APPLICATION OF FINITE ELEMENT METHOD AND GENETIC ALGORITHMS IN BRIDGE SCOUR DETECTION

Hsun-Yi HUANG*, Wen-Yen CHOU*, Shen-Haw JU*, and Chung-Wei FENG*
Department of Civil Engineering, National Cheng Kung University, Taiwan*

***ABSTRACT*:** In this study, an integrated model that combines genetic algorithms and simulation technology is developed to estimate the scour depth around bridge piers by using the natural frequency of the bridge structure. Scouring around bridge piers is an important safety issue of bridge management since it could lead to bridge slanting and collapsing. However, the mechanism of water flow around the pier structure is complicated, which makes it is very difficult to develop a generic model to determine the scour depth and the bridge safety. Many researchers have tried to estimate the scour depths around bridge piers by simulating the bridge model with the consideration of various factors such as the depth of water, average velocity of flow, and diameter of sand. However most of models require predefined conditions and can only be applied to certain types of bridges. In order to well simulate the bridge environment and recognize the important factors which influence the result between scouring depth and natural frequency, finite element method is used in this study. The finite element method could simulate various conditions by mesh such as pile foundations type, soil strength, and scour depth. Since simulations generate a huge amount of data, which makes it hard to analyze and find the relation between the scour depth and the natural frequency. Then, genetic algorithms are used to find the fitted generic formula that defines the relationship between the scour depth and the natural frequency. In this paper, soil strength compare with natural frequency within different bridge scour depth is discussed.

KEYWORDS: Natural Frequency, Genetic Algorithm, Scouring around bridge piers

1. INTRODUCTION (11pt, bold, capital)

The bridge is crucial components of traffic system, so it is important to ensure its health and safety. Shirole and Holt who observed over 1,000 failed bridges in United State between 1960 to 1990 recognize that 60% of these failures are due to scour [1]. From literatures [2] [3], these papers investigated recent bridge failures in United State, and also obtained the conclusion that scour is one of the major reasons for bridge failures. Dargahi presented the scour mechanism which is coupled to the three-dimensional separation of the upstream boundary layer and the periodic vortex shedding in the wake of the cylinder. [4] Melville et al. published the book “bridge scour”. The book covers the description, analysis and design for scour at bridge foundations. The central focus is the combination of old and new design methods into a complete methodology for bridge-scour design. The book is based upon an extensive summary of existing research results and design experience [5]. Due to environmental factors to know the mechanism of water flow around the pier structure is still hard. Therefore, Johnson discussed a method that incorporate uncertainty into bridge pier design using a risk based design method and the probability of failure [9]. Johnson et al. determined the probability that the bridge failed at various points by simulating pier scour for a period of time. Johnson et al. investigated the actual cases of bridge damage [10]. Lebeau, and Wadia-Fascetti using fault tree analysis to analyze the historic bridge failure of the Schoharie Creek Bridge. That provides engineers and managers to recognize historical bridge failures It is helpful to maintain public safety and structure preservation [11].

For bridge safety purpose, to know the scour depth is another major topic to estimate the state of bridge. Melville presented an integrated approach to the estimation of local scour depth at bridge piers and abutments [6]. Richardson et al. presented a fully three-dimensional hydrodynamic model which simulated the flow occurring at the base of a cylindrical bridge pier within a scour hole. The simulations could be supplemented by Lagrangian particle-tracking to estimate the depth of the equilibrium scour condition [7]. Bolduc et al. used probability of exceedance to estimate for scour depth around bridge piers [8]. However, it is also a challenge for real operation since the pile exposure cannot be always observed directly, because piles are often under water, especially at the condition of flood. And the detection devices installed under water are often unstable after flood invading. To provide prior warning of bridge failure base on direct detecting the scour depth around bridge piers are hard tasks. For this reason, to develop a method as well as tools to detect the scour depths is useful.

