

Review

A Review on Bridge Scour Analysis in Cohesive Soils and Scour-Susceptible Rocks

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Abstract

Bridge scour analysis, especially scour depth calculation practices implemented mostly by hydraulics and geotechnical engineers, was traditionally built upon flume tests with cohesionless materials, e.g., sands. As a result, the analysis of bridge scour in cohesive materials, i.e., cohesive soils and scour-susceptible rocks, was less understood and thus has been gaining increasing attention. This paper presents a state-of-the-practice survey on the analysis of bridge scour in cohesive materials represented by cohesive soils and scour-susceptible rocks. This includes a literature review covering the concepts and understanding of scour susceptibility, material sampling, erodibility tests, bridge scour calculation methods for cohesive soils and rocks, and a summary of the information gathered in communications with engineers from state Departments of Transportation (DOTs) in the U.S. Through this review, it was found that scour analysis in cohesive soils and scour-susceptible rocks continues to require further research and engineering development despite substantial recent progress. Undisturbed sampling and appropriate erodibility characterization remain critical for reliable scour prediction. Existing research and engineering practice continue to focus primarily on pier scour, while comparatively limited information is available for contraction and abutment scour in cohesive soils and rock formations. The survey of state DOT practices further indicates considerable variability in the implementation of scour evaluation procedures for cohesive and rock materials, including the use of SRICOS-EFA, the Erodibility Index Method, NCHRP 717, agency-developed procedures, and geotechnical consultation workflows.

Keywords: bridge scour; cohesive soil; scour-susceptible rock; scour analysis; state DOT



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1. Introduction

Soil removal from a stream channel (including riverbed and river-banks) due to flowing water is called river scour [1]. General scour is a natural phenomenon, which takes place irrespective of the existence of structures [2,3]. The presence of a structure like a bridge in a river or a stream can cause extra or/and different soil erosion, especially during flood events [3,4]. Scour occurring around a bridge foundation such as a pier and an abutment is called local scour [2,5]. The existence of a bridge can also initiate scour called 'contraction' or 'constriction scour' at the constricted section of the channel [2,6]. Local scour and contraction scour together are called localized scour. Localized scour can occur

as ‘clear-water scour’ or ‘live-bed scour’. Scour is called clear water scour if the scour hole remains pristine after the flood and is called live bed scour if the scour hole gets sediment deposition from the upstream [2,7].

Catastrophic bridge failures due to scour can result in a direct economic loss of millions of U.S. dollars and an indirect cost that can be five times higher [1,8,9] in addition to the loss of human lives [10,11]. Approximately 60 percent of highway bridge failures in the U.S. resulted from scour [8,9]. For example, during the 1985 flood season, 73 bridge failures occurred in Virginia, West Virginia, and Pennsylvania. In 1987, 17 bridges were damaged due to scour in New England and New York. In 1994, 23 bridge failures occurred in the upper Mississippi basin, and 500 bridges in Georgia were affected [7]. In 1993, more than 2500 bridges were significantly affected by scour caused by severe flooding in the midwestern states [12].

The failure of the Interstate Highway (I-90) Bridge over Schoharie Creek in New York during a flood in 1987 prompted the Federal Highway Administration (FHWA) to develop guidelines for the evaluation of all highway bridges with scour-critical conditions [13]. Comprehensive guidelines for scour-related practices were published as three Hydraulic Engineering Circulars: “HEC-20 Stream Stability at Highway Structures” [14], “HEC-18 Evaluating Scour at Bridges” [7], and “HEC-23 Bridge Scour and Stream Instability Countermeasures” [15]. The HEC-18 manual is the primary guidance document for bridge scour analysis methodologies and is based generally on geomaterials and conditions in which scour can develop. Most of the U.S. Departments of Transportation (DOTs) have adopted the FHWA HEC-18 procedures, although in some cases modifications are made to allow for a state’s specific conditions [16–19]. The HEC-18 equations for pier scour, abutment scour, and contraction scour in non-cohesive (or cohesionless) materials, which have been in practice since the late 1980s, have been relatively well established for non-cohesive beds [20]. These equations (referred to as HEC-18 equations for non-cohesive sediments throughout this paper) are the CSU pier equation for both clear-water and live-bed scour, Froehlich and HIRE abutment equations for live-bed scour, and modified Lauren’s contraction equations—one for live-bed scour and one for clear-water scour.

