THEORETICAL MODAL CHARACTERISTICS OF INTEGRAL ABUTMENT BRIDGE WITH BORED PILES FOUNDATION

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ABSTRACT

Since 2008, the Public Works Department of Malaysia had adopted the integral abutment bridge concept as one of the initiatives to reduce the maintenance costs of bridges. Although this type of bridge is popular in the developed country such as United States, United Kingdom and Japan, the use of integral bridges in the South East Asia Country is considered relatively new. While most of the researches focussed on theoretical dynamic characteristic of bridge founded with H-piles, this paper presents the theoretical dynamic characteristics of integral bridge abutment with bored piles determined by the FE modal analysis performed by using ABAQUS software. A single-span integral bridge located in Pahang, Malaysia has been selected as the case study. The modal characteristics of the same design of bridge with simply supported bridge yield different values of modal frequency, which are higher. From the FE modelling result, it was found that the integral bridge with the bored piles type of foundation possess lower natural frequencies compared to the simply supported bridge of similar type of foundation.

Keywords: Modal Analysis, Integral Bridge, Natural Frequency, ABAQUS software, Dynamic Characteristics.

1. Introduction

Every mechanical structure can be resonated. Resonance is a phenomena when the structure the vibration frequencies collide with the natural frequency. As the development of modern FFT analyser in 1970, modal analysis has become one of the most popular methods in determining the dynamic properties of a structure.

Integral bridge has been widely used as a new system in bridge design to eliminate the uses of bearing and expansion joint [1, 2]. In the integral type of bridge, the deformation under external load will be carried by the frame action and eventually transmitted to the foundation level. Beside the elimination of these two elements in Integral Bridge Abutment, the other most discuss advantages of using the kind of system is, the active pressure of soil behind the abutment wall which contribute to adverse impact to the structure and can be turned into the positive contribution to wall performance.[3, 4]

The proposed use of integral bridge in Malaysia is one of the initiatives to reduce maintenance costs by the Government of Malaysia. The cost of maintaining bridge bearings
and expansion joints contributes to most of the maintenance budget for our national bridge stock.

In 2003, the Public Works Department of Malaysia (JKR) embarked on the use of integral bridges to minimise the cost of the maintenance and benefit from the advantages offered by integral bridge construction. Integral bridge construction method has become a matter emphasized in the Design Terms of Reference since 2008 by the Bridge Unit of the Jabatan Kerja Raya to be considered by bridge designers, whether in the private or government sector [5].

This paper is part of the research carried to determine factor affected the dynamic characteristic on an integral abutment bridge with bored pile foundation.

2. Dynamic Characteristic of a structure

The use of dynamic characteristics or modal parameter in mechanical and aerospace engineering is already extensive. Any prototype of mechanical product should undergo the experimental modal analysis to determine their dynamic properties [6]. The designer of these products should ensure the designed product does not have the natural frequency at the same or near to the vibrating part in the system.

The applications of free vibration in civil engineering are rather new and limited due to the experimental limitation such as size and mass of the subject. Most of the experimental work is carried out in the lab and field testing of the real structures are considerably scarce [7]. While the conservative thought that the civil engineering structure are relatively stiff and the tendency of the mass to vibrate is less, the new trend of having lighter/more flexible structure made the use of modal analysis become more prominent in civil engineering use.

On the other hand, due to the size and mass of civil engineering structures made this method unpopular. The difficulties to excite the structure using measureable equipment become one of the main reason why this method not a favorable option in assessing the dynamic characteristic of the structure.

The dynamic characteristic of a structure which represented by the natural frequency value and its eigenvalue can be fundamental derived from the equation of motion expressed as:

\[ m\ddot{u} + c\dot{u} + ku = p(t) \]  

where \( m \) is the mass of the structure, \( \ddot{u}, \dot{u} \) and \( u \) is the acceleration, velocity and displacement of a node in the system of a given time domain respectively while \( c \) and \( k \) is the damping and the stiffness of a system respectively. The right hand term represents the excitation \( p(t) \) at the given time \( t \). By dividing the equation 1 with \( m \) and rewrite again, the equation 2 below is obtained [8]:

\[ u + 2\zeta\omega_n u + \omega_n^2 u = \left( \frac{\omega_n^2}{k} \right) p(t) \]  

where \( \omega_n^2 = \frac{k}{m} \) and \( \zeta = \frac{c}{c_{cr}} \),

while \( c_{cr} \) is given by;

\[ c_{cr} = 2m\omega_n \]
The term $\omega_n$ is called undamped circular natural frequency and its unit are radians per second. $\xi$ is a dimensionless quantity called viscous damping factor and $c_{cr}$ is called the critical damping coefficient. The solution for the differential equation in Equation 2 consist of a particular solution $u_p(t)$ and a complementary solution $u_c(t)$.