In this study, the natural frequency of bridge structures which is calculated by the finite element method is used as a proxy to detect the scour depth around bridge peers. A series of simulations are first performed on a pre-stressed box girder bridge by setting different scour depths and environmental conditions such as soil distribution, foundation dimensions, and pier condition to determine the possible values of the natural frequency. To analysis the huge amount of data generated by finite element method genetic algorithms are applied to find the fitted generic formula that defines the relationship among the scour depth and natural frequency within various environmental factors. Therefore, one could find a bridge natural frequency at a certain foundation to locate the initial point in the approximate relationship and evaluate the bridge state.

2. METHODOLOGY

In this section, using finite element analysis to simulate and calculate the bridge natural frequency, and adopting genetic algorithms to find the fitted generic formula between the bridge natural frequency and exposure depth are introduced.

2.1 Simulation of bridge natural frequency

Structure natural frequency calculation is a motion of a dynamic problem. For the problem the equation is:

$$\mathbf{M\ddot{X}} + \mathbf{C\dot{X}} + \mathbf{KX} = \mathbf{F} \tag{3.1}$$

where M, C, and K are mass, damping, and stiffness matrices, respectively, X is the displacement vector, and F is the external force vector. If the damping and external force are neglected, one obtains:

$$\mathbf{M\ddot{X}} + \mathbf{KX} = \mathbf{0} \tag{3.2}$$

The displacement vector is assume to be $\mathbf{X} = \mathbf{\Phi} e^{i\omega t}$, and equation (3.2) changes to

$$(\mathbf{K} - \omega^2 \mathbf{M})\mathbf{\Phi} = 0 \tag{3.3}$$

Equation (2.3) is a standard eigenproblem, where ω is a natural frequency and Φ is a modal shape.

To simulate the eigenproblem of bridges accurately, the foundation and soil cannot be ignored, since the bridge foundation often contains a large portion of the total structure. Especially for the scoured bridge, its natural frequency should be sensitive to the exposure of the bridge foundation. Figure 1 and 2 show the finite element mesh of the bridge with and without the exposure of the foundation.

