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Modelling of 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. This kind of bridges are becoming very popular due to different aspects such as 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. Various 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 various finite elements model which explicitly incorporates the nonlinear soil and linear structural response considering various soil constitutive models and finite element mesh.

***Keywords*—**Constitutive Models, FEM, Integral Abutment Bridges, Soil-structure Interactions

I. Introduction

INTEGRAL Abutment Bridges (IAB) is defined as simple or multiple span bridges in which the bridge decks are cast monolithically with the abutment walls. Integral bridges offer a durable and reliable solution compared to traditional or conventional jointed bridges. While elimination of expansion joints prevents structural damage associated with leakage, it also reduces the capital cost, maintenance costs and enhancing the life expectancy of the superstructures. Other benefits include improved construction tolerance, increased structural redundancy and enhanced seismic resistance [2],[5],[8],[9],[13],[16],[17],[20],[22],[23],[25]. 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 structures, especially foundation and soil medium is potential to alter the actual behaviour of any structure considerably compared to the analysis of the structure alone. Since, Integral Abutment Bridge's behaviour is interdependent between its structural components and soil medium, it is vital to determine the relevant parameters of soil to represent its behaviour. In general modelling of the structural element i.e. superstructure and foundation piles are rather simple and straightforward compared to soil medium. The complex behaviour of soil due to its heterogeneous, anisotropic and nonlinear in force – displacement characteristics [19] need to be accounted for in its modelling.

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The need for proper material and structural modelling of integral bridges has also been highlighted by Mohd Salleh Jaafar et.al [13].

II. Lateral Earth Pressure

The performances of the Integral Abutment Bridges are known to be affected by the interaction between the backfill soil and the abutment, which involves relative displacement and soil stress-strain behaviour due to the lateral earth pressure. Generally, lateral earth pressure is influenced by soil properties (i.e. soil friction angle, density, cohesion, stress etc.) and its responses. Therefore a reasonable soil constitutive model needs to be used to represent the soil properties in an analysis. Soil constitutive models are drastic idealizations of soil characteristics and essential feature for practical applications.

Several studies (i.e. [1],[3],[15],[26]) showed that both the deformation mode (i.e. translation and/or rotation) and the magnitude of the deformation of structure affect the magnitude and the distribution of the earth pressure. It has been suggested that the lateral earth pressure should be predicted as function of structural (i.e. abutment, pile and wall) displacement, since the distribution and the magnitude of the lateral soil-structural resistance are highly dependent on the structural displacement [1],[3],[8],[15],[26].

A. Constitutive Model

Essentially, the soil behaves as an elastic-plastic material, i.e. initial deformation behavior is elastic deformation and followed by behavior of materials which undergo irreversible plastic deformation without fracture or damage. Soil deformations are basically inelastic since upon load removal, unloading follows an entirely different path from that followed by loading.

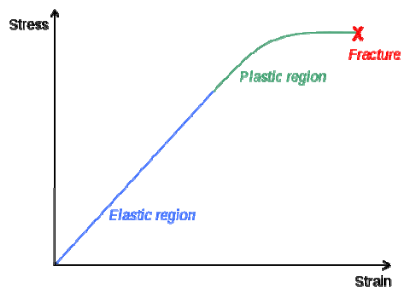


Fig 1 Stress-strain Curves

Large variety of models has been recommended in recent years to represent the stress-strain and failure behaviour of soils [4],[19]. In general, the choice of soil constitutive model should take into consideration the simplicity and (reliably) realistic representation of real soil behaviour. Generally, the nonlinear response of soil materials is influenced by factors such as state of stress, stress path, inelasticity, volume changes, type and rate of loading and anisotropy (inherent or induced). Therefore, the chosen constitutive soil model should be able to represent the behaviour of soil material under a reasonably wide range of conditions and the material parameters can be determined from standard laboratory tests.

Table I below gives a brief description on the commonly used soil constitutive models in soil-structure interaction which have been discussed in several literatures.

