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Verfügbar unter/Available at: <https://hdl.handle.net/20.500.11970/100327>

Vorgeschlagene Zitierweise/Suggested citation:

Dumas, Christopher E.; Krolack, Joseph (2002): A Geotechnical Perspective: Design and Construction of Highway Bridge- Foundation of Scour. In: Chen, Hamn-Ching; Briaud, Jean-Louis (Hg.): First International Conference on Scour of Foundations. November 17-20, 2002, College Station, USA. College Station, Texas: Texas Transportation Inst., Publications Dept.. S. 112-119.

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A Geotechnical Perspective: Design and Construction of Highway Bridge Foundations for Scour

By

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ABSTRACT

Scour of foundation soil and rock is the most common cause of bridge failures. To address this problem, AASHTO and FHWA developed and implemented comprehensive and stringent design guidelines and codes during the late 1980's and early 1990's. Although, scour related losses have been significantly reduced as a result of their implementation, significant concurrent increases in foundation costs and construction difficulty have occurred as well.

This paper examines the causes of scour related escalation in foundation costs and constructability difficulties from a geotechnical perspective. The focus will be on: (a) key considerations within the current scour design and construction processes; (b) application of scour codes and guidelines; (c) gaps in processes and guidelines; and (d) scour research priorities.

INTRODUCTION

By far, the most common cause of bridge failure is the scouring of soil and rock from around the foundations. The seriousness of this problem with respect to the cost of direct damage, economic disruption, and loss of life led FHWA and AASHTO to develop and implement comprehensive and stringent design guidelines and codes. As a result, scour related losses have been significantly reduced since in the late 1980's and early 1990's, when these guidelines and codes were implemented. However, concurrently, there has also been a significant increase in foundation costs and construction difficulty associated with scour foundations. It is not uncommon for foundation costs increasing by a factor of between two and four. For a single \$100 million bridge project, this can represent an increase foundation cost of between \$10 million to \$40 million. On an extremely large project, scour requirements increased the cost of a single pier foundation by \$10 million. In most instances, these cost increases are attributable to:

- (i) A non-interactive, compartmentalized process where little interaction/coordination exists between hydraulic, geotechnical and construction engineers.
- (ii) Conservative and/or incomplete application of AASHTO and FHWA requirements
- (iii) Gaps within the current guidelines
- (iv) Various combinations of items i through iii.

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This paper presents a geotechnical perspective of: (a) key considerations within the current scour design and construction process; (b) how and why Highway Agencies, consultants, should develop and fully implement detailed written protocols for the determination of foundations scour; and (c) improvements needed in processes, guidelines, and research.

SCOUR PREDICTION PROCESS

Scour is a fundamental component of bridge foundation design. Scouring of foundation soils directly impacts foundation performance and, therefore, the type, size and constructability of the foundation.

At the same time, scour is fundamentally dependent upon the foundation type, size, and geometry. Therefore, foundation design, and the estimation of scour depths, should inherently be an iterative and interactive activity between Bridge Engineers, Geotechnical Engineers, and Hydraulic Engineers.

The need for this interdisciplinary process is explicitly stated and implicitly embedded throughout the FHWA scour evaluation guidelines (1).

Unfortunately, the current practice by which scour prediction and foundation design are executed is not interactive, iterative or interdisciplinary. Often, the hydraulic engineer becomes involved in design at a relatively late stage of the process. They are presented with a bridge design where major structural, geometric (layout), and geotechnical elements have already been established a-priori. Unfortunately, these designs (often inefficient from a hydraulic perspective) can introduce the very factors that result in large scour magnitudes. An example is a recent interchange project where thirty percent bridge plans were developed without consideration and incorporation of issues that were known by hydraulic engineers as of importance. Piers were designed skewed to the stream and flood plain flow, and the selected foundations cause significant flow constrictions. The results of the subsequent hydraulics analysis showed excessive scour as well as backwater flood levels, which did not meet FEMA permitting requirements. Expensive and time consuming redesign activities ensued.