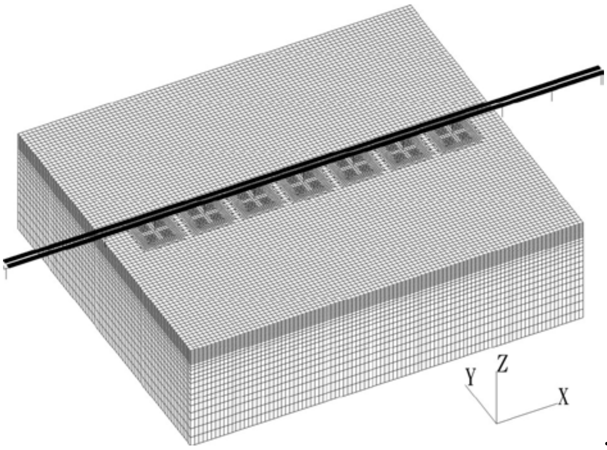

Fig. 1 3D finite element mesh without the exposure of the foundation

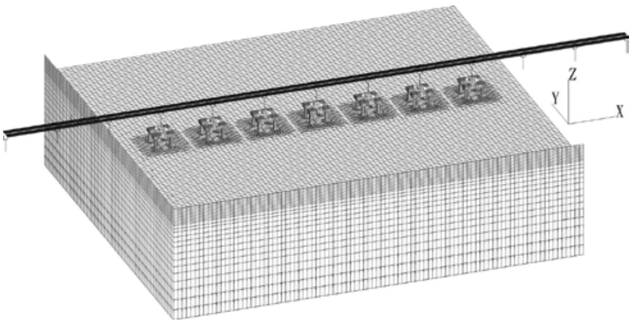

Fig. 2 3D finite element mesh with the exposure of the foundation

The total number of natural frequencies and modal shapes is the same as the total number of degrees of freedom (NDF) of the finite element mesh. The subspace iteration method was used to solve the eigenproblem of equation (3.2). The major advantage of this method is that first N eigenvalues and eigenvectors can be obtained, where N can be decided by users. For a finite element problem with large degrees of freedom, such as million or over, the subspace iteration method is efficient, since it is often required only first several modes, such as 40 to 60 modes. Since the mode shapes of soil, foundations, and superstructures may be coupled together, but the measurement devices installed on the superstructures can only obtain the natural frequencies of the superstructures. In this study, the effective mass above the soil surface is used to determine the natural frequencies of the superstructures. And the effective mass ratio can be used to represent the importance of this mode under the seismic load. If this value is large, such as 30%, this mode can be categorized as a mode shape in that direction. Figure 3 shows the natural frequency of the bridge after the finite element calculation. The results are verified by field experiment. Errors in the x direction and y direction are about 2.64%~4.58% and 1.42%~4.99%. The finite element results are in acceptable accuracy

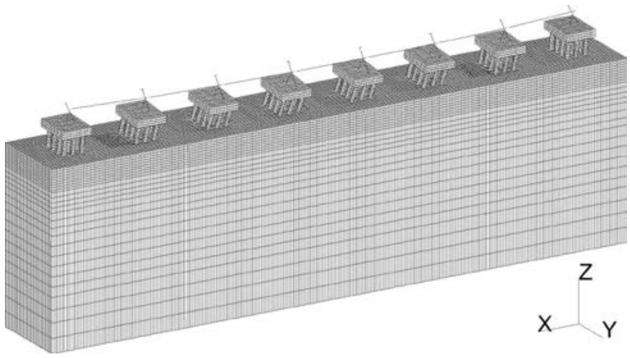

Fig. 3 Mode 1 in eigen-analysis

2.2 Genetic algorithms for fitting formula

From the above simulation method, one can change the parameters, such as soil distribution, foundation dimensions, and pier condition, to perform numerous finite element analyses and get bridge natural frequencies. However a huge numbers of data will be generated and make it difficult to generate a universal formulation to predict the scour depth. Genetic algorithms (GA) are then applied to find an approximate relationship between the bridge natural frequency and the scour depth. GAs are search algorithms developed by Holland [12] which are based on the mechanics of natural selection and genetics to search through decision space for optimal solutions [13]. In GAs, a string (chromosome combination) represents a potential solution to a problem. Each string is evaluated on its performance with respect to the fitness function (objective function). The crossover and mutation schemes will exchange the information (gene) between strings to produce various solutions. And a selection scheme such as roulette selects the strings (solutions). That string with higher performance will be selected with higher probability. The brief GA process is shown in Fig.4

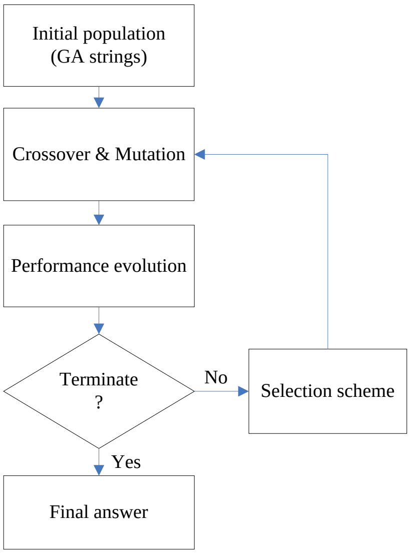

Fig. 4 Flowchart of GA

In this problem, the general form of equation can be written as:

$$Y = f(X, \theta) + \varepsilon \qquad (3.4)$$

where Y is the dependent variable, X is an (n x1) vector of independent variables, θ is a (k x1) parameter vector, and ε is a random error.

$f(X, \theta)$ could be displayed in various forms such as (3.5) to make the fitting function more suitable.

$$Y_i = \theta_0 Sin(X_i^{\theta_1}) + \varepsilon_i \qquad (3.5)$$

As a result, a GA string which represents a potential solution for fitting formula should determine the variables including θ, numerical parameters to adjust the dependent variable, and the transform functions such as trigonometric function.