TABLE I
TYPE OF SOIL CONSTITUTIVE MODELS

Constitutive Model	Brief description
Winkler Model	Idealized the soil medium as linear and/or nonlinear elastic springs. Considered as oversimplified idealization of soil medium. However it is adequate and suitable for computational purpose for its reasonable performance and simplicity.
Mohr-Coulumb Model	It's an elastic-perfectly plastic model. The model's stress strain behaves linearly in the elastic range. Friction angles and cohesion of soil defines the failure criteria.
(Modified) Cam-Clay Model	It's an elastic plastic strain hardening model where the nonlinear behaviour is modelled by means of hardening plasticity. This model is an elastic plastic strain hardening model. It is reported that this model is suitable to describe deformation compared to failure for consolidated soft soils.
Duncan-Chang Model	It is a stress-dependant model which could represent the nonlinear behaviour of soil. Also known as Hyperbolic Model. This model is capable to describes nonlinearity, stress-dependant and inelastic behaviour of both cohesive and cohesion less soil. Its soil parameters can be derived or obtained easily from standard triaxial test.
Elastic Continuum Model	It is a conceptual approach of dealing with boundary distances and loaded areas. It is an infinite soil media representation. It has been found that this idealization may provide more information on the stresses and deformations within soil mass compared to Winkler model but often fails to represent the physical behaviour of soil very closely [19]

B. Modelling of Soil-Structure Interaction

Structure with its loading conditions imposes stresses and forces on the ground, which in turn deforms and as a consequence transmits back additional forces and deformation to the structure. This process continues until full equilibrium of the whole soil-structure system is satisfied, or until both the soil and the structure fail in the case of excessive loading and deformations of the system [6].It's known that the behaviour of structure and the soil media are profoundly different. Therefore, the modelling and analysis of these two elements varies significantly. As far as the structural analysis is concerned, the modelling has developed gradually to address the followings;

i. Variety in structural build-ups
ii. Geometrical variations: Linear to nonlinearity
iii. Response of the structural elements under various loading conditions: Serviceability to extreme conditions

However, for geotechnical analyses, the followings as been the concerns;

i. The constitutive models to represent the behaviour of soil
ii. Coupling of adjacent mechanisms with soils: Soil-structure interaction
iii. Modelling of special boundary conditions
iv. Time dependent processes: Consolidation and creeps

Since integral abutment analysis is a typical soil-structure interaction problem, a very realistic and reliable modelling approach has to be adopted. The approach employed to model the soil-structure interaction should be able to complement each other to provide reliably accurate analytical results. In general, structural analysis simplifies soil behaviour, while geotechnical analysis simplifies structural behaviour. There are about six modelling approaches employed by researchers in the area of soil structure interactions;

i. Winkler Spring approach (Fig. 2), known as field elimination method where the soil media represented by spring element [5], [12],18],[21]
ii. Finite element analysis: Monolithic approach [2],[5]
iii. Integrated Modelling, it's a finite element approach as well and also known as coupled soil-structure interaction system accounting for interface elements [24]
iv. Partitioned Analysis (Fig. 3), here the analysis of these two elements treated as isolated entities [6]
v. Staggered Approach (Fig. 4); in this approach two physically partitioned and independent domains are involved representing both soil and structure respectively and it is known that this approach is suited to transient dynamic analysis only [6]
vi. Iterative coupling (Fig. 5); this is similar modelling approach as the staggered but here, the computing is done parallelly.