Another non interdisciplinary process is one in which each of these discipline develops their own scour prediction estimates. The hydraulic engineer makes his/her estimate based very limited, or generalized, input provided with respect to the foundation size and special geotechnical considerations. This scour prediction value is then passed onto the geotechnical engineer who in turn develops a geotechnically modified value, and sends it to the bridge engineer who then develops his modified value.

The one typical outcome of these processes is that all parties are surprised at the complexity and rapidly increasing cost of the project. In essence, all three parties have engaged in a non-interactive, non-iterative compartmentalized process does not permit any optimization. As described later in this paper, this process can be particularly costly at sites requiring scour countermeasures and those with multiple soil layers and rock.

PERMANENT SCOUR COUNTERMEASURES

Similar to scour prediction, there is a lack of focus on fundamental design and construction issues, and a lack of appropriate interaction between hydraulic, geotechnical, and construction engineers. This is demonstrated by the fact that the number one cause of failures for countermeasures is not the

hydraulic design and/or countermeasure selection, but inadequate geotechnical, geosynthetics, and installation design. Specifically, these countermeasure are based and constructed upon underwater soil slopes that typically require benching and geosynthetics.

In particular, benching is required for short term and long term stability of the slope. The countermeasure needs to be properly keyed into the soil so that it will remain stable and avoid undermining (2). To be effective, benching requires specialized knowledge of soil engineering characteristics, slope stability, and construction placement, specifications, and quality control.

Geosynthetics are essential for filtration, and bridging of the countermeasure weight. Filtration allows the water pass, but leaves the soil in place. Bridging keeps the countermeasure intact by spread the load out over a large soil area and, thereby, keeping the countermeasures from sinking non-uniformly. This requires specialized knowledge of geosynthetics and their construction (3). Selection of an appropriate geosynthetics requires knowledge of (a) material characteristics such as creep, long term filtration capability for the site specific soils, degradability, susceptibility to construction damage; (b) material specific quality control methods and testing; and (c) writing geosynthetics specifications. Successful installation requires detailed knowledge and experience in placing geosynthetics underwater, and writing effective construction specifications and quality control protocols.

GEOTECHNICAL SITE INVESTIGATION

Another area where interdisciplinary coordination is in needs of improvement is geotechnical site investigations. Specifically, field and laboratory information needed for a detailed site specific scour analysis is frequently not evaluated and incorporated into the geotechnical investigation. Investigation and laboratory testing guidance is provided in FHWA HEC 18 and the 1991 FHWA Memorandum on rock scourability. Insufficient coordination and/or incomplete application of FHWA guidance too often result in cost increases and time delays from:

- a. Conservative and difficult to construct foundations. Insufficient information is collected to execute, or rely upon, a site specific scour evaluation as recommended and outlined in HEC 18 scour estimation procedure (page 2.1), and the 1991 FHWA Memorandum on rock scourability.
- b. Additional drilling mobilizations and lab work. If the initial site investigation and scour prediction indicates an extremely costly scour depth, a site specific evaluation may be undertaken. Consequently, a second phase drilling will probably be required, as well as a lab program to obtain pertinent information not collected in the first phase. The costs and time associated with second phase are considerable once initiated. For example,
 - Two-months to scheduled and begin drilling, one to six month to execute drilling, and one to two months to perform lab work, and revise scour prediction and foundation calculations—four to ten months total.
 - \$10,000 Mobilization Cost
 - \$5,000 per day of drilling, or \$100,000 per month of drilling.
 - \$10,000 to \$50,000 in lab testing costs.

MULTI-LAYER GROUND STRATIGAPHY

Currently, there is no direct guidance for estimating scour for sites with multi-layer ground stratigraphy. As a consequence, the scour prediction is frequently based on the very fine upper soil layer which in turn results in unrealistic scour design values—calculated scour values can significantly exceed the depth of the soil layer itself. This extremely conservative approach is one of the more frequent causes of high foundation costs. From a geotechnical perspective, scour calculations for a multi-layer site need to be performed in as series of scour calculations that emulate the sequence of scour occurring at the site. In addition, this situation strongly demonstrates the need for a site specific scour study as outlined in HEC 18.

SCOUR IN ROCK

In 1991, the FHWA Bridge Division issued a Memorandum (4) that provided “interim” guidance on empirical methods and testing to assess rock scourability, until result of ongoing research permit more accurate evaluation procedures.

Prior to this Memorandum, the lack of guidance on rock scour had frequently resulted in unrealistic conservative rock scour estimates that profoundly increased foundation costs and construction difficulty, while no quantifiable improvement to bridge reliability. Two common methods that result in these extremely conservative scour estimates where:

- Scour estimates where based on the particle size of the soil above the rock.
- Over-reliance on calculated scour values versus site specific historical behavior.

The 1991 Memorandum set out guidance to address this problem as follows:

- a. Introduce some level of understanding of common geotechnical information and methods for indexing the engineering characteristics that could rationally be employed by hydraulics engineers for the prediction of rock scourability.
- b. Establish and clarify that the geotechnical information is an Index Testing based approach which should be supplemented by local experience and historical data (bridge inspection reports, etc.)
- c. Begin and interdisciplinary approach to scour prediction.
- d. Bring an awareness of the cost and construction implications of scour

The Memorandum did succeed at many of the objectives, but a key issue not explicitly stated in this 11-year old memorandum is that the scourability of rock is typically very different than that for soil. Specifically, rock formations are not large gravel deposits for which an extrapolation of particle size and water velocity method for sands is reasonable. Rock formations are commonly large masses that have cracked in-situ over time. The rock segments are extremely large and are held in place

not only by gravity, but also by very high interlocking friction. In these cases, it is rock erode-ability that will impact the removal of support from the foundation. The Memorandum did provide recommendations on appropriate testing procedures for indexing of rock erodeability (Slake Durability, Soundness, Abrasion), but did not provide explicit guidance about how testing procedures should be used in conjunction with RQD, unconfined compressive strength, local experience, and interdisciplinary interaction.

The New River Bridge Replacement project is an excellent example of common interpretation and application of the 1991 Memorandum. The foundation design called for a spread footing keyed into the dense limestone. The limestone was horizontally bedded, and had an RQD average of about 40%. As per the Memorandums recommendation for RQD values lower than 50%, the designer called for the limestone around the footing to be removed for a considerable distance around the footing, and replaced by a rip rap countermeasure. A “strict” reading of the Memorandum and FHWA scour countermeasure guidelines (4) would have resulted in this design becoming the constructed configuration. However, in this case, review of the proposed design by the DOT and FHWA triggered the DOT to perform a more detailed site-specific geotechnical and hydraulic evaluation of the existing bridge’s foundations.

The investigation found no evidence of scour, or rock erosion, at the existing foundations, and concluded that the scour performance would be better without removal and replacement. Removal techniques would further fracture the existing rock, and replacement with rip rap would change a rock erosion scour condition, to a large particle scour condition. The understanding of the nature of the site allowed design of a more suitable scour countermeasure. The site investigation saved construction time, difficulty, and cost (i.e., several million dollars) while providing a significant reduction in rock scour potential. The site investigation saved construction time, difficulty, and cost while providing a significant reduction in rock scour potential.

SCOUR ESTIMATE METHODS, AND RESEARCH NEEDS

Due to extreme complexity, foreseen and unforeseen interactions, and the highly site specific nature of soil conditions, geotechnical engineering relies heavily on semi-empirical design methods developed via correlation and calibration of field observations. Intrinsic to the effectiveness of this method is the ability to obtain direct measurements of actual performance (load testing, etc.) and site geotechnical conditions. New methods and theories are always evaluated, and calibrated with these direct field measurements.

Scour estimation is, at the least, an equally complex task that is also highly site specific and influenced by many foreseen and unforeseen interactions. From a geotechnical perspective, scour estimation and research activities should be driven by this reality. Unfortunately, this does not seem to be the case for scour. The current equations and methods for calculating bridge scour are based primarily on laboratory research. For a multitude of reasons, very little field data has been collected to verify the applicability and accuracy of the various design procedures for the range soil conditions, flow conditions, and bridge configurations.

RECOMMENDATIONS

This paper has presented a geotechnical perspective as to the causes of scour related escalation in foundation costs and construction difficulties. From this perspective, key scour design and construction processes; guidance documents, and research priorities were identified and examined. Recommendations for improvements in these areas are presented below.

1. Scour Prediction Process (Soil and Rock). Highway Agencies, Consultants, and other Organizations involved in the design and construction of bridges should develop and fully implement detailed written protocols for the determination of foundations scour. These protocols should be based on the design philosophy, concept and procedures as presented in FHWA publication HEC 18 , and reflect the iterative, interactive, and interdisciplinary nature of scour prediction for bridge foundations.
2. Permanent Scour Countermeasures. Successful design and installation of scour countermeasure requires advanced hydraulic, geotechnical, and construction engineering expertise. The depth of expertise in each of these disciplines far exceeds what a single hydraulic, geotechnical, or construction engineer will possess. Therefore, as with the scour prediction process, interactive and interdisciplinary protocols for the selections and design of countermeasures should be developed and implemented.
3. Geotechnical Site Investigation. The planning and execution of geotechnical site investigations should encompass information needed for the overall site specific scour evaluation and prediction analysis. This would include drilling locations, soils data, and lab testing as outlined in HEC 18, and the 1991 FHWA Rock Scour Memorandum.
4. Multi-Layer Ground Stratigraphy. Scour calculations for a multi-layer site should be performed in as series of scour calculations which emulate the sequence of scour occurring at the site. A possible procedure is as follows:
 - i. Calculate the scour depth using hydraulic and geotechnical data for the top soil layer. If this number is greater than the depth of the top layer, the top layer is scoured away. Go to step ii.
 - ii. Adjust the input parameter to account for the removal of the top soil layer. Calculate a scour depth using the adjusted input, and geotechnical data from the second layer. If this number is greater than the depth of the top layer, the top layer is scoured away. Go to step iii.
 - iii. Repeat step two until a calculated scour value doesn't exceed the specific soil layers thickness.

6. Scour in Rock.

- a. Rock Scour estimates should always include consideration of specific historical behavior, and performance of rock. Estimates should not be based solely on RQD nor should they ever be based on the particle size of soil above the rock.
- b. Interdisciplinary Task Force should be assembled with the mission of developing clear guidance for differentiating between erode-able and scour-able rock. This may be best achieved by expanding the 1991 FHWA Memorandum to include more direct guidance as to how the geotechnical index tests for erode-ability should be used in conjunction with RQD, unconfined compressive strength, local experience, and interdisciplinary interaction.
- c. Develop a national Standard RQD, and Coring equipment and methods. RQD and coring methods are not homogeneous across the USA.

7. Scour Estimate Methods, and Research Needs. The number one priority of scour research and allocation of funds should be focused on:

- I. Developing equipment for accurately measuring insitu scour depth as they occur. This not a hydraulics, geotechnical, or civil engineering problem. It requires individual experts in sensor, wireless technologies, and electrical engineering. Great advances in technology for non civil engineering application have occurred over the last ten years--technologies that could be adapted to this specific use.

An example of this is ultra high bandwidth wireless technology that can transmit signals through concrete. In addition, it is essential that the decision process for developing and implementation of such equipment and systems evaluates the cost of the system relative to the hundreds of millions of dollars that can be save in a few short years via improved scour prediction reliability, and not relative to the initial installation costs.

- II. Designing and implementing a comprehensive national monitoring program that will generate the data needed to improve the accuracy of scour predictions over a wide variety of geotechnical, hydraulic, and structural conditions. This a very similar approach to earthquake research in which instruments are installed to “listen” and record seismic events which may decades after their installation.

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