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Scour Stability Evaluation of Bridge Pier Considering Fluid-Solid Interaction

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Abstract

Nowadays, the fluid behavior around pier is simplified by linear force distribution in bridge design when current force is considered. Therefore, the stability of the bridge may be overestimated because of the negligence of nonlinear force generated by down flow, wake verities and other fluid behavior in the vicinity of the pier. In order to consider the complicated fluid impact, finite element simulation is applied in this study by creating a fluid-solid interaction (FSI) system. Simulation result for both fluid and solid systems is transferred to each other in the FSI system. In this way, the force generate by fluid system can be added back to solid system to estimate the dynamic response of the pier. By analyzing the dynamic data of the pier, the safety factor of scour stability at each scour level and flow rate can be defined, which has the interval of 0.5m and 0.5m/s, respectively. The stability safety factor is further compared with the result from static numeral calculation, verifying the influence of dynamic fluid on pier scour stability. Finally, a stability contour of the safety factor, flow rate and scour depth is plotted. According to the numerical simulation, the limit flow rate at each scour depth can be easily determined, and applied as a guideline for bridge and traffic control, supporting disaster prevention and evacuation while flood strikes bridges.

Keywords: bridge scour; stability evaluation; fluid-solid interaction; soil spring

Introduction

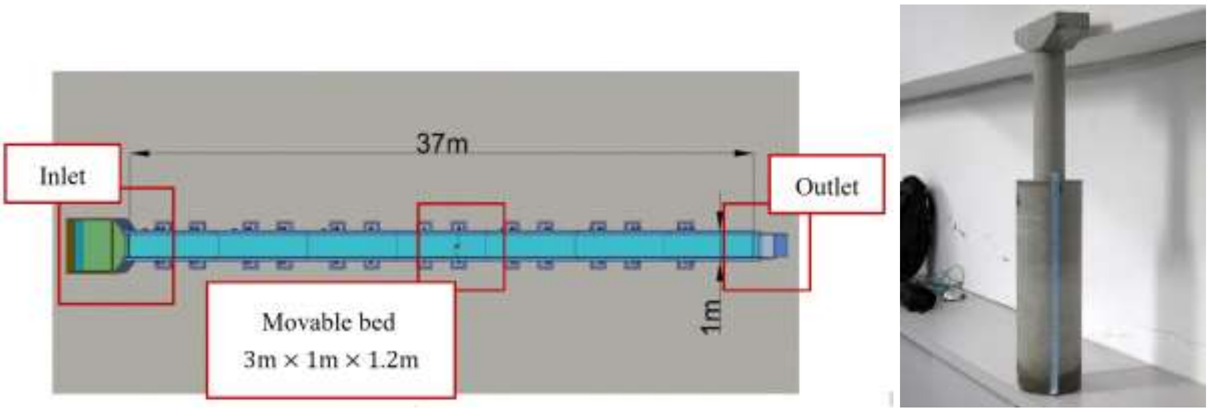
A survey (Shirhole and Holt 1991) in U.S. indicated that around 60% of bridge failure mode belongs to hydraulic while only 3% belongs to seismic, and a similar result was found in other survey in Taiwan. Scour, where the characteristic is classified as hydraulic, happened at pier while water flows by and causes lost of bed material near piers. Studies had shown how scour effects stability, bearing capacity and other performance of bridge foundation. Prendergast L.J. et al. (2013) builds numerical and realistic model for scaled and full-scale pile models. Analyzing the model response excited by an impulse force, loss of structure natural frequency, which implies a lower constraint, can be observed while scour happened. Focusing on pier of offshore wind turbine, Prendergast L.J. et al. (2015) and Tseng W.C. et al. (2018) both conclude that natural frequency drops and deformation increases while pier lost vicinity bed material by structure response and numerical model respectively.

Complicated fluid behavior in the vicinity of pier is simplified as a linear force in most building regulations. For studies about flow pattern and vortex around cylinder or scoured pier, Brücker C. (1995) plotted 3D vorticity downstream of a cylinder by Digital-Particle-Image-Velocimetry (DPIV) scanning technique. Graf W.H. & Yulistiyanto B. (1998) measured the velocity and vorticity fields around cylinder, describing the fluid behavior at pier vicinity. Akilli H. and Rockwell D. (2002) observed Kármán vortex and other vortex formations in shallow water. Graf W.H. and Istiarto I. (2002) measured the velocity field alone upstream and downstream of scaled pier model. These researchers concluded that fluid behavior of water at pier vicinity, especially pier with scour, is highly nonlinear, and velocity and vorticity fields change alone time and distance from pier. Normally, the fluid behavior might be minor comparing to live load and dead load of bridge. However, bridge failure might happened due to overestimation of stability while severe scour happened, which performances of pier are relatively worse.

Scaled model experiment

As barely study used fluid-solid combined numerical model to simulate a bridge pier, a scour experiment of a scaled hypothetical structure is conducted to provide a simulation target for FSI system in this study, verifying the capability of ANSYS that simulates the complicated interaction between fluid field and multi-degree-of-freedom (MDOF) system composed of bridge pier and soil springs.

In the scaled model experiment, a 37m by 1m sink with 1.2m-depth is set to have a constant flow rate of 2.5m/s as watercourse (see Fig. 1(a)) while a pier with 0.49m-caisson-foundation (see Fig. 1(b)) having initial embedded depth by 0.099m (see Fig. 2).



(a) *(b)*

Fig. 1. (a) The sink for experiment; (b) the scaled pier model

Ambient vibration is collected in three axes by 3 velocity meters set on top of pier model. In order to analyze the dominant frequency of pier alone time series, Short-time Fourier Transform (STFT) (Eq. 1), using 2048-point Hanning window with 50% overlap as window function, is applied in this study. According to the result of experiment (see Fig. 2), several sets of data, buried depth at 8, 6, and 5 cm which having main frequency at 10.76, 10.41, and 10.21 Hz, respectively, is select for numerical simulation.

$$X(\tau,\omega)=\int_{-\infty}^{\infty} x(t)\,w(t-\tau)\,e^{-i\omega t}\,dt$$

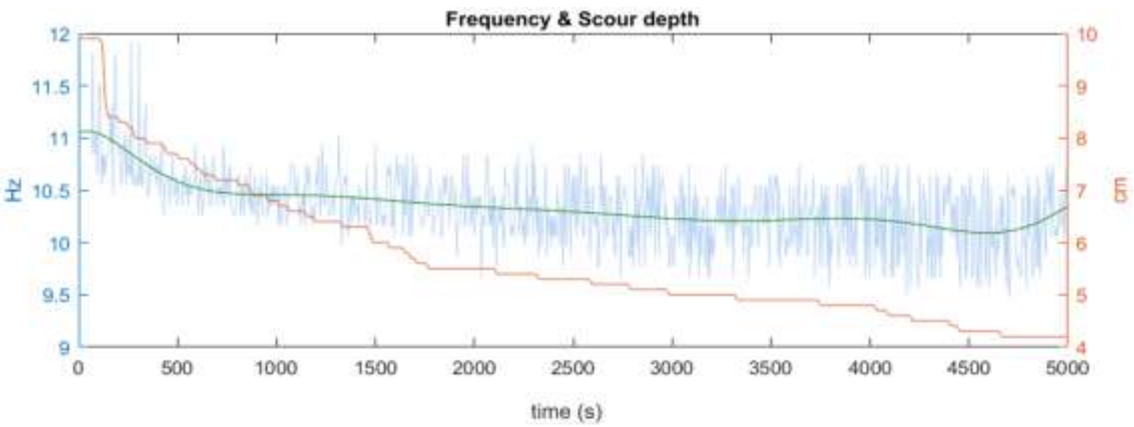
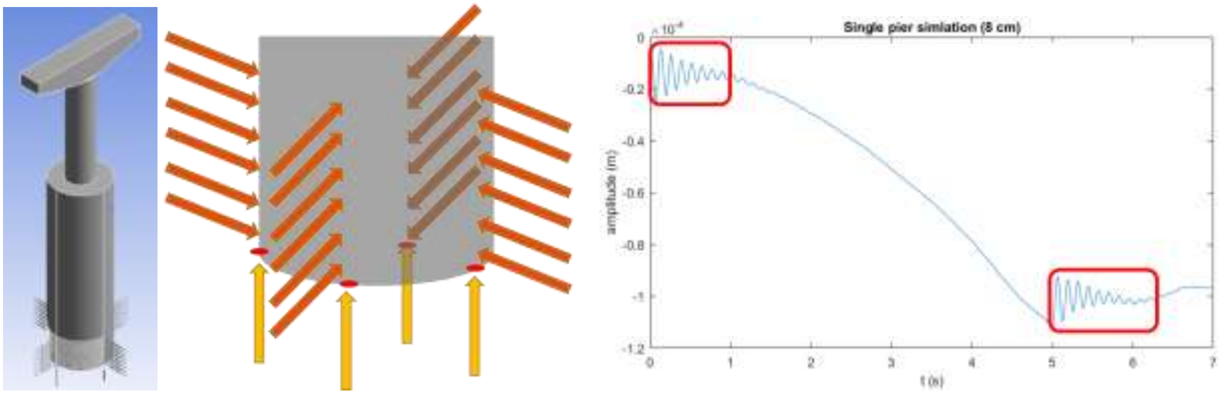


Fig. 2. dominant frequency(blue line) and scour depth(red line) of pier model

Numerical simulation

A numerical model is built by FSI system in ANSYS, and soil springs is set horizontally and vertically on the lower part of model to simulate soil pressure applied to the pier (see Fig. 3(a)(b)), and is removed according to the scour condition. In order to prevent model collapse and calculation error, a linear increment velocity of flow rate is applied in this simulation. As seen in Fig. 3(c), two free decay signals, having same vibration period, can be observed from the response on top of model at the very start and end of linear increment velocity of flow rate, and are later used in defining the natural frequency of pier model.



(a) *(b)* *(c)*

Fig. 3. (a)(b) Numerical model of scaled pier build in ANSYS; (c) response at the top of model

By analyzing the model response in simulation, natural frequency of model at each scour condition are shown in Table 1. Natural frequency of model in both experiment and simulation drops while buried depth decrease, caused by scour and removing soil spring, which reflects the reduce of soil constraint. FSI system shows its capability and applicability on pier scour simulation with a low error percentage of model natural frequency. The error might come from the negligence of friction between pier and soil, which underestimates the constraint condition.

Table 1. Simulation result

Buried depth (cm)	8	6	5
Freq. (experiment)	10.76	10.41	10.21
Freq. (simulation)	10.77	10.07	9.70
Error	0.1%	3.2%	5.0%

Conclusion

According to the result of simulation, pier scour simulation can be conducted with FSI system in the consideration of fluid behavior. The low simulation error, which is under 5%, of natural frequency of pier model represents that the established model can correctly simulate behavior of a scaled pier buried in riverbed, meaning which demonstrates the feasibility of conducting full-scale simulation for the dynamic characteristic including displacement and angle of inclination of piers of a practical structural. In the future, a numerical model in full-scale will be constructed to represent a practical engineering bridge, and scour stability considering fluid-solid interaction will be evaluated. The result can be applied to disaster prevention and traffic control while flood strikes.

References

Shirhole, A.M. and Holt, R.C. 1991. Planning for a comprehensive bridge safety program, Transportation Research Record, 1290.

Prendergast, L.J., Hester, D., Gavin, K., and O'Sullivan, J.J. 2013. An Investigation of the Changes in the Natural Frequency of a Pile affected by Scour, Journal of sound and vibration, 332(25), 6685-6702

Prendergast, L.J., Gavin, K., and Doherty, P. 2015. An investigation into the effect of scour on the natural frequency of an Offshore Wind Turbine, Ocean Engineering, 101, 1-11.

Tseng, W.C., Kuo, Y.S., Lu, K.C., Chen, J.W., Chung, C.F., and Chen, R.C. 2018. Effect of Scour on the Natural Frequency Responses of the Meteorological Mast in the Taiwan Strait, Energies, 11(823), 1-18.

Brücker C. 1995. Digital-Particle-Image-Velocimetry (DPIV) in a scanning light-sheet: 3D starting flow around a short cylinder, Experiments in Fluids, 19, 255-263.

Graf, W.H. and Yulistiyanto, B. 1998. Experiments on flow around a cylinder; the velocity and vorticity fields, Journal of Hydraulic Research, 36(4), 637-654.

Graf, W.H. and Istiarto, I. 2002. Flow pattern in the scour hole around a cylinder, Journal of Hydraulic Research, 40(1), 13-20.

Akilli, H. and Rockwell, D. 2002. Vortex formation from a cylinder in shallow water, Physic of Fluid, 14(9), 2957-2967.