, a 180mm thick concrete deck and 100mm thick asphalt concrete resting on 4m high, 2m thick abutments, which are supported by six equally spaced 1000mm diameter bored piles, as shown in Figure 5. In the structural models, the equivalent width of the abutment and slabs is set equal to the spacing of the girder and pile. Full composite behaviour between the slab and girder was assumed. The loading for this study was in accordance with BD 37/01 (BD37/01, 2001).

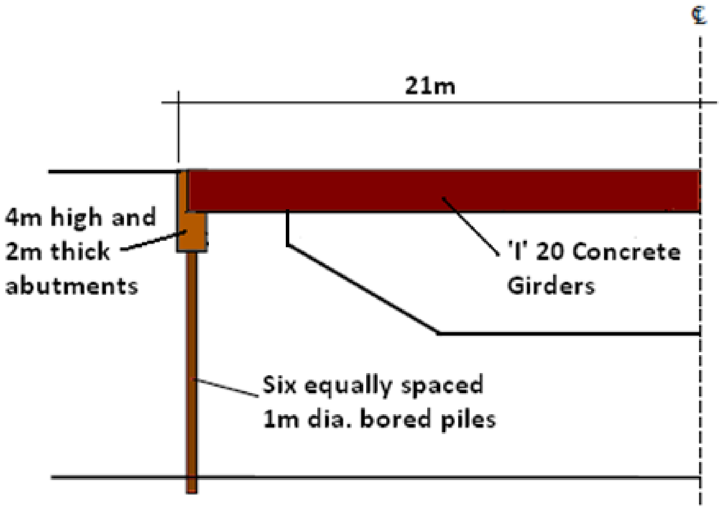


Figure 5: Structural Geometry of the Modelled Integral Abutment Bridge

The analyses focused on the behaviour of a single span Stub-type Integral Abutment under either imposed traffic load; gravity load; thermal load and a combination of imposed and thermal load. The models were developed after much deliberation and consideration given to convergence and sensitivity studies. These models were validated qualitatively and quantitatively with reported and published research works (Arsoy, 2000; Faraji *et al.*, 2001; Thevaneyan, 2005; Rollins & Cole, 2006; Thevaneyan & Forth, 2011).

4.2 Material Model Parameter

Studies by Faraji *et al*. (2001) and Dicleli & Albhaisi (2004c) showed that the backfill stiffness has a significant effect on integral abutment bridge performance. Since the behaviour of the soil is nonlinear, the hyperbolic Duncan Chang soil constitutive model properties are used to simulate the behaviour of the backfill soil and foundation soil. As well as the hyperbolic Duncan Chang model, the Elastic Mohr Coulomb model was also used in this study to try and gain further understanding of the influence of the soil constitutive model chosen on integral abutment bridge performance.

Two sets of material properties were used in this study. The first set of selected soil material properties (Table 2) are for the purpose of model validation, based on the previously conducted studies and published research (Rollins & Cole, 2006; Anoosh *et al.*, 2007). The second set of soil material properties for this study was based on an actual soil profile from a Malaysian Geotechnical consultant. The soil was modelled using both the Duncan-Chang Hyperbolic and Mohr-Coulomb properties. Four types of soil were used for the purpose of this study. Table 3 summarises the soil material properties used in the study.

This study adopted a common and typical bridge superstructure cross-section that consisted of precast, pre-stressed concrete girders with a cast-in-situ concrete slab, with modulus of elasticity of $30GN/m^2$, and cast-in-situ concrete bank-seat abutments with modulus of elasticity of $27GN/m^2$. A common integral abutment bridge pre-bored concrete pile with modulus of elasticity of $33GN/m^2$ was assumed for the pile foundation. Table 1 summarises the bridge structural material properties

Table 1: Linear Properties of Integral Abutment Bridge

Element/ Material	Properties: Modulus of Elasticity, E (GN/m^2)	Poison ratio, ν
Superstructure		
Girder and Slab – Precast, prestressed concrete girders with cast-in-place concrete	30	0.3
Substructure		
Abutments - Cast-in-place concrete	27	0.3
Piles - Pre-bored concrete	33	0.3

Table 2: Set of Soil Properties for Validating Purpose (Rollins & Cole, 2006; Anoosh *et al.*, 2007)

Type	γ (kN/m^3)	m %	ν	c (kN/m^2)	φ	R_f	n	n_{ur}	K	K_{ur}
Clean Sand	18.4	13.4	0.3	3.83	39	0.98	0.81	0.81001	200	530
Silty Sand	19.2	14.6	0.35	31.0	27	0.97	0.81	0.81001	100	500
Fine Gravel	20.8	5.5	0.3	4.0	34	0.98	0.81	0.81001	200	550
Coarse Gravel	23.2	4.0	0.3	12.0	40	0.95	0.80	0.80001	200	550

Table 3: Material Parameters used in this Study

		Material Properties							
		Linear Property		**Non-linear Property**					
Element	**Material**	**E (kN/m^2)**	**ν**	**n**	**Pam**	**E_t**	**R_f**	**C**	**∅**
Girder	Concrete	27000000	0.35						
Abutment	Concrete	27000000	0.35						
Pile	Concrete	27000000	0.35						
Soil	Clay	25000	0.3	0.98	101	290	0.846	10	4
	Silt	45000	0.3	0.995	101	200	0.88	22	19
	Silt + Sand	50000	0.35	0.9	101	200	0.875	21	19
	Silt + Gravel	65000	0.35	0.81	101	230	0.885	25	16

γ- *Bulk unit weight ;m- moisture content;* ***ν***- *poison ratio;* ***c***- *cohesion;* ***φ*** *- friction angle;* ***R_f*** *- Failure ratio;* ***n*** *- stress index of proportionality; n_{ur} - n for unload/reload; K – constant for proportionality, K_{ur} – K for unload/reload*

4.3 Validation of Model

Models based on previous research (Table 2) were developed by considering an approach suggested by Ellis & Springman (2001) based on a typically constructed integral abutment bridge whereby the piles are first installed to support the stub-type abutments. Ellis & Springman (2001) incorporated 3D effects in a 2D plane strain section. The structural behaviour of a pile group is represented by an equivalent sheet pile wall. For the purpose of the validation, field testing by Rollins & Cole (2006), who investigated the cyclic lateral load behaviour of a pile, pile cap and backfill, was used. In this investigation, models using Oasys SAFE were developed to replicate the field testing (Table 2) reported by Rollins & Cole (2006).

