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MONITORING OF BRIDGE SCOUR USING CHANGES IN NATURAL FREQUENCY OF VIBRATION – A FIELD INVESTIGATION

LA SURVEILLANCE DE L'AFFOUILLEMENT DES PONTS EN UTILISANT DES CHANGEMENTS DE FRÉQUENCE NATUREL DE VIBRATION – UNE ÉTUDE SUR SITE

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ABSTRACT – The high profile failure of the Malahide Viaduct in late 2009 in Dublin was attributed to erosion of the supporting soils, commonly referred to as foundation scour. This is a more widespread geotechnicalstructural problem, where foundation scour has been identified as the number one cause of bridge failure in the United States. In light of current changes in climate, increased frequency of flooding, coupled with the increased magnitude of these flood events, leads to a higher risk of bridge failure occurring. Monitoring scour is of significant importance to ensure the continued safe operation of the aging bridge asset network. Most monitoring regimes are based on using expensive underwater instrumentation that is often subject to damage during times of flooding, when scour risk is at its highest. In this paper, a technique based on using dynamic measurements to monitor scour is described. Accelerometers placed on the structure, above the waterline, may be used to detect changes in natural frequency arising from the loss of stiffness due to scour.

1. Introduction

Scour can be defined as the excavation and removal of material from the bed and banks of streams as a result of the erosive action of flowing water (Hamill, 1999). Scour occurs in three main forms: General scour, contraction scour and local scour. General scour occurs naturally in river channels and includes the aggradation and degradation of the river bed that may occur as a result of changes in the hydraulic parameters governing the channel such as changes in the flow rate or changes in the quantity of sediment in the channel (Forde et al., 1999). Contraction scour occurs in the general vicinity of channel obstructions, in this case, a bridge. It manifests itself as an increase in flow velocity, and resulting bed shear stresses, caused by a reduction in the channel's cross-sectional area at the location of a bridge. Finally, local scour occurs around individual bridge piers and abutments. It is caused by the generation of vortices as water accelerates around these obstructions. Downward flow is induced at the upstream end of bridge piers leading to very localized erosion in the direct vicinity of the structure (Hamill, 1999).

The depth of scour around a bridge structure is the addition of the individual scour depths caused by the aforementioned mechanisms. The scour hole generated has the effect of reducing the stiffness of foundation systems and can lead to catastrophic structural failure. In one study of 500 bridge failures in the United States that occurred between 1989 and 2000, 53% of failures were attributed to adverse hydraulic action, including scour (Wardhana and Hadipriono, 2003).

Scour can be combatted in a number of ways. At the bridge design stage, it is possible to allow for

scour mitigation by providing both hydraulic and structural countermeasures. Hvdraulic countermeasures pertain to the prevention of rapid flow expansion caused by sudden induced changes in flow direction that would occur at blunt pier faces. These sudden flow changes create vortices (horseshoe and wake) responsible for the occurrence of scour in these areas. They can be prevented by maintaining larger bridge openings and also by streamlining pier geometries (May et al., 2002). Structural countermeasures can be implemented at the design stage by ensuring spread footings are located below maximum design scour depths, or as remediation by adding rockarmour to the base of piers and abutments. A more effective and economically viable method of combatting scour is to monitor its evolution over time. A number of instruments have been developed that can monitor the depth of scour around bridge piers. These are outlined in section 2.



Figure 1. Malahide Viaduct Collapse, 2009

2. Scour Monitoring

2.1. Scour Monitoring using Underwater Instrumentation

A myriad of existing instrumentation aims to observe the change in scour depth over time. These instruments can be broadly segmented into the following categories: single-use devices, pulse / radar devices, buried / driven rod systems, soundwave monitoring devices, and electrical conductivity devices.