In the case of free vibration, the excitation $p(t)$ is equal to zero. Thus, the equation motion at which $p(t)$ is zero is then expressed by:

$$u + 2\xi\omega_n u + \omega_n^2 u = 0$$  \hspace{1cm} \text{Eq.}(3)

The general techniques for solving Equation (3) is to assume a solution of the form:

$$u = Ce^{\omega_n t}$$  \hspace{1cm} \text{Eq.}(4)

By substituting Equation (4) into (3), the Equation (3) becomes:

$$(\ddot{s}^2 + 2\xi\omega_n \ddot{s} + \omega_n^2)Ce^{\omega_n t} = 0$$  \hspace{1cm} \text{Eq.}(5)

For the Equation (5) to be valid for value of time $t$, it be then set to be zero and thus;

$$(\ddot{s}^2 + 2\xi\omega_n \ddot{s} + \omega_n^2) = 0$$  \hspace{1cm} \text{Eq.}(6)

Equation (6) is called the dynamic characteristic equation of a system under free vibration motion.

### 2.1 Natural Frequency

Natural vibration happen when a system tends to vibrate without a driving force. In the other hand, natural frequency can be defined as frequencies that cause a system to vibrate by itself without external force. The vibration without external force is referred as free vibration.

In the simple form, natural frequency is a relationship between stiffness and the mass of a structure. Natural frequency represented by $\omega$ is given by:

$$\omega = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$  \hspace{1cm} \text{Eq.} (7)

where:

- $\omega$ = natural frequency
- $k$ = stiffness
- $m$ = mass

Natural frequency can be expressed either damped or undamped natural frequency. The damped natural frequency is equal to the square root of the collective of one minus the damping ratio squared multiplied by the natural frequency. If the damped properties are significant, the damped natural frequency can be written as:

$$\omega_d = \sqrt{1 - \xi\omega}$$  \hspace{1cm} \text{Eq.} (8)

where:

- $\omega_d$ = damped natural frequency
- $\xi$ = damping ratio
In some cases, when the damping is too small and can be neglected, the damped frequency equal to the natural frequency of a system. Gonzalez [9] mentioned that the damping for bridge can be neglected, due to the damping is relatively small and does not give significant impact on the natural frequency of the bridge. The research by Gonzalez reviewed all previous modal tests that have been conducted by other researcher all over the world and the value of damping collected from each test. It is shown that, although the damping value still can be obtained from each bridge structure, the value is too small ranging from 0.3% to 2.2%.

Each object has a series of natural frequency up to several modes. The lowest natural frequency of a series called as fundamental frequency. And the tendency of shape happens to each frequency called as mode shape.

2.2 Mode Shapes

When a structure being excited to its natural frequency, the structure tends to deform its respective modal shape. Each series of natural frequency has their own respective shapes so called as mode shape. Mode shape usually divides into two groups. Bending shape and torsion shape. Most of the structure exhibit this two type of mode shape as their deflected shape.

3. Case study - Bridge Configuration

The Sg Damak Bridge with the ID number as in the JKR Bridge Management System (FT 068/039/40) in Kuala Lipis, Pahang State has been selected as the case study in determining the dynamic characteristic of an integral abutment bridge. Location of the bridge as shown in Figure 4(a-b). The approach road view of proposed bridge as Figure 5(a-b). The bridge is a single span of integral abutment bridge type whereby the superstructure and the substructure are monolithically connected with full moment transfer.
stressed Beam which is a common beam being used in federal and state bridge construction. The deck slab is 200mm thick. Figure 3 shows the schematic diagram of the case study bridge while Figure 4 shows the close up connection between beam, diaphragm and abutment.

![Figure 3: Sg Damak Side Elevation [10]](image)

![Figure 4: Rigid Connection between Beam, Deck and Abutment Wall](image)

4. 3-D Finite Element Modeling

The dynamic characteristic of the case study bridge was performed by using ABAQUS software package. Figure 5 shows the 3-D modelling of the bridge including the bored pile foundation. 4-nodes solid linear tetrahedron meshes were used for all the elements of the bridge (Figure 6). Basic material assignment was used through the analysis. The dynamic response and the natural frequency of the bridge were obtained through the frequency step module and natural frequency extraction capability offered in ABAQUS software. In this module, the Lanczos eigensolver method was selected with the minimum number of eigenvalues of 5. The implementation of the Lanczos eigensolver as a powerful tool for extraction of the extreme eigenvalues and the corresponding eigenvectors of a sparse symmetric generalized eigenproblem has been well accepted by many researchers [11].

To ensure proper calibration and credible results, the FE analysis were divided into two stages. The first stages at which the model was first analysed as a simply supported and the natural frequency was obtained and compared with the open literatures. Also at this stage, all the input value i.e. Density, Poisson Ratio and Modulus of Elasticity for the bridge are verified and checked against the past researchers results in open literatures.

The model was then extended to become a fully integral abutment bridge model where full moment transfer at the articulation point between deck slab and abutment is achieved. At this stage, the soil structure interaction was introduced to the model to replicate the behaviour of soil pressure onto the pile foundation. The model of soil structure interaction was=modelled
using the equation as per Geoguide 1, 1993\cite{12,13} to replicate the actual soil on site. The soil data are obtained from the soil investigation done on site. The stiffness of the soil are modelled using element spring constant in Abaqus \cite{11}.

![Figure 5: The Abaqus model of Integral Abutment Bridge with Bored Piles Foundation](image1)

![Figure 6: Meshed model of Integral Abutment Bridge with Bored Piles Foundation](image2)

The constructed model using Abaqus is shown in Figure 5. It is a necessity to make sure all the elements in the structure, including pile and structure were modelled together to obtain the actual behaviours \cite{13}.

### 4.1 Soil structure-interaction

To model the interaction between the soil and the body of bored pile, spring type of element was used with designated boundary conditions. The properties of the soil modulus and stiffness and were derived based on the two (2) boreholes data from the bore logs as tabulated in Tables 1 and 2 respectively. The boreholes for this bridge were done at each side of abutments to give an accurate soil profile.

| Layer to Analyse | Depth of Pile (meter) | Soil Type | N value |
|------------------|-----------------------|-----------|---------|
| 0.0              | 0.0                   | SILT      | 0       |
| 1.5              | 1.5                   | CLAY      | 0       |
| 1.5              | 3.0                   | CLAY      | 4       |
| 1.5              | 4.5                   | CLAY      | 6       |
| 1.5              | 6.0                   | SILT      | 7       |
| 1.5              | 7.5                   | SILT      | 28      |
| 1.5              | 9.0                   | SILT      | 43      |
| 1.5              | 10.5                  | SILT      | 50      |
| 1.5              | 12.0                  | SILT      | 50      |
| 1.5              | 13.5                  | SILT      | 50      |
| 1.5              | 15.0                  | SILT      | 50      |
| 1.5              | 16.5                  | SILT      | 50      |

| Layer to Analyse | Depth of Pile (meter) | Soil Type | N value |
|------------------|-----------------------|-----------|---------|
| 0.0              | 0.0                   | SAND      | 0       |
| 1.5              | 1.5                   | CLAY      | 0       |
| 1.5              | 3.0                   | CLAY      | 5       |
| 1.5              | 4.5                   | CLAY      | 8       |
| 1.5              | 6.0                   | CLAY      | 7       |
| 1.5              | 7.5                   | SILT      | 9       |
| 1.5              | 9.0                   | SILT      | 31      |
| 1.5              | 10.5                  | SILT      | 39      |
| 1.5              | 12.0                  | SILT      | 50      |
| 1.5              | 13.5                  | SILT      | 50      |
| 1.5              | 15.0                  | SILT      | 38      |
| 1.5              | 16.5                  | SILT      | 50      |
| 1.5              | 18.0                  | SILT      | 50      |
| 1.5              | 19.5                  | SILT      | 50      |
| 1.5              | 21.0                  | SILT      | 50      |
5. Result and Discussion

In evaluating the natural frequency on an integral abutment bridge, two factors must be considered i.e. the stiffness of the bridge sub and superstructures as well as the interaction between soil and the foundation. From the analysis, the output frequency and mode shape can be obtained. The natural frequency is determined at which the frequency is relatively constant and stabilized as the mode shape number increases as Figure 7 whereas for simply supported bridge shows an increment as the mode shape number increase as shown in Figure 8.

Figure 7. Natural Frequency vs Mode Shape for Integral Abutment Bridge with Bored Piles Foundation

Figure 8. Natural Frequency vs Mode Shape for 15 meter simply supported beam deck bridge

Figures 9(a) to 6 (e) show the mode shape pattern of the first 6 mode numbers. The corresponding eigenvalues of the first 6 mode number were between 0 to 1200 respectively.
From Figures 9(a) to 9(e), it was found that the natural frequency of the case study bridge is between 5.04 Hz to 5.17 Hz up to the fifth mode shape.

6. Conclusion

From the result of the FE modelling and analysis, it can be found that the natural frequency of integral abutment bridge is between 0.45 Hz to 5.17 Hz corresponding to the first 5 mode numbers. This value can be deduced as close to the resonant frequency of conventional bridge induced by of most commercial vehicles [15].

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