Models considering backfill lengths of between 10m to 150m were developed to identify an appropriate length of backfill soil (i.e. the external boundary position of the soil) such that the boundaries would not compromise the influence of the soil on the structural model. A backfill length of 30m was determined. Generally, finite element computational efficiency is influenced by the number of elements considered. Therefore, reduced bandwidth through a renumbering process (Oasys, 2009) within the software was used to select a suitable number of elements to represent the soil. Figure 6 shows the model. The material properties and backfill soil types considered in this model are shown in **Error! Reference source not found.**.

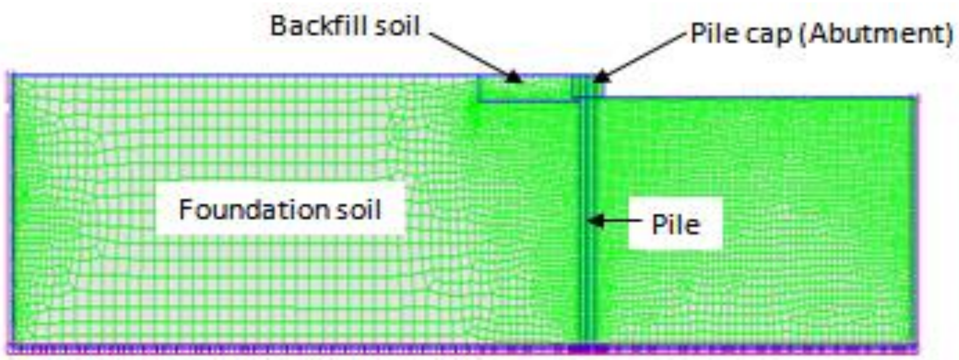


Figure 6: Verification Model

Table 4: Properties of Validation Model

Parameter	Description
Pile height	12.2m
Pile size	1.1m diameter
Pile cap height	1.12m
Pile cap Width	2m
Soil type	Clean sand, silt-sand, fine gravel, coarse gravel

One of the main concerns at this stage was how to determine an appropriate soil model to replicate the soil behaviour accurately. Therefore, the effects of different soil constitutive models for clean sand were compared to the field results obtained by Rollins & Cole (2006) to identify an appropriate soil model. On the basis of this study (Figure), it was determined that the Duncan-Chang Hyperbolic soil model best represented the soil behaviour. Figure 7 also showed that the Mohr-Coulomb soil model represented the soil behaviour reasonably well up to 8mm of displacement. This indicates that at any laterally induced movement less than 10mm, the Mohr-Coulomb soil model which requires fewer parameters compared to Duncan Chang soil model could be used to represent the soil behaviour.

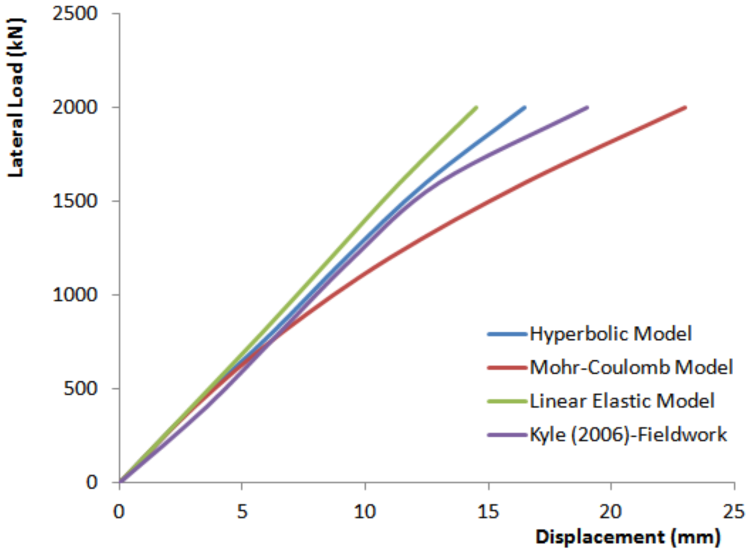


Figure 7: Lateral Load-Displacement Profile for Clean Sand

Analyses were done for four different types of backfill soil parameters as presented in Table 2, using Oasys SAFE. In the analyses, the lateral load was applied in a similar manner to how it was applied during the field tests. In the field tests, the pile cap was incrementally loaded laterally to achieve a predetermined maximum displacement of 25mm. In the numerical analyses, the maximum loading was predetermined and applied in 10 increments. Displacements of the pile cap at the point of load application were recorded at each increment. The results of the numerical analyses were plotted (i.e. load-lateral displacements) for all four types of backfill soil (Figure 8 – 11) and compared with the field test results (Rollins & Cole, 2006).

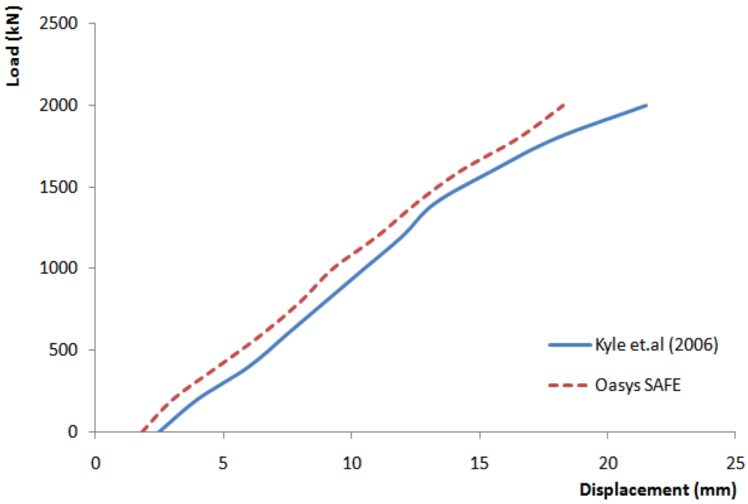


Figure 8: Load-displacement for Clean Sand

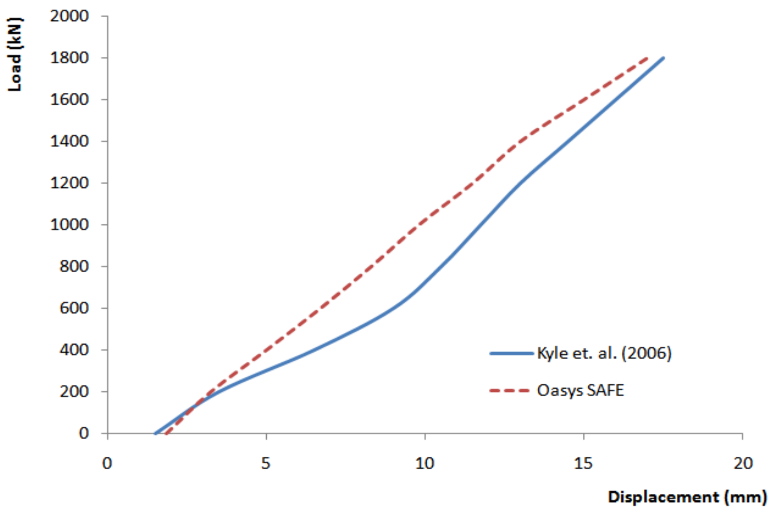


Figure 9: Load-displacement Silt-sand

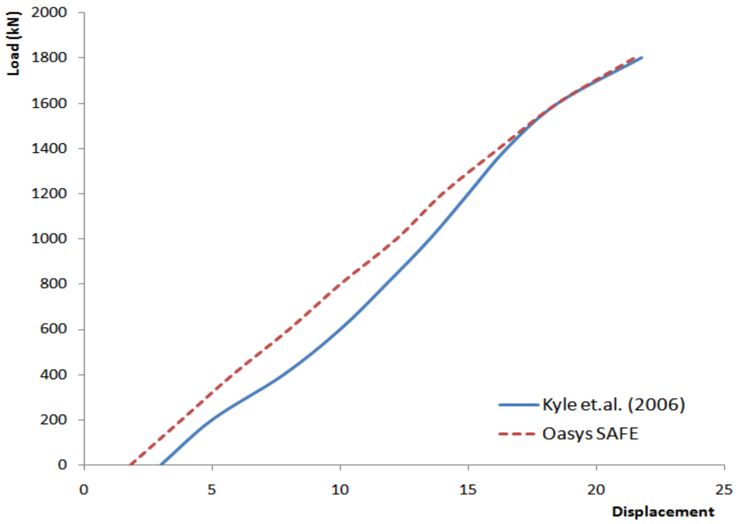


Figure 10: Load-displacement Fine gravel

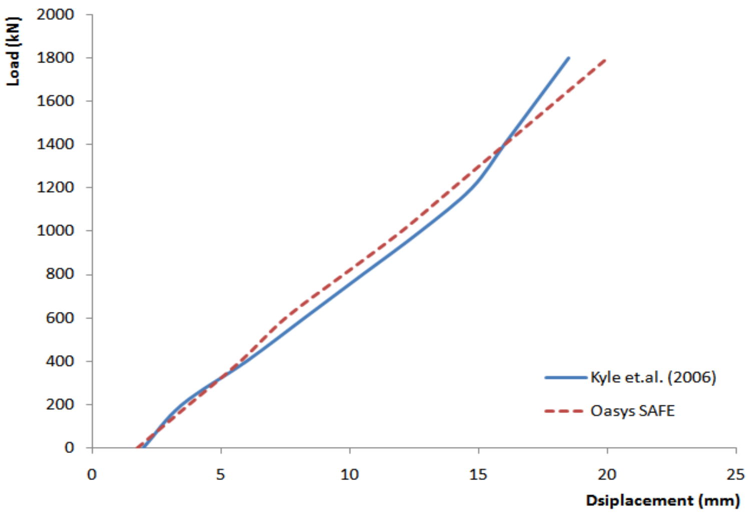


Figure 11: Load-displacement Coarse Gravel

The numerical analyses agree reasonably well with the field test results (variability falls within 10%). Simplification of the field test conditions in the numerical analyses could explain the differences. It was also observed that the numerical models yield typically linear load-displacement results.

Cyclic analysis was then carried out to further ascertain the competency and reliability of the model. The pile was laterally loaded in 10 increments for 10 cycles. Again, the results of the numerical analyses (see Figure 13) were found to compare reasonably well with the field test results (see Figure 12) from Rollins & Cole (2006). The cyclic loading suggested that the changes due to the cyclic loading of the pile/pile cap were generally gradual with no abrupt change in the behaviour after the second cycle.

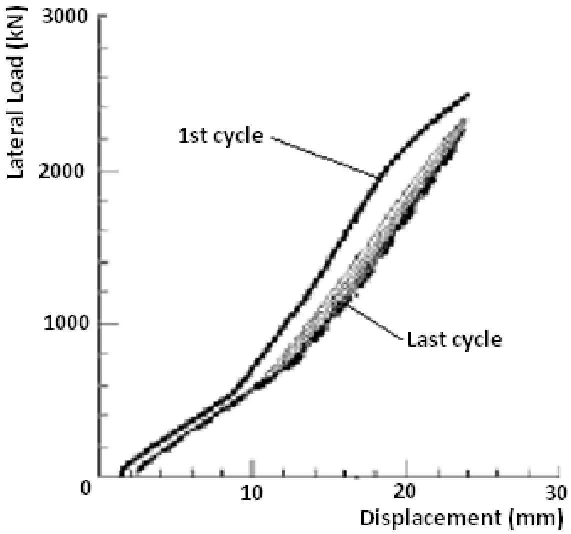


Figure12: Lateral load-displacement curve for fieldwork cyclic loading (Rollins & Cole, 2006)

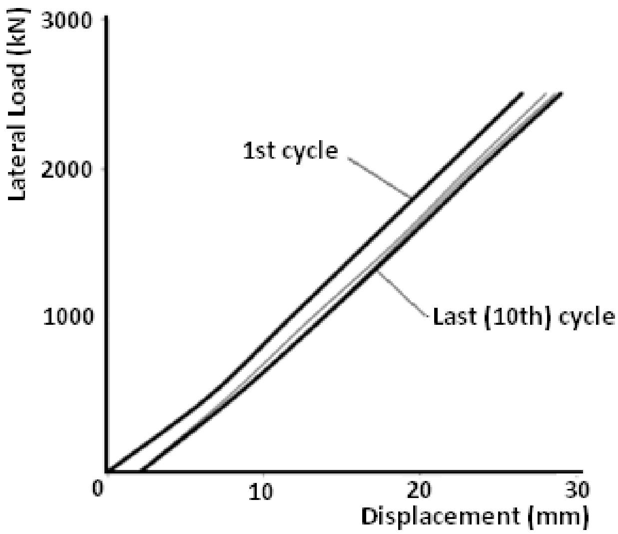


Figure 13: Lateral load-displacement curve for numerical analysis cyclic loading

5.0 Results

A series of finite element analyses were performed to study the relationship between stub-type integral abutments and backfill soil. The lateral load applied represents the forces exerted on the abutment from the superstructure, i.e. as the temperature increases or decreases the superstructure expands or contracts applying a lateral load.

The primary aim of this study was to assess the effect of varying backfill properties (backfill soil types) derived using two different soil constitutive models on the backfill earth pressure distribution. As mentioned previously, the two soil constitutive models used in this study are the Mohr-Coulomb (SAFE MC) and the Duncan-Chang hyperbolic soil (SAFE DC). It was also desirable to identify the relationship between the lateral displacement of the stub-type abutment for a given geometry and the backfill pressure for various backfill soil types. The effect of cyclic loading on the backfill pressure and the stub-type abutment displacement with regard to various backfill soil types was also investigated.

5.1 Stub-Type Integral Abutment-Backfill Pressure Relationship

Lateral loads were applied via the bridge superstructure (these lateral loads are thermally induced by an increase in temperature i.e. expansion). The SAFE DC and SAFE MC Models were used to examine the interaction of the stub-type integral abutment with various soil types (see Table 3), specifically, the effect of soil type and soil constitutive models on the backfill pressure behind an integral abutment.

Figures 14 and 15 demonstrate the effects of different soil types (derived using two soil constitutive models (SAFE DC and SAFE MC)) on the backfill soil pressure behind the stub-type abutment resulting from a lateral load. The pressure profile is a typically classical triangular shape, with increasing pressure with depth of abutment.

A comparison between the backfill pressure shape and intensity predicted by the SAFE MC and SAFE DC models (Figure 14 and 15, respectively) was made and as anticipated, the SAFE MC model predicts a slightly higher backfill pressure compared to that predicted by the SAFE DC model. This is consistent with the published literature. Variations in maximum backfill pressure ranging from between 1.5% (for clay) and 13% (for silt-gravel) were observed between the SAFE MC and the SAFE DC models. This variation can be attributed to the parameter considered in their respective constitutive models. The variations between the soil properties, very loose to very dense were found to affect the results in these two soil constitutive models.

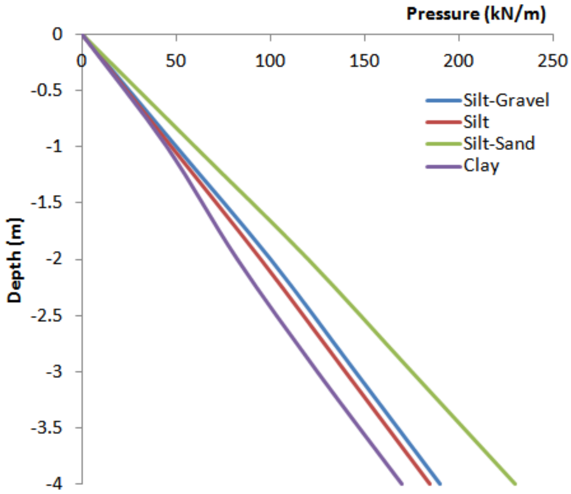


Figure 14: Backfill pressure distribution for different backfill/foundation soil using Mohr-Coulomb Soil Model.

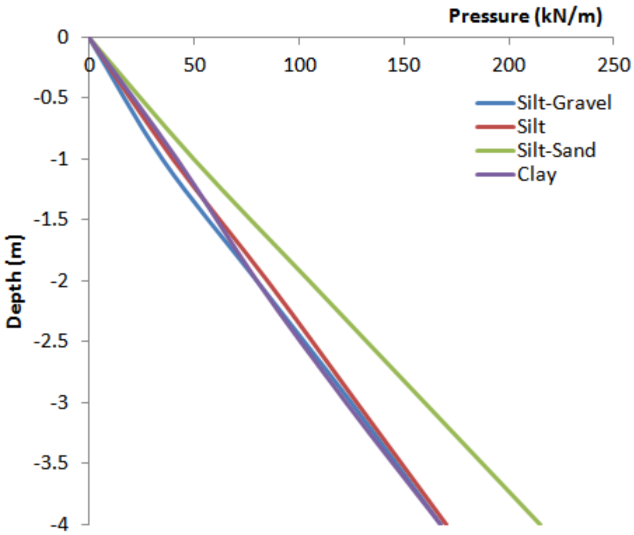


Figure 15: Backfill pressure distribution along the abutment for different backfill/foundation soil using Duncan-Chang hyperbolic Soil Model.