Single-use devices consist of float-out devices and tethered buried switches. These devices are installed in the ground, near a pier or abutment of interest. They remotely send signals to dataacquisition systems indicating their status, be it in position or floated out. They float out of the soil once the depth of scour reaches their installation depth. The primary difference between both of these devices is that tethered buried switches have three status indicators, "in position", "floated out" or "not operational" whereas float-out devices typically only have two settings, "in position" or "floated out".

Pulse / radar devices utilize radar signals or electromagnetic pulses to determine changes in the material properties that occur when a signal is sent through a changing medium. This typically occurs at a water-sediment interface and thus indicates a scour depth at a particular location. Time-domain Reflectometry (TDR) is one method that uses changes in the dielectric permittivity constants between materials to determine a depth of scour at a particular location. Measuring probes are installed into the soil at a location of interest and a fast-rising step impulse is sent down a tube which determines the interface between the water and the soil, and hence the depth of scour. These devices may be used to observe the changing scour depth with time (Hussein, 2012). Ground-Penetrating Radar (GPR) uses radar pulses to determine the water-sediment interface and hence the depth of scour. The device works similarly to the TDR arrangement above but does not require probes to be installed into the stratum. It involves floating a GPR transmitter along the water surface and obtaining a geophysical profile of the riverbed as it passes. A disadvantage of this method is that it requires manual operation and cannot be used during times of heavy-flood flow when scour is often at its highest risk.

Piezo-electric film sensor devices can comprise Fibre-Bragg Grating sensor elements arranged along cantilevered rods installed into the soil near a bridge pier. These systems monitor the real-time progression of scour depth by picking up straindeformation in the sensor elements, as they become exposed to the flow. When the rod is surrounded by soil, no bending occurs and hence no strain. However, when exposed, the rod bends and the strains can be used to show the scour depth. As more of the rod is exposed, more of it bends indicating that the scour depth has increased. These devices work particularly well at monitoring the change in scour depth with time.

Other driven / buried rod systems include the Magnetic sliding collar, the "Scubamouse", the Wallingford "Tell-tail" device and Mercury Tip Switches. These instruments work on the principle of a manual or automated gravity-based physical probe that rests on the streambed and moves downward with increasing progression of scour depth. A remote sensing element is typically used to detect the level change of the gravity sensor. In the case of a magnetic sliding collar, the location of the collar relative to its original position is determined by the closure of magnetic switches along the structurally rigid rod. The "Scubamouse" works in a very similar way to the magnetic sliding collar, except in this case the location of the collar is determined by sliding a radioactive sensing element into the supporting steel tube, which locates the collar. Mercury tip switches work on the very basic principle that when a steel pipe is augured into the ground, switches located along the shaft fold up against the pipe, which closes the circuit. As streambed material is eroded away, the switches open iteratively which breaks the circuit and monitors the progression of scour.

Numerous devices have been developed that use sound waves to monitor the progression of scour holes. They work on the same principle as devices that use electromagnetic waves, in that waves are reflected from materials of different densities thus establishing the location of watersediment interfaces and hence, the depth of scour at a particular location. Sonic fathometers can be mounted on bridge piers and use these methods to build up continuous profiles of the streambed. Reflection seismic profilers can be towed manually across water surfaces and can build up profiles of the streambed and observe where scour holes exist. Echo sounders work in a very similar manner to reflection seismic profilers also and can be used to determine scour hole depths (Anderson et al., 2007).

Finally, many devices have been developed that use the differences in electrical conductivity of different media to determine the location of the water-sediment interface. An example of a device is Probes. This Electrical Conductivity device measures the ability of a solution to conduct an electric current between two electrodes. In solution, current flows by ion transport. An increase in ion concentration will result in higher conductivity values. The conductance of streambed material will be different to that of flowing water. Therefore, as these probes are exposed, the conductance value measured will be different to the unexposed case allowing for scour to be measured.

Most of the instrumentation described in this section has the disadvantage of either requiring underwater installation, which can be costly, or can only be used discretely as part of routine inspections. This is a notable disadvantage. Monitoring the response of the bridge structure has gained significant interest in recent times and is described in section 2.2.