The numerical parameter (θ) can be displayed as:

$$\theta = \alpha \times 10^{\beta} \qquad (3.6)$$

Set α is a number around -1 to 1 with acceptable precise such as 6 decimal places. And also set β within a acceptable range, such as 0 to 3 and accurate to 3 decimal places. As a result, α and β could be coded in binary. Then, the GA strings of θ are defined. For example, the bits (string length) required for α in this case are 21, since α equal size range is smaller than or equal to 2^{21}. The calculation formulation is shown in (3.7)

$$2^{m-1} < (b-a) \times 10^{d} \le 2^{m} \qquad (3.7)$$

where m is the required bits, b and a are the upper and lower bound of the range, and d is the decimal places. A GA string for α is like Fig. 5

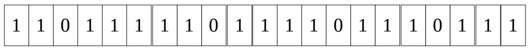

Fig. 5 GA string

For the selection of transform functions, a 100% percentage number is divided into equal parts to represent each transform functions. Then a random number between 0 to 1 is used to determine the selection of transform function by means of the location of the percentage. The random number is then coded in binary as the GA strings for transform functions selection. Fig. 6 illustrates an example with 2 transform functions.

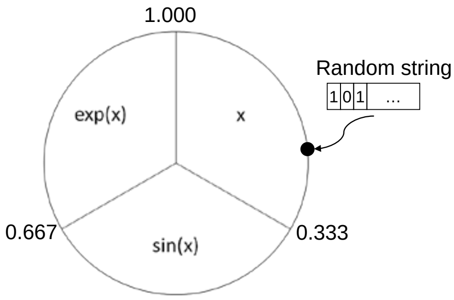

Fig. 6 Illustration of transform function selection

Root mean square error (RMSE) is finally used to measure the performance of the GA string (solution). Thus, the fitness function could be displayed as (3.8):

$$\gamma = \sqrt{\frac{\sum E_i^2}{n}} \qquad (3.8)$$

where γ is RMSE, $E_i = Y_i - Y_0$ (Y_i : estimate value, Y_0 : real value), and n is the number of data.

The error means the different between the result of fitting formula and the scour depth which is simulated by finite element analysis. When the error is lower than an acceptable level, GA process finish and the formula is conducted.

3. CASE STUDY

The model presented in this study is first applied to analyze the soil effect on bridge natural frequency. The bridge mesh is a seven-span pre-stressed box girder bridge with the span length of 30 m, in which simply supported girders are used. The length of the pier foundation is 5 m, and the pile length is 31 m under the ground. The bridge section is shown in Figure 7. The finite element meshes with different bridge scour depth are then generated. Figure 8 illustrates one of the meshes with the scour depth of 13 m.

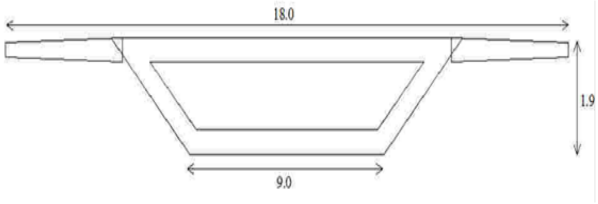

Fig. 7 The size of the bridge section (unit=m)

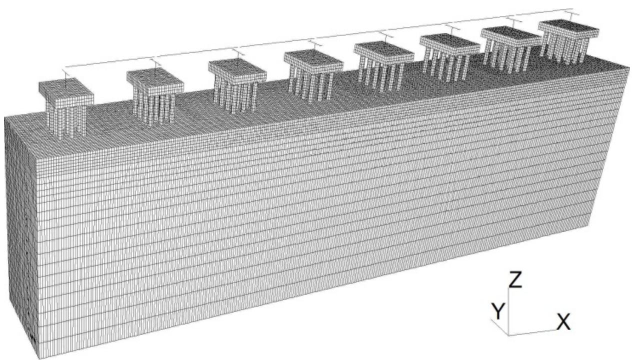

Fig. 8 The bridge mesh with 13m scour depth

Then the Young's modulus (E) that represents the different soil strength will be applied as a parameter in this study. Six soil cases are as follows:

Case 1: $E = 0.1\times10^{5}\,KN/m^{2}$ on the top of soil

$E = 0.8\times10^{6}\,KN/m^{2}$ at the bottom of soil

Case 2: $E = 0.2\times10^{5}\,KN/m^{2}$ on the top of soil

$E = 0.8\times10^{6}\,KN/m^{2}$ at the bottom of soil

Case 3: $E = 0.1\times10^{6}\,KN/m^{2}$ on the top of soil

$E = 0.8\times10^{6}\,KN/m^{2}$ at the bottom of soil

Case 4: $E = 0.5\times10^{6}\,KN/m^{2}$ on the top of soil

$E = 0.8\times10^{6}\,KN/m^{2}$ at the bottom of soil

Case 5: $E = 0.8\times10^{6}\,KN/m^{2}$ on the top of soil

$E = 0.8\times10^{6}\,KN/m^{2}$ at the bottom of soil

Case 6: $E = 0.8\times10^{6}\,KN/m^{2}$ on the top of soil

$E = 0.2\times10^{6}\,KN/m^{2}$ at the bottom of soil

For cases 1 to 4, the variation of the Young's modulus is linearly increasing from the top to the bottom of soil. For case 5, the Young's modulus remains constant. For case 6, the variation of the Young's modulus is linearly decreasing from the top to the bottom of soil. Each case will be analyzed to obtain the natural frequencies with 10 different scour depths, which are 0, 2, 3, 4, 6, 8, 10, 13, 16, and 19 m.

The finite element results are shown in Figure 9. The natural frequencies are reduced with the increasing of the scour depth in each case. The curves also show that the soil strength does not have a great influence on the bridge natural frequency.

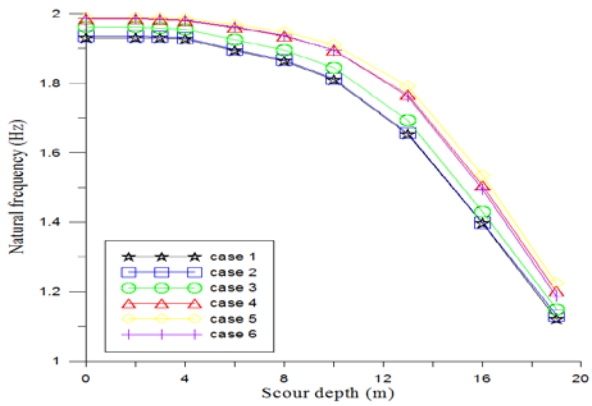

Fig. 9 The relationship between natural frequency and scour depth for each soil case

In order to obtain a more normalized result, all the natural frequencies will be divided by the natural frequencies of the case without scour. Thus, a normalized result is presented in Figure 10. Obviously, the curves show that the soil strength does not have much impact on the natural frequency. Especially from the scour depth 0 m to 6 m, the differences among each case are unobvious.

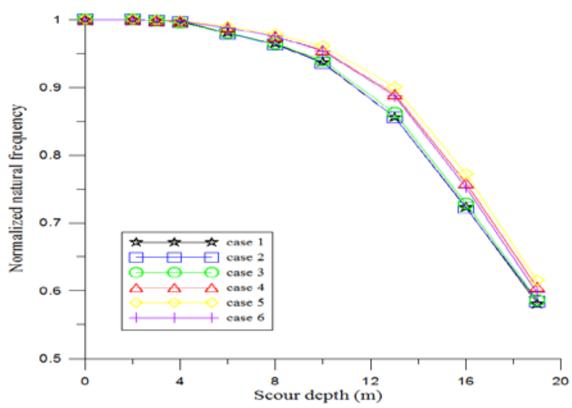

Fig. 10 The relationship between normalized natural frequency and scour depth

4. CONCLUSION

In this paper, an integrated model that combines simulation technology and genetic algorithms to estimate the scour depth around bridge piers by using the natural frequency is introduced. Since measuring the bridge scour depth using contact measurement schemes are difficult, the natural frequency of bridges is thus an alternative proxy to measure the scour depth and provide reference resources for bridge safety. In this study, finite element analysis of bridges are used to calculate bridge natural frequencies. Through a series of computer simulation by setting different conditions of bridge, a large numbers of natural frequencies are generated. Genetic algorithms are then applied to find an approximate relationship between the bridge natural frequency and the scour depth base on simulation data and conduct the formula. Thus, the scour depth of bridge could be easily computed in the field experiment by using natural frequency.

By presented model different soil strength effects on natural frequency are discussed. It reveals that soil strength does not have much effect on the natural frequencies of bridges, and whatever cases the scour depth from 0 to 6 m, the natural frequency changes little. From 6 to 10 m, the natural frequency becomes deceasing obviously. However, when the scour depth reaches 12 m, the natural frequency will decrease sharply. As a result, the scour depth of 6m to 10m could be a warning index. It provides a basic sight when natural frequencies are within such ranges, the bridge may need specific inspection or maintenance to ensure the bridge safety.

For the further research, different environment conditions such as the bridge forms, soil types, piers forms and…etc will be applied in this model. More important factors will be find out and conduct a useful formula for bridge scour depth detection.

REFERENCES

[1] Shirole A.M., and Holt, R.C., 1991. “Planning for a Comprehensive Bridge Safety Assurance Program”, Transp. Res. Rec. No. 1290, *Transportation Research Board, Washington D.C.,* 137-142

[2] Wardhana, K. and Hadipriono, F.C., 2003. “Analysis of Recent Bridge failures in the United States”, *Journal of Performance of Constructed Facilities*, Vol. 17, No. 3, pp. 144-150.

[3] Biezma, M.V. and Schanack, F., 2007. “Collapse of Steel Bridges”, *Journal of Performance of Constructed Facilities*, Vol. 21, pp.398-405.

[4] Dargahi, B., 1990. “Controlling Mechanism of Local Scouring”, *Journal of Hydraulic Engineering*, ASCE, Vol.116, No.10, pp.1197-1214.

[5] Melville, B. W, Coleman, S. E., 2000. *Bridge Scour*, the University of Auckland, New Zealand.

[6] Melville, B.W., 1997. “Pier and Abutment Scour: Integrated Approach”, *Journal of Hydraulic Engineering*, ASCE, Vol.123, No. 2, pp. 125-136.

[7] Richardson, J.E. and Panchang, V.G., 1998. “Three-Dimensional Simulation of Scour-Inducing Flow at Bridge Piers”, *Journal of Hydraulic Engineering*, ASCE, Vol. 124, No. 5, pp. 530-540.

[8] Bolduc, L.C, Gardoni, P. and Briaud, J.L., 2008. “Probability of Exceedance Estimates for Scour Depth around Bridge Piers”, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No. 2, pp. 175-184.

[9] Johnson, P.A., 1992. “Reliability-Based Pier Scour Engineering”, *Journal of Hydraulic Engineering*, ASCE, Vol. 118, No. 10, pp. 1344-1358.

[10] Johnson, P. A. and B. M. Ayyub, 1992. “Assessing Time-Variant Bridge Reliability Due to Pier Scour” *Journal of Hydraulic Engineering*, ASCE, Vol. 118, No. 6, pp. 887-903.

[11] Lebeau, K.H. and Wadia-Fascetti, S.J., 2007. “Fault Tree Analysis of Constructed Facilities”, *Journal of Performance of Constructed Facilities*, Vol. 21, No. 4, pp.320-326.

[12] Holland, J. H., 1975. “Adaptation in natural and artificial systems”, *University of Michigan Press*, Ann Arbor, Mich.

[13] Goldberg, D. E., 1989, “Genetic algorithms in search”, *Optimization and Machine Learning*, Addison-Wesley, Reading, Mass.