Both soil constitutive models predict higher lateral earth pressure values for the silt-sand soil at the bottom of the stub-type abutment (i.e. 28% higher in the SAFE DC model and up to 35% higher in the SAFE MC model). These were found to be consistent with the density of the soil considered. This result may also indicate that silt-sand soil is significantly stiffer compared to the other types of soil, which may potentially result in a greater resistance to the integral abutment displacement.

Varying lateral load effects on the backfill pressure profile for silt-sand was evaluated using both soil-constitutive models in the SAFE software. The abutment was subjected to a varying lateral load, which resulted from an increase in temperature from 6^0C up to a maximum of 30^0 C in the superstructure (approximately 5 degrees C per increment). Figures 16 and 17 show the shape and intensity of the backfill pressure due to the varying lateral load as predicted by the SAFE MC and the SAFE DC soil models. The models show a steady linear increase in pressure with depth. The value at 4m is similar for both models; the SAFE DC model pressure is less linear. It is clear that there is a significant effect on the backfill pressure due to temperature increments.

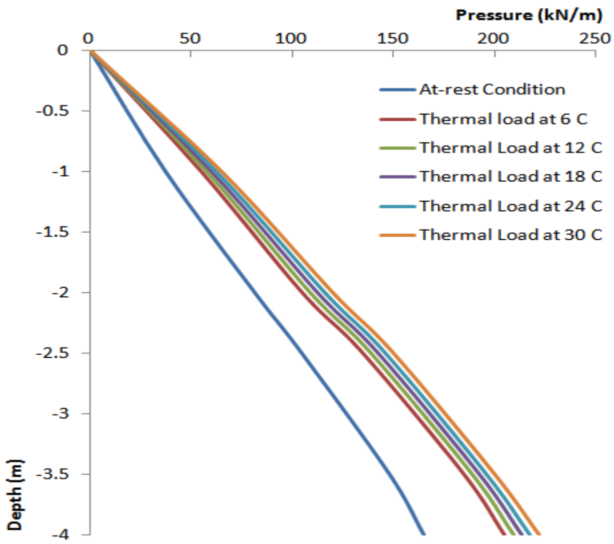


Figure 16: Backfill pressure distribution for silt-sand behind the abutment for increased thermal expansion using Mohr-Coulomb Soil model.

These results suggest that the soil type and the incremental lateral load only have minimal influence on the backfill pressure. This could lead to the assumption in design of certain limiting values of lateral loading in terms of lateral displacement of integral abutments inducing backfill pressure as suggested by Kerokoski (2006). In the following section these possibilities have been investigated.

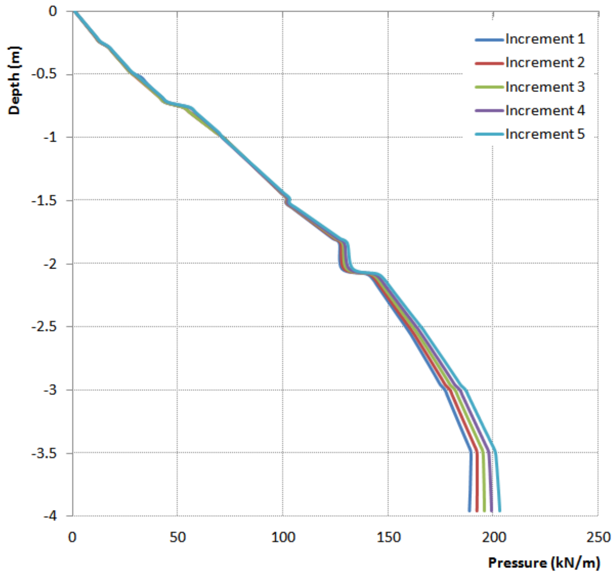


Figure 17: Backfill pressure distribution for silt-sand behind the abutment for increased thermal expansion using Duncan-Chang Soil model.

5.2 *Lateral Displacement (Stub-Type Abutment) – Backfill Pressure Relationship*

The effect of lateral displacement of stub-type integral abutments on the shape and intensity of the backfill pressure was assessed to identify, if there were any limiting lateral displacements. Figure 8 and 19 show the lateral displacement-backfill pressure relationship for the four soil types at 2m and 4m depth using SAFE MC Model.

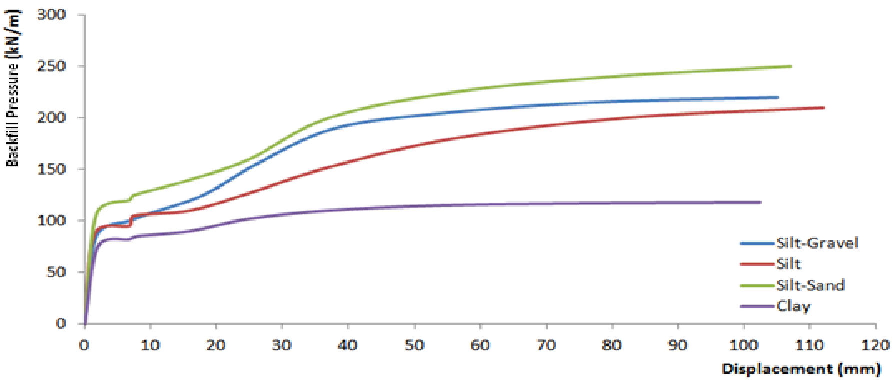


Figure 18: Displacement-backfill pressure relationship at 2m depths using SAFE MC Model

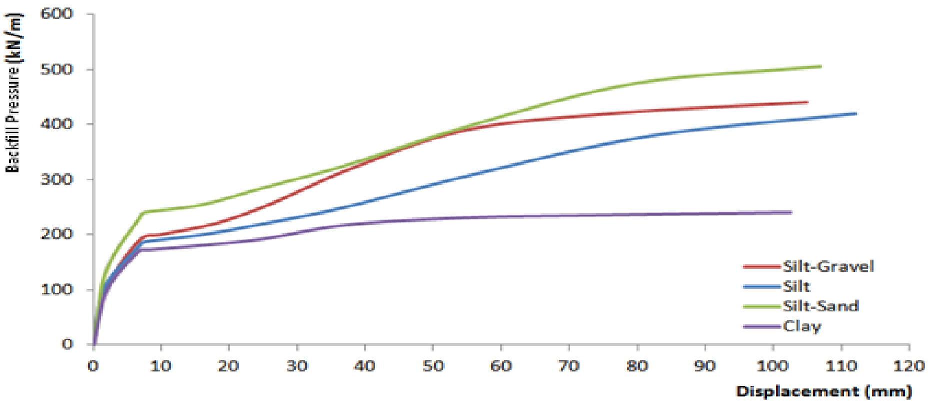


Figure 19: Displacement-backfill pressure relationship at 4m depths using SAFE MC Model

At 2m depth (see Figure 18), the shape of the earth pressure intensity for all soil types increases sharply at around 3mm horizontal displacement. There was an increase of about 25 per cent in the backfill pressure noted after displacements of 3mm to 25mm (i.e. Clay) and was almost constant thereafter. Similar trend of behaviour was observed for other soil types with little variations. At 4m depth, the backfill pressure increased rapidly as the wall moved horizontally against the backfill until a displacement of 7mm or 0.002*H was recorded. The increase in backfill pressure intensity reduced greatly as the displacement increases from 7mm to 70mm and becomes almost constant thereafter.

The backfill pressure in relation to the soil type at the threshold value (i.e. under 10mm) indicates that the soil type has no significant effect on the backfill pressure, particularly when the lateral displacement is below 3mm. The results also indicate stiffening (densification) of the soil behind the stub-typed integral abutment as the lateral displacement (i.e. lateral load) increases the backfill pressure.

It is also noted that very early on, the clay exhibited an almost constant backfill pressure with relation to increased displacement, as early as at a lateral displacement of 35mm or 0.009*H. Therefore, 0.009*H horizontal displacement can be considered to be the limiting value for the Clay soil specified in this analysis. The limiting values of displacement for the other soils are 50mm or 0.0125*H for silt-gravel soil and 70mm or 0.0175*H for Silt and Silt-sand soils. The result suggests that for the given soil types, the lateral displacement of the integral abutment has a limiting effect of between 0.009*H to 0.0175*H on the development of backfill pressure. This limiting value falls within the guideline provided for integral bridge design by previous researchers (Dicleli & Albhaisi, 2004c; Arsoy 2004).

5.3 Integral Abutment – Backfill Profile Relationship

The behaviour of stub-type integral abutments in correlation with the backfill soil type has been investigated. Figure 20 shows the variation in the maximum bending moment of the stub-type integral abutment at 0.5H as a function of lateral displacement for various soil types. From Figure 20, it can be seen that the integral abutment bending moment increases steadily as the displacement increases for all soil types; there is only about an 8 per cent variation across all soil types.

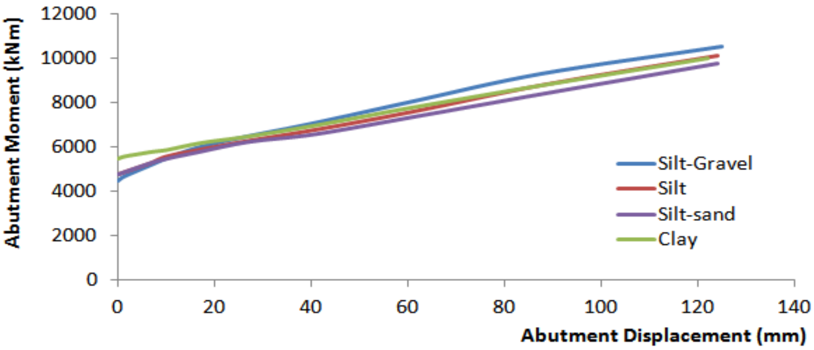


Figure 20: Variation of integral abutment maximum bending moment at 0.5H as a function of horizontal displacement for various soil types

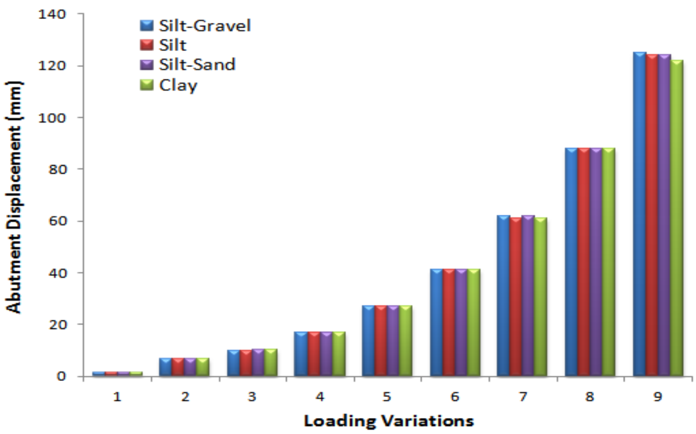


Figure 21: Variation of abutment's top displacement for various soil types at different loading values

Figure illustrates insignificant lateral displacement variations at the top of the stub-type integral abutment for various soil types at different lateral loading values. The effect of the various backfill soils on the horizontal displacement of the stub-type integral abutment subjected to a lateral load which corresponded to a positive temperature increase of 30^{0}C, were found to be similar for all the soil types (see Figure 22). This shows that the soils and their properties used in this analyses have a negligible effect on the behaviour of the stub-type integral abutment.

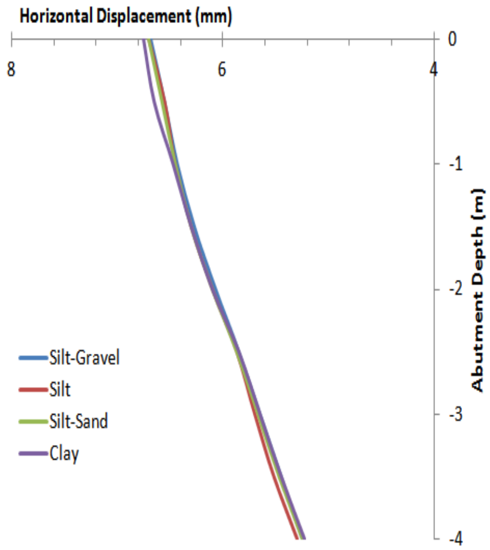


Figure 22: Integral abutment's horizontal displacement at 30 degree positive thermal loading for various types of soil

5.4 *Cyclic Loading Effect: Backfill Pressure and Stub-type Integral Abutment Deformations*

The backfill pressure and cumulative deformations within the backfill soil resulting from the cyclic loading were investigated in order to identify the cyclic effect on the stub-type integral abutment. The behaviour resulting from the lateral loading corresponding to a ± 30 degree Celsius change in temperature are presented here. Silt-gravel, silt, silt-sand and clay (Table 3) were utilised as backfill soils and analysed using the SAFE DC model. The SAFE DC model was used for these cyclic analyses to accommodate the non-linearity of the soil behaviour.

The backfill pressure distributions for the various soils are illustrated in
c. Silt-sand d. Clay

Figure 23. Initially, the analyses were performed for up to 100 cycles. However, these numbers were reduced to 25 cycles as there were no significant differences in the results beyond 10 or less cycles. The variation between the first and second cycles was distinct along the entire stub-type integral abutment height and was greater near the bottom of

the abutment compared to the top (see Figure 23). The variations were only up to 3 per cent for the upper half of the abutment but up to 20 per cent at bottom. The subsequent cycles (i.e. beyond the second produced less than 2 per cent variations; the pressures became constant after the third cycle. A similar trend of cyclic behaviour was observed for all four types of soil.

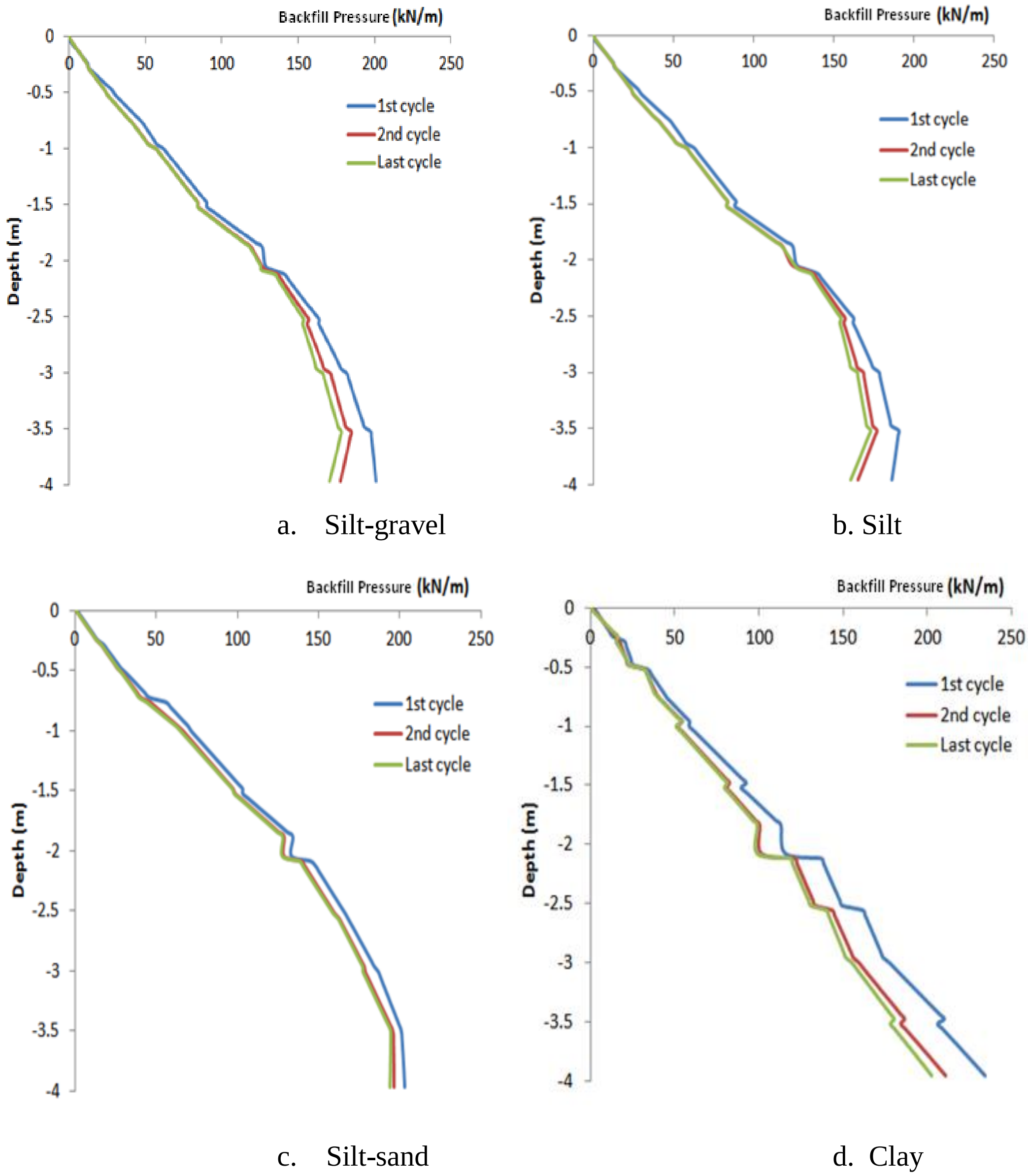
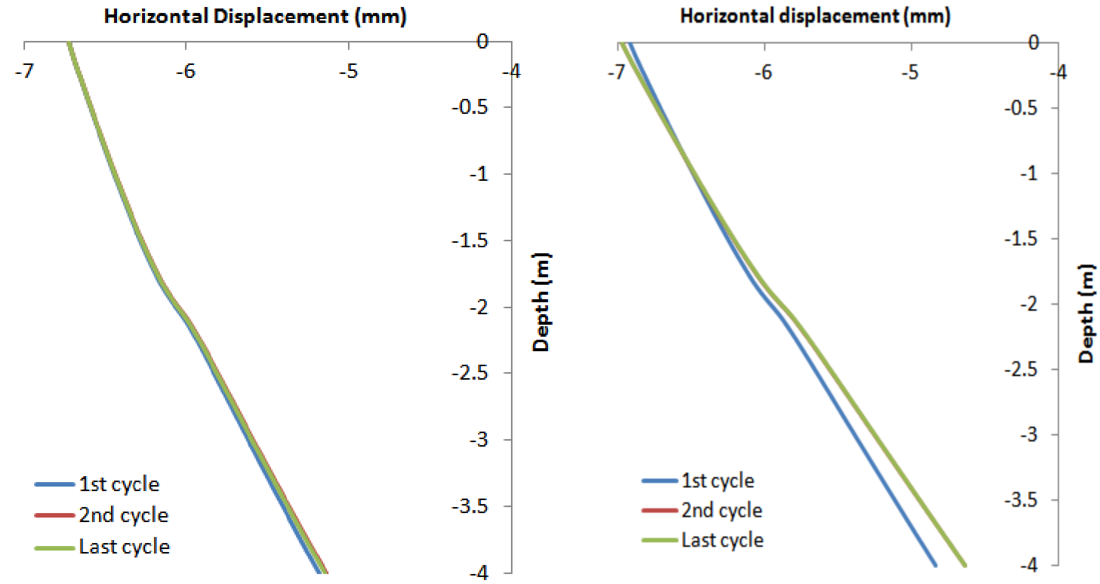


Figure 23: Backfill pressure in backfill soil after first, second and last cycles for various soils.

These trends in the reduction in backfill pressure with number of cycles possibly suggest an initial degradation of the soil stiffness after the first cycle. Especially as there is little change in the backfill pressure beyond the second or third cycle.

The displacements of the abutment subjected to these cyclic effects, using Silt-gravel and Clay which represent the two extreme conditions, are presented in Figure 24. The cyclic displacements of the stub-type integral abutment were found to be consistent with the development of backfill pressure behind the stub-type integral abutment (see Figure 24).



a. Silt-gravel b. Clay

Figure 24: Horizontal displacement of abutment for first, second and last cycles for a. silt-gravel and b. clay backfill soils

It may be concluded that the thermally induced lateral cyclic loading has some effect on the development of backfill pressure in the backfill soil behind the stub-type integral abutment during the initial cycles. However, these effects were negligible after the first few cycles. This decrease in backfill pressure due to thermally induced cyclic movements should be recognised in the design of an integral abutment.

6.0 Summary and Conclusions

Investigations on the effect of different types of soil and lateral loading on the behaviour of the backfill soil and the stub-type integral abutment were carried out. Two-dimensional finite element models were developed using OASYS SAFE; these models were based on a typical stub-type integral abutment bridge with backfill and foundation soil. Lateral loading, resulting from temperature variations in the superstructure, and lateral cyclic loading were applied at the superstructure level.

The objective of developing a two-dimensional finite element model was to provide a simple yet comprehensive and realistic depiction of the stub-type integral abutment bridge-soil interaction in order to achieve a reliable and accurate representation of the soil-structure thermally induced lateral movement. The performances of two soil constitutive models (the Mohr-Coulomb and the Duncan-Chang Hyperbolic soil model), which are available for use in the OASYS SAFE software, were used in this investigation.

Stub-type integral abutment-backfill soil relationship was investigated in the analyses; four different soil types; Silt-gravel, Silt, Silt-Sand and Clay were considered. Non-cyclic and cyclic thermally induced lateral movements were considered to further assess the soil-structure interaction of a typical stub-type integral abutment.

The results of the study suggest the following conclusions:

1. Backfill soil properties have a significant effect below 0.25 times the depth of stub-type abutment on the development of backfill pressure along the depth behind the integral abutment.
2. The study suggests that both the Mohr-Coulomb and Duncan-Chang Hyperbolic soil model gives approximately the same outcome especially in non-cyclic analyses.
3. In general, backfill pressures were found to be a function of the integral abutment displacement. Analyses on various types of soil suggest that the limiting values for the abutment displacement inducing maximum backfill pressure behind the abutment are similar. The study suggests that the limiting value for the soils considered are between 0.009*H and 0.0175*H.
4. The bending moment – displacement relationship for various types of soil shows that the soil properties have negligible effect on the behaviour of the stub-type integral abutment. However, load shape and intensity were obviously found to have a significant effect on the displacement behaviour of the abutment.
5. For this investigation, cyclic effects become constant or negligible after the second or third cycles on the development of backfill pressure. A drop in backfill pressure was observed for consecutive cycles. This drop may suggest soil stiffness degradation after initial incremental cyclic loading.

Based on the findings of this investigation, the lack of design specifications (Arsoy *et al.*, 1999; Dicleli, 2000; Huang *et al.*, 2004; Dicleli & Erhan, 2010; Kim & Laman ,

2010) for integral abutment bridges, an insufficient understanding of the behaviour of integral bridges in general (Huang *et al.*, 2004; Lawver *et al.*, 2000; Dicleli & Albhaisi 2004c; Comisu & Gheorghita, 2010) and insufficient comprehensive computational model availability to analyse the behaviour of integral abutment bridges (Dicleli, 2000; Jaafar *et al.*, 2003; Arockiasamy & Sivakumar, 2005; Kim & Laman, 2010). Further extensive research is required in areas comprising:

1. Instrumented bridges for practical field data
2. Centrifuge experiments, and
3. Numerical modelling – validation and parametric

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