Despite the progress, a primary concern in the existing practice of bridge scour analysis is that the prevalent HEC-18 scour calculation method based on equations developed using flume studies with sands, i.e., the HEC-18 Sand Equations, likely over-predicts the scour depth for certain geologic and hydraulic conditions [21–27]. One major reason for the over-prediction is the unreasonable scaling and/or unrealistic representation of field conditions, especially considering the wide diversity of hydrologic, hydraulic, and geotechnical conditions across the nation [13,27]. Consequently, it is of interest to many road agencies to modify and/or calibrate the equations for more accurate scour depth calculations [17,28].

The second concern, which is the focus of this study, is the inadequate consideration of cohesive materials, i.e., mainly cohesive soils and scour-susceptible rocks, in the widely used scour prediction equations. Scour in cohesive soils and scour-susceptible rocks has been a challenge for engineers in designing safe and cost-effective bridges [13,29]. Cohesive soils and rocks exhibit significantly different scour processes from cohesionless soils [13,30]. As a result, loose granular soils are rapidly eroded by flowing water, while cohesive or cemented soils are more scour resistant [4,7]. A considerable amount of research has been conducted to understand the uniqueness of cohesive soils, while a few studies are available for scour in scour-susceptible rocks. Some methods have been summarized in the fourth [31] and fifth [7] editions of HEC-18, and NCHRP-717, but their applications in practice far lag behind the traditional HEC-18 Sand Equations. These facts necessitate a review study of the existing literature and engineering practices of scour analysis in

cohesive materials represented by cohesive soils and scour-susceptible rocks to understand the state of the art and identify future research directions.

In this context, the objective of this study is to provide a structured review of bridge scour analysis in cohesive soils and scour-susceptible rocks by explicitly linking erosion mechanisms, material characterization, erodibility testing methods, and scour prediction approaches. While a considerable number of studies have addressed individual aspects of these topics, a systematic synthesis that connects these components and evaluates their applicability in engineering practice remains limited. This study therefore not only summarizes existing methods but also discusses their relative advantages, limitations, and practical implications, with the aim of providing a clearer framework for both researchers and practicing engineers.

For this goal, the current state of practice for bridge scour analysis in cohesive soils and scour-susceptible rocks is examined through (1) a review of existing literature covering erosion mechanisms, sampling, erodibility determination, and scour prediction methods, and (2) an evaluation of engineering practices based on communications with state Departments of Transportation (DOTs) in the United States. The literature review was organized around the practical workflow of bridge scour evaluation: identifying scour mechanisms, obtaining representative samples or field observations, determining erodibility, selecting a scour prediction method, and interpreting the results for engineering practice. The review gives emphasis to methods that have influenced or entered U.S. bridge-scour practice, including SRICOS/SRICOS-EFA for cohesive soils, the Erodibility Index Method, NCHRP 717, and agency-specific procedures. Foundational studies from outside routine U.S. DOT practice are also discussed where they support the development of these methods. The U.S. emphasis reflects the state-DOT practice component of the paper and the central role of FHWA HEC-18 in U.S. bridge-scour evaluation; it is not intended to imply that bridge scour in cohesive soils and rock is only a U.S. problem.

