Discussion on Some Problems of Bridge Scour in Both Experiment and Simulation

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Abstract. The scour of bridge piers is one of the important factors causing bridge damage. The research on the scour mechanism of bridge pier includes two main ways: physical experiment and numerical simulation. In this paper, the research progress in recent decades is summarized, and the influencing factors that include the Reynolds number, pier shape in physical experiments and the selection of models such as RANS, LES, DES in numerical simulation are sorted out. Both physical experiment and numerical simulation are used to investigate the depth of scour hole and flow structures. Finally, it is pointed out that the stress characteristics generated by scouring flow are one of the directions for further research.

1. Introduction

With the increase of the number of Bridges, more and more attention is paid to the safety and stability of Bridges. A safe bridge can bring convenient traffic to both sides of the straits and promote their economic development. Once the bridge is unstable, the safety accident caused by it will bring incalculable loss of life and property. According to the data collected by Renyan Yi \cite{1}, between 2000 and 2014, 106 bridge collapse accidents occurred in the operation stage in China, of which up to 30\% were caused by scour. More than a quarter of Bridges in the United States have structural or functional defects, according to annual national Bridges report of the Federal Highway Administration (FHWA) \cite{2}. Valdana and Hadiprio studied 503 piers that crashed between 1989 and 2000 and found that 50 percent of them were caused by erosion, including flooding and other hydraulic factors \cite{3}. British engineer D. W. Smith studied the causes of 143 bridge accidents that occurred between 1847 and 1975 and made a statistical analysis. He found that 70 bridge accidents, or about 50\% of them, were caused by flood scouring \cite{4}.

Scour has a great influence on the safety and stability of the bridge, but the scour mechanism, especially the scour mechanism of bridge pier, is still not enough. Long-term scour of piers poses a great safety hazard to the bridge infrastructure. In the flood period, severe scour and violent impact of floods will easily lead to instability and damage to the bridge structure. However, the complex flow structures around the piers make it difficult to study the scour mechanism of piers.
2. The Research Status
Local scour has been investigated as one of the categories of channel scour by both experimental and numerical ways. Melville and Raudkivi observed particular scour process by the way of physical experiment [5]. The flow patterns, turbulence intensity distributions and boundary shear stress distribution at the pier were found. Ahmed and Rajaratnam studied on smooth, rough and mobile beds, and had results of the frontal downflow and of the process of the scour hole [6]. They corrected the value of downflow in front of piers, but didn’t reveal the mechanism. To reveal more resemblant mechanism of local scour, Thomas et al. conducted experiments in a laboratory flume and validated against other laboratory and field data by a process-based method which relates certain dependent morphometric variables to an adapted obstacle Reynolds number [7]. There is still difference between the conditions of piers and obstacles that the horseshoe vortex system and downflow is stronger in front of the piers.

The horseshoe vortex (HV) system was always investigated by both experimental and numerical ways. G.Kirkil et al. got the result that the overall structure of the HV system varies considerably in space and time, though a large, relatively stable, primary necklace vortex is present practically all times inside the scour hole by ways of a dye tracer and image recording [8]. And G.Kirkil came up with the point that the large-eddy simulation (LES) is better suited computation technique than Reynolds-averaged Navier-stokes equation simulation (RANS) to understand the coherent structures present in the flow fields associated with pier scour, in particular the structure of the HV system around the pier. Therefore, the simulation what G.Kirkil did by LES successfully observed high levels of the mean bed shear stress beneath primary necklace vortex, especially over the region where the bimodal oscillations are strong, as well as beneath the small junction vortex at the base of the cylinder. As the perfect results were obtained by G.Kirkil, Christian Gobert and Ulrich C.E. Zanke compared their results with it [9]. That was demonstrated that because of the difference in Reynolds number the findings varied a lot and the increase of Reynolds number would change the HV system.

3. Physical Experimental Research
Experimental studies were carried out for several years by many investigators in different situations, e.g. a clear water scour or a live bed scour, steady or unsteady flow, uniform or non-uniform sediment, the number of the piers, and their arrangement. These conditions would lead to big differences, so the investigators wanted a macroscopic parameter to analysis the results that is the Reynolds number. B.Dargahi conducted a experiment in a fully developed turbulent open channel flow and had a result that there were a vortex system and the wake vortices which were independent with the vortex system and the number of the wake vortices increased with increasing Reynolds number [10]. And the Reynolds stress was considered as a factor of the bed-shear stresses distribution in the experiments conducted by Subhasish Dey and Rajkumar V. Railar within the developing scour holes at a cylindrical pier [11]. The experiments also revealed the evolution of the characteristics of the horseshoe vortex flow associated with a downflow from the intermediate stages to equilibrium condition of scour holes. Chang Lin et al. defined four major categories while the Reynolds number varies from 400 to 11000 and the height-to-width ratio changes from 0.5 to 4.0, including steady vortex system, periodic oscillation vortex system with small displacement, periodic breakaway vortex system and turbulent-like vortex system [12].

Except the Reynolds number the investigators had interests in the number of the piers and the shape of the pier. B.Ataie-Ashtiani and A.A. Behshiti conducted the experiments under steady clear-water scour condition to predict the maximum local scour depth which considered the number and arrangement of the piers [13]. And the experiment about shape of a pier is carried out by Ali Khosronejad and Seokkoo Kang under clear water scour with cylindrical, square, and diamond cross-sectional shape that indicated the strength of the mean turbulent HV system the intensity of the bi-modal turbulent HV system fluctuation depend critically on the details of the pier nose geometry and in particular on the so-called bluntness factor [14]. There are also some researchers focus on the particular piers in particular situations, e.g. W.Y. Chang et al. [15], who mounted a rectangular pier in
the middle of a river and changed the angle of attack to find out the role of HV system during the start of the scour, and Shaghayegh Ben Mohammad Khajuh et al. [16], who mounted an inclined cylindrical bridge pier in the apex of a sharp 180-degrees bend to measure the places of the highest and the lowest scour depth.

4. Numerical Simulation Research

Due to the limitations of measurement technology and the development of computation, many investigator turned to simulation of the field which can express the distribution of HV system around the pier and the downflow in front of the pier successfully. In 1998, John E. Richardson and Vijay G. Panchang compared their results of the numerical simulation by RAN model with the laboratory observations by Melville and Raudkivi(1977) [17]. The RAN model provides a possibility to simulate the transport processes. But the limitation of RAN model was pointed that the local vertical flow and turbulent fluctuation are not involved in case of the simulation. Therefore, investigators tried to simulate more precisely the scouring process with other models e.g. URANS, DES, LES. 

The simulation of a bridge foundation mounted on a fixed flat bed was done by Liang Ge et al. and was compared with the experiments, and that showed the URANS model can be used not only to study the structure of water flow, but also to study the physics of water flow [18]. The capability of URANS to calculate the intensity of vortexes around the pier was discussed by investigators who focus on the dynamics and the energy of turbulence HV system. LES also worked well in these aspects that can capture even small numerical change of the vortex. R.Pasiok and E.Stilger-Szydlo simulated the flow structures which were carried out with LES that showed a strong interdependence of vortexes around a pier, including down flow, horseshoe and wake vortexes, and the mutual influence was worth to be studied [19]. It shows some superiority in calculation of vortex and bed shear stress. But the ability is limited by the Reynolds number, and LES is not helpless for high Reynolds number. 

Joongcheol Paik and Fotis Sotiropoulos chose a DES model to simulate dynamics upstream of a long rectangular block in a channel of a high Reynolds number and relatively approximated to the results of the experiment [20]. DES is a kind of combination of RANs and LES that will reduce computation while maintaining a certain precision at a high Reynolds number. Therefore, the basic conditions of the scour and the component that need to be solved determine the selection of the model of simulation which is the key to simulate successfully.

5. Study on Depth of Scour Hole and Flow Structures

Whatever the study is experimental or numerical, the objective is almost two: the depth of scour hole and the flow structures. The depth of scour hole is the standard to determine the accuracy of simulation, and it’s maximum value is the standard to design the protection of piers. Cheng Lan-yan et al. placed a semi-circular baffle on the pier where was about a third of the depth of flow to bed, and it was found that the maximum depth of the scour hole had reduced by 57.6% [21]. The common protections include expanding the base of the bridge pier, riprap protection et al. and all the protections are to reduce the scour depth, particularly the maximum depth which is often found directly in front of the piers.

The flow structures, a research hotspot, are considered as the inner reasons how the scour hole forms. The flow structures are a more popular research topic than the former over the last couple of decades. W.A. Eckerle and L.S. Langston found a vortex system which was named as horseshoe vortex system and was a contribution to scour around a single pier, especially in the initial stage of the scour process [22]. But it isn’t the sole reason, and there are two more kinds of vortexes named downflow and wake rollers which exist by the pier and also make a contribution to the scour.

Ahmed and Rajaratnam investigated the downflow past cylindrical piers on smooth, rough, and mobile beds respectively with Acoustic Doppler Velocimetry (ADV) which might disturb the flow structure [6]. To measure the accurate data J. Unger and Willi H. Hager conducted an experiment with Particle Image Velocimetry (PIV) [23]. And these data they measured indicated the downflow in front of pier didn’t show an obvious evolution with time but was still considered as an important role during
the scour process. As is well-known the place where scour starts is the leaning toward the pier in the initiate stage rather than the front where there are both the strong downflow and horseshoe vortex. It’s considered that the sediment placed directly in front of pier is not easy to move contrast to the other that is laterally from the pier and can move along the boundary of the pier base and bed. Additionally the downflow might creates a pressure stress on the surface of the bed and increases the difficulty of the sediment entrainment. As the scour process and the entrainment of lateral sediment proceed, the sediment in front of pier moves and separates from the sides of pier. And the strength of downflow and horseshoe vortex becomes a more important role in the local scour and led to the formation of the deepest hole.

Contrary to the downflow the wake roller in the wake region forms a more shallow scour hole. G. Kirkil et al. made a simulation with DES model and realized there was a strong upwelling phenomena behind the pier actually [24]. It was considered the wake roller was under influence by the separation point. The separation point is formed under the double function of the boundary and shear layers. The side of the pier exists the adverse pressure gradient which is affected by the flow velocity at different heights. Under the effect of the adverse pressure gradient and the frictional resistance along the pier the separation point will be dependent to the height. And it is proved that the separation point will move upstream as the distance from the bed increases. That might cause a cavity and make the flow upward. The drag force plays a more role in the wake region and the shear stress is weaker. And sediment is harder to move while it’s under the action of a force that is only one direction.

6. Question and Discussion
There was a lot of research been done past decades about both scour mechanism and simulation. The dynamics had been applied to analyze the vortex evolution, particularly in the front of pier. But there are still differences between experiments and simulation about the depth of scour hole. The maximum depth is the straight front of pier for experiments, while it’s a little of to the side for simulation. This might be the reason that the force produced by downflow changes the architecture of forces in the scour hole and it’s not on the table. As a kind of sandy solid the destruction mechanism of sediment is under the effect of forces clearly. Because of the presence of the horseshoe vortex system, the effect of downflow to sediment is still difficult to quantitative.

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