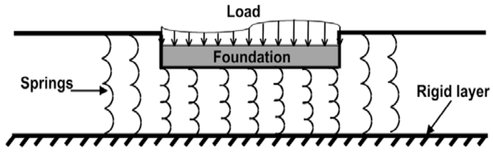
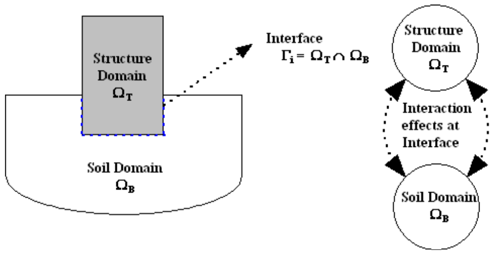


Fig. 2 Winkler Spring Approach



Fi.g 3 Partitioned Approach of soil-structure interaction [6]

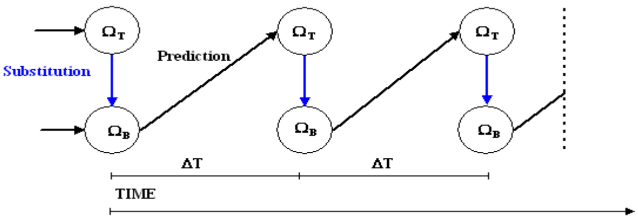


Fig. 4 Staggered Coupling Approach [6]

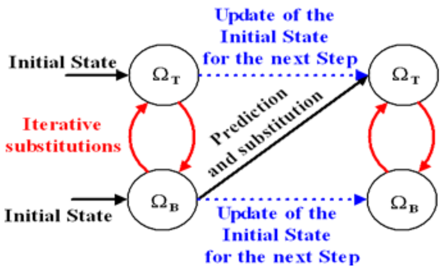


Fig. 5 Schematic of sequential iterative coupling approach [6]

III. Gapping

A. Mechanism of the Gapping

In purely elastic conditions within the soil, the lateral displacements of the structure (i.e. pile and abutment) and soil are equal. In reality, it is not true, soil has limited ability to take tension and it is likely that separation/gap/wedges may occur near the top of the adjacent structure. This separation or gap may cause large compression stresses to develop in front of the structure and tensile stresses behind the structures. This separation is more likely to happen due to cyclic effect (loading and unloading process) on the structure. The cyclic nature of loading will cause the structural element to move in and out of contact with the soil as it moves laterally.

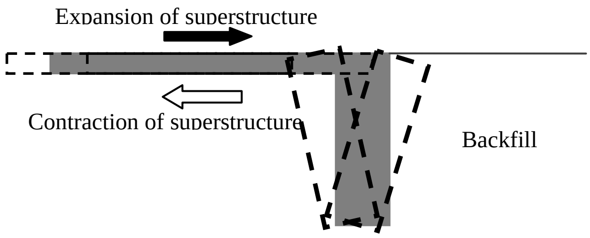


Fig. 6 Cyclic Loading induced by corresponding loads

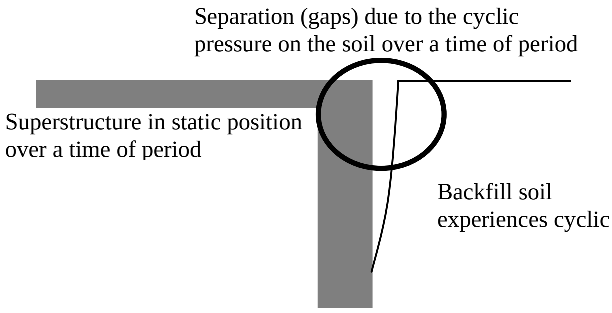


Fig. 7 Separation due to Cyclic Pressure

A full scale study on the effect of cyclic lateral loading on the behaviour of pile cap and backfill, by [29] has shown that, separations can form even for coarse-grained soils under the influence of cyclic loading. It was also found out that the separations were typically manifested as the pile cap deflection exceeded 1.0% of the pile cap height. These separations significantly decreased the passive resistance capacity afforded to the structure.

Poulus and Davis (1980) described that this separation/gap and local yield (due to high pressure near top of pile) are the main causes of the marked nonlinearity in load-deflection behaviour that is observed in lateral loading test.

It can be summarised that the primary effects of gap formation on the performance of structures as follows:

i. The gaps significantly decreased the passive resistance afforded to the structure
ii. Significantly affect the load-deflection behaviour of the foundation. Study by [29] shows that the load-deflection path is typically linear until the pile cap makes contact with the backfill soil and then exhibits a concave shape.
iii. The effect of gap may also lead to an increase in displacements and rotations of 30% to 100% [7],[18]
iv. Causes cyclic degradation in the stiffness of the structure and soil [18]

B. Gapping Modelling and Analysis

Researches on the effect of gapping (gap formation) have been carried out limiting to the soil-pile interaction under the influence of static and/or cyclic loading. Works on the effect of gapping on other structures (i.e. retaining wall, abutment) has not been much of interest; however, the importance of the gapping effect on these structures cannot be neglected, specifically in integral abutments. Integral abutments are known to directly expose to lateral movement due to deck expansion and contraction under various condition.

The researchers who have been working in the area of gapping in soil-pile interaction, to name few are as in the Table II below:

TABLE II
MODELING AND ANALYSIS METHODS FOR GAPPING

Researcher/Title of Paper	Brief Description: Modeling and Analysis Method
Matlock et.al. (1978): Simulation Of Lateral Pile Behaviour Under Earthquake Motion	Known to be first attempted to study the influence of gap formation in soil-structure interaction (i.e. soil-pile interaction).Developed a simplified model using finite difference technique where Winkler model was used to represent the gapping phenomenon. Analysis is performed using cyclic p-y curves.
SS Rajashree & TG Sitharam (2001): Nonlinear Finite Element Method Of Batter Piles Under Lateral Load	In this study, the soil nonlinearity represented by hyperbolic and modified hyperbolic relations for static and cyclic load conditions, respectively. The degradation and gapping factors were modeled by an empirical relation incorporating into the modified hyperbolic relation, which is represented by Winkler Spring elements. The cyclic load analyses were performed adopting an incremental-iterative procedure.
Satyawan Pranjoto & MJ Pender (2003): Gapping Effects on the Lateral Stiffness of Piles in Cohesive Soil	The researchers investigated the effects of gapping on the behaviour of piles, where the pile-soil interaction and gapping factors are modeled using detachable Winkler spring at front and rear of the pile shaft. The analyses were performed with finite element method using p-y approach.
Wei Zheng & Ronaldo Luna (2006): Liquefaction Effects on Lateral Pile Behaviour for Bridges	A study on the liquefaction effects on lateral pile behaviour of the highway bridges was taken up using coupled pile-soil-structure interaction. Pile-soil interaction is simulated by the dynamic nonlinear p-y method taking into consideration the effects of gapping, soil nonlinearity and liquefaction. The gap component modeled as nonlinear closure spring elements (Fig 8).
Anoosh Shamsabadi et. al. (2007): Nonlinear Soil-Abutment Bridge Structure Interaction for Seismic Performance-Based Design	In this study, the soil is represented by nonlinear hyperbolic model developed by Duncan-Chang (1970). The soil resistance and the gapping effects been modeled as spring element using SAP2000 (Fig.9). The gap element represents the seat of the abutment that engages the spring when the bridge deck pushes toward the backfill but allows the bridge deck to freely separate from the soil. The analyses were performed using finite element approach.

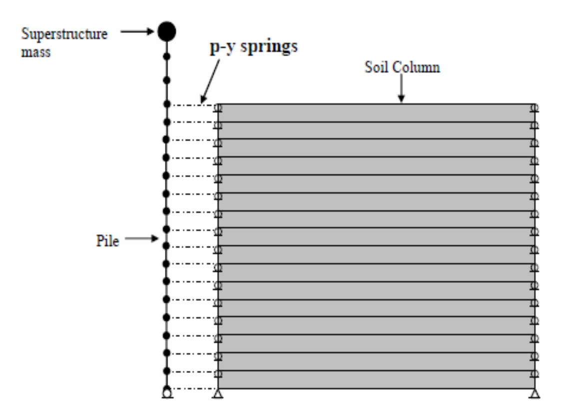


Fig. 8 Coupled Pile-Soil-Structure Interaction Model [24]

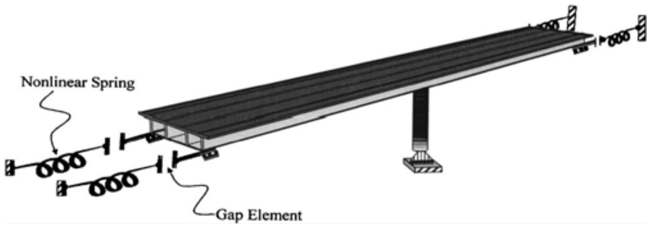


Fig. 9 Two-span 3D Bridge Structural Model Considering Gapping Effects [1]

Literatures reviewed, reveals that the gapping effects has a significant influence on the behaviour of soil-structure interaction. While over the past 35 years attempts has been made to study the soil-structure interaction, the gapping effects, however, has been ignored or neglected. Gapping effect has been prominent in the studies of pile behaviour under lateral cyclic loading. Winkler model was used by Matlock *et al*. (1978) to represent the gapping phenomenon. The modelling and analysis process adapted (which has been the basis for most of the researches in this area) can be summarized as below:

i. The foundation system was modelled as two series of detachable Winkler springs on either side of the pile.
ii. The soil adjacent to the pile was modelled with zero tensile strength, therefore when the force in a spring element reduced to zero, the spring detached from the foundation element.
iii. The element reattached when the forces in the soil were no longer tensile.
iv. Once detached, the spring no longer had any influence in the system, as would be the case when gapping occurs.

Kyle M. Rollins and Andrew Sparks (2002) did a study on the lateral resistance of pile cap with granular backfill by full scale experimental work and computer modeling. In their study, the reduced pile-soil-pile resistance due to gaps were modeled by neglecting the soil strength to a depth of about 4 pile diameters (which was found to be deemed from in-situ testing).

According to Liam M. Wotherspoon (2009), Swane and Poulos identified that during cyclic loading a stable gap length may be generated where there is no further reduction in pile stiffness or growth in gap length, defining this mechanism as shakedown. However, it is known that gapping width and depth is influenced by ratio of lateral to vertical stress, spring stiffness and number of cycles [18].

IV. Present Study

Oasys General Structural Analysis (GSA) Version 8.5 is being used for finite element modelling. The usage of GSA would be considered pioneering in integral abutment bridge analysis. The proposed software packages were adopted based on their availability and capability in carrying out the proposed study where the scope expands from linear to nonlinear.

Initially, models without soil meshing were developed to choose a suitable meshing density for the structural elements. Selection of a finite element mesh density for numerical analysis is very important in finite element modelling. A convergence of results is obtained when an adequate number of elements are used in a model. This is practically achieved when an increase in the mesh density has a negligible effect on the results. Therefore, in this study a convergence study was carried out to determine an appropriate mesh density [4].

Three models were developed to study the behaviour of a single span Integral Abutment Bridge. These three models are:

1. Finite Element Mesh (SM), where both the soil media and structural elements are modelled as 4 or 8 node finite element members
2. Finite Element Mesh with Spring element which connects the backfill soil media to abutment and pile
3. Finite Element Mesh with Spring element which connects the backfill and riverside soil media to abutment and pile

These models were analysed for various load cases for preliminary studies under linear static analysis. The result of these preliminary analyses agrees well with previous work done by [28]. 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 analyse the behaviour 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' behaviour. To achieve this objective, a 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.

Other concerns include the 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 mentioned above [14]. 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 behaviour of an integral abutment bridge by researcher.

V. Conclusions

Though extensive studies on various aspects of Integral Abutment Bridges have been conducted since 1930's, there are still concerns over the behaviour of this structure. For instance, the need to study the behaviour of the structural elements of integral abutment bridge under environmental loading has been highlighted by Jimin Huang et.al, 2008. Youseff Dehne and Sophia Hassiotis also stated that provisions for accurate soil-structure interaction are needed.

In this paper, modelling of soil-structure interaction for Integral Abutment Bridges and related issues were reviewed, and the present work by researcher at the University of Leeds are introduced.

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