Figure 2. Scour Monitoring Devices

2.2. Scour Monitoring using dynamics

The evolution of scour monitoring has mostly been based on using underwater instrumentation that measures the progression of scour depths with time. Little research had been undertaken until recently into the effect that scour has on the response of the structure itself. This is a very important aspect of the scour process, since its occurrence can lead to bridge failure.

The response of a bridge to both static and dynamic loads is governed by the soil-structure interaction (Foti and Sabia, 2011). This interaction process is quite complex. Scour has the effect of reducing the stiffness of foundation systems upon which bridges are founded. The reduction in stiffness has an effect on the dynamic response of sub-structural components of a bridge. A reduction in the natural frequency of bridge piers is expected as scour removes soil material from around the base of the structure. The natural frequency of the bridge pier-foundation system can be determined from accelerometers placed on the structure.

Several authors have investigated the feasibility of using dynamic measurements to detect the presence of scour. A full scale investigation was undertaken in Northern Italy on a bridge that had been adversely affected by scour during a flood in 2000 (Foti and Sabia, 2011). One of the supporting piers had to be replaced. A dynamic survey was undertaken on the bridge before and after the replacement of the pier. A numerical model of the bridge was developed to act as a sensitivity analysis in determining the parameters of interest for scour monitoring. The bridge spans were analyzed by undertaking a modal analysis to determine the natural frequencies both before and after the pier retrofit, whereas the pier response was analyzed by looking at the asymmetric dynamic response of the foundation system. The research concluded that the presence of scour was detectable but the extent of the scour was not.

A laboratory and field investigation undertaken in the United States recently aimed to study the effectiveness of various instruments at monitoring scour, including the use of accelerometers (Briaud et al., 2011). A scaled bridge was constructed in a large hydraulic flume at Haynes Coastal Engineering Laboratory, Texas A&M University. Two foundations types were tested, shallow and deep, as these are the most common foundations used on bridges. The study showed that accelerometers placed on bridge piers showed significant potential at detecting the presence of scour at laboratory scale, where impact tests were performed to simulate traffic excitation. However, the full-scale bridge monitoring attempt was not as successful. Low excitation due to the traffic loading as well as the high energy required to transmit accelerometer data were given as the reasons for the lack of success at field deployment.





3. Field Investigation

A full-scale field investigation is planned to take place at the University College Dublin dense sand test site located in Blessington, approximately 25 km southwest of Dublin City. The test aims to observe the effect that scour has on the frequency response of a driven steel pile, much like those used to support road and rail bridges. An openended steel pile was driven into the sand stratum to a depth of 6.5 m. A 2.26 m long section was left exposed above the ground line, along which accelerometers were fitted.



Figure 4. Installed Pile with Accelerometers

The site conditions at the Blessington site comprise a very dense, fine sand that is partially saturated. The main properties of the site are a bulk density of 2.10 Mg m⁻³, a unit weight of 19.8 kN m⁻³, a constant volume friction angle of 37° and a peak friction angle ranging from 54° to 40° over the depth of embedment of the pile (Gavin and Tolooiyan, 2012; Tolooiyan and Gavin, 2011).

The scour test planned aims to observe the change in frequency with increased depth of scour as the lateral restraint provided by the sand is removed in progressive experiments. As sand is removed, the global system stiffness is compromised and a reduction in the natural frequency is expected. By comparing the results obtained to a reference numerical model, it may be possible to predict the scour depth around a foundation structure based on an observed value of natural frequency.

4. Conclusions

Most scour monitoring equipment involves expensive underwater installations that often are subject to damage by flood debris. In this paper, the use of dynamics to monitor the progression of scour is discussed and a full-scale field test is planned. Reference numerical models may be used to obtain a depth of scour for a particular observed natural frequency value.

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