In this paper, the term cohesive materials is used in a practical bridge-scour context to include cohesive soils and scour-susceptible rocks. The review is organized into these two sub-topics because this distinction is commonly used in HEC-18-related practice, DOT guidance, erodibility testing, and scour prediction methods. However, the boundary between cohesive soil and rock is not always sharp. Transitional geomaterials, such as cemented soils, highly indurated glacial till, weathered shale, clay-rich mudstone, weak rock, and partially lithified sedimentary materials, may exhibit properties of both groups. For such materials, classification by name alone may be insufficient. Instead, the dominant erosion mechanism, sample quality, in situ structure, degree of cementation or weathering, discontinuity characteristics, and the availability of appropriate erodibility testing should be considered when selecting a scour-analysis approach. Because a universal classification of transitional materials would require additional field and laboratory data, this paper discusses them as an important limitation and future research need rather than proposing a new classification system.

2. Bridge Scour Susceptibility

Soil erosion involves complex mechanisms. The erosion process in a channel bed depends on the cohesion of the bed material. While a typical non-cohesive bed erodes particle by particle, a cohesive or sand-clay mixture bed erodes chunk by chunk, particle by particle, and/or aggregate by aggregate [32,33]. Even soils with similar classification may exhibit significantly different erodibility due to variations in mineral composition, structure, and environmental history [34]. Under normal flow conditions, a cohesive riverbed may erode over several days; by contrast, a sandy or fine gravel bed may erode within hours. Rocks are generally more scour-resistant. For example, sandstones, glacial

tills, and shales need months to erode, limestones require years, and granites remain coherent over centuries [4,7]. Factors and mechanisms that can affect the scour susceptibility of bridges founded on cohesive soils and scour-susceptible rocks will be introduced in the following sub-sections.

From a mechanistic perspective, the fundamental distinction between cohesive and non-cohesive materials lies in the role of interparticle forces and structural bonding. While erosion in non-cohesive sediments is primarily governed by hydraulic forces acting on individual particles, cohesive soils exhibit resistance due to electrochemical bonding and fabric structure, resulting in time-dependent erosion processes. In contrast, scour in rock is governed by material strength, discontinuities such as joints and fractures, and hydraulic loading, leading to distinct failure modes including block removal and surface degradation. These differences necessitate different approaches for material characterization and scour prediction.

2.1. Scour Susceptibility of Bridges on Cohesive Soil

Cohesive soil's erodibility increases with the increase of the void ratio, soil swell, sodium absorption ratio, soil temperature, and water temperature. On the contrary, an increase in the soil unit weight, undrained shear strength, plasticity index, or amount of clay content can strengthen the cohesive soil against scour [7,35]. The erodibility of cohesive soil can be assessed in terms of the bed strength, e.g., the Unconfined Compressive Strength (UCS) and vane shear strength [36]. While the UCS is suitable for clay–sand–gravel mixed beds [33,37–40], the vane shear strength is good for soft clayey channel beds [33,41]. The bed strength parameter is related to the critical shear stress, a very significant parameter for assessing scour susceptibility of cohesive beds [42]. Below this shear stress value, cohesive soil shows no or little trace of erosion; when this value is exceeded, remarkable erosion takes place [43]. Studies found that the critical shear stress of cohesive soil is directly proportional to the UCS, vane shear strength, unit weight, and consolidation stress but inversely proportional to the water content and void ratio [36,44]. As a preliminary step, erodibility, or in other words, scour susceptibility of a cohesive stream bed, can be determined from the erosion rate vs. shear stress chart proposed by Briaud [45]. If the stream-bed material is known, the critical shear stress of the material can be estimated from this chart [7,46].

2.2. Scour Susceptibility of Bridges on Rock

For bridges founded on rock, the scour mode is an essential term in scour susceptibility testing [47]. Rock erosion can take place in four different modes in natural channels: dissolution, cavitation, quarrying and plucking, and abrasion [7,48,49]. Dissolution is the scour mode common in soluble rocks. Only strong soluble mineral types, e.g., limestone and dolostone, are used for bridge foundations, and they usually do not have any evidence of scour within the life span of the founded structures [50]. Mineral types with noticeable dissolution in engineering timescales, e.g., halite, sylvite, and anhydrite, are usually identified in the site investigation before construction, and as a result, structures would not be founded on these rock types considering their general poor mechanical properties [28]. Cavitation is a very common phenomenon in pipe and tunnel design [50]. Though cavitation sometimes can also take place in natural streams, it is not common at bridge sites [7,13]. The quarrying and plucking mode of scour usually occurs in rocks with fractures and/or joints. The process in this mode involves block removal and, therefore, is governed by the block size and geometry, stream velocity, and turbulence intensity [50]. Abrasion is the gradual and progressive mode of scour for degradable rocks, which takes place due to hydraulic loading over time. This type of scour of degradable rocks depends not only on

their geological properties but also on the flow conditions of the channels [13]. Apart from these scour modes, physical and chemical weathering, wetting and drying, heating and cooling, and freezing and thawing can also lead to rock degradation [7,51].

NCHRP-717 report titled 'Scour at Bridge Foundations on Rock' presents a flow chart for identifying possible bridge scour modes in scour-susceptible rocks based mostly on geologic conditions [13,50]. For example, jointed/fractured rocks having one or multiple of the following geologic conditions—blocky structure, presence of irregular channel, headcut, and/or plunge pool—will be placed under the quarrying and plucking mode. By contrast, the presence of abraded, sculpted, and pitted and/or slaked rock materials will be placed under the abrasion mode of scour. Niemann, Wait and Keaton [47] worked with the West Virginia DOT and proposed a risk-based screening approach for bridge foundations in scour-susceptible rocks. In this approach, a bridge site is scored based on the geologic province, rock type, weathering effect, longitudinal flow profile, presence of joints, condition of the scour surface, sample field test, and lab test results. Based on that, any bridge founded on rock can be labeled as one of three tiers: Tier I is for bridges that are safe from future scour, Tier II is for bridges exposed to the abrasion mode of scour, and Tier III is for bridge sites having the quarrying mode of scour [47,52].

3. Sampling and Erodibility Testing

Core samples representative of undisturbed earth materials are desired for obtaining material properties needed for the subsequent erodibility determination and scour depth calculation in a typical bridge scour analysis task [13,53]. Sampling is especially critical to the accuracy of erodibility determination and scour calculation [54]. However, this component of scour analysis was traditionally not emphasized, but instead, scattered throughout relevant disciplines such as geotechnical engineering, hydraulics, surveying engineering, and geology [55]. In the following, common sampling techniques that are relevant to scour analysis will first be reviewed for cohesive soils and rocks. Then, available erodibility tests will be summarized.

3.1. Sampling

Core drilling techniques are commonly used to obtain representative samples for scour analysis. These include single, double, and triple corers, with the selection depending on the required sample quality and material type. Rotary coring is widely used for both soils and rocks, while other methods such as augers and buckets may be applied when less stringent sample quality is acceptable.

3.1.1. Sampling of Cohesive Soil Samples

Sampling techniques for cohesive soils vary depending on soil consistency and required sample quality, as summarized in Table 1 [56]. Core drilling methods, particularly thin-walled sampling such as Shelby tubes, are commonly preferred for obtaining relatively undisturbed samples suitable for erodibility testing and scour analysis.

For bridge scour analysis, relatively undisturbed samples are preferred to accurately determine erodibility. Standard Shelby tube samples are commonly used for cohesive soils due to their ability to minimize sample disturbance [53]. Other sampling methods may also be applied depending on site conditions, although increased disturbance may affect the reliability of erodibility testing results [57–60].

3.1.2. Sampling of Rock Samples

For rock scour evaluations, sampling must consider geological characteristics such as joints, fractures, and discontinuities, which strongly influence scour behavior. The assessment of quarrying and plucking modes typically requires field observations, in-

cluding identification of joint sets, spacing, condition, and gouge characteristics [7,13]. These characteristics can be classified using the descriptions summarized in Table 2, which was developed with information from Kirsten [61], Annandale [62], Keaton, Mishra and Clopper [13], and the fifth edition of HEC-18 [7].

Table 1. Recommended sampling techniques for different conditions of cohesive soils [56].

Cohesive Material Category	Sampling Tool	Presence of Fluid
Very soft to soft fine soil	Stationary piston core drill	N/A
	Thin-walled core drill with casing	Slurry
	Rotary bucket with auger	N/A
Firm, fine soil	Stationary piston core drill	N/A
	Thin-walled core drilling with or without casing	Slurry or N/A
	Triple corer with overturning case	Water or slurry
	Triple corer	Water or slurry
	Double corer	Water or slurry
	Rotary bucket with auger	N/A
	Sampling blocks by hand	N/A
	Sampling blocks by box	N/A
	Sampling loose sample by mechanical shovel	N/A
	Thin-walled corer	N/A
Stiff to very stiff fine soil	Thick-walled corer	N/A
	Triple corer with overturning case	Water or slurry
	Triple corer	Water or slurry
	Double corer	Water or slurry
	Simple corer	N/A
	Rotary bucket with auger	N/A
	Sampling blocks by hand	N/A
	Sampling blocks with box	N/A
	Sampling loose sample with mechanical shovel	N/A
	Triple corer with overturning case	Water
Hard, fine soil	Triple corer	Water
	Double corer	Water
	Simple corer	Water
	Rotary bucket with auger	Water
	Sampling blocks by hand	Water
	Sampling blocks with box	Water
	Sampling loose sample with mechanical shovel	Water

Note: 'N/A' means None or No when answering "Presence of Fluid".

For the abrasion mode of scour in rock, samples collected by rock coring are generally used [13]. When coring is not possible, hand-picked samples can be an alternative [28]. Though being widely used for collecting undisturbed rock samples, coring has some disadvantages [54]. Rock coring may produce rock samples with engineering properties that are significantly different from those of the natural rocks. For example, coring in hard

rocks that are highly resistant to bridge scour can generate highly fractured rock due to the stresses induced by drilling. The use of such rock samples can lead to false test results that indicate the rock is scour-susceptible [55]. An extremely long core barrel, a bottom-hole fill, and an extremely low rotation rate might lead to jamming within the core barrel, while significant mud invasion and an extremely high rotation rate might severely damage the sample. Also, vibration and improper weight transfer on the bit can cause either jamming or damage to the sample [54,63,64].

Table 2. Rock joint and gouge categorization.

Number of rock joint/fissure category	Intact, no or few joints/fissures
	One joint/fissure set
	One joint/fissure set plus random
	Two joint/fissure sets
	Two joint/fissure sets plus random
	Three joint/fissure sets
	Three joint/fissure sets plus random
	Four joint/fissure sets
	Multiple joint/fissure sets
	Stepped joints/fissures
Condition of joint category	Rough or irregular, undulating
	Smooth undulating
	Slickensided undulating
	Rough or irregular, planar
	Smooth planar
	Slickensided planar
	Joints/fissures either open or containing relatively soft gouge of sufficient thickness to prevent joint/fissure wall contact upon excavation
Description of gouge	Shattered or micro-shattered clays
	Tightly healed, hard, non-softening impermeable filling
	Unaltered joint walls, surface staining only
	Slightly altered, non-softening, non-cohesive rock mineral or crushed rock filling
	Non-softening, slightly clayey non-cohesive filling
	Non-softening, strongly over-consolidated clay mineral filling, with or without crushed rock
	Softening or low friction clay mineral coatings and small quantities of swelling clays
	Softening moderately over-consolidated clay mineral filling, with or without crushed rock
	Shattered or micro-shattered (swelling) clay gouge, with or without crushed rock

Sampling disturbance can directly influence measured erodibility and, therefore, predicted scour depth. For cohesive soils, Shelby tube samples are commonly used for EFA testing because they preserve the soil structure better than remolded samples, while field

JET-type tests reduce extraction-related disturbance but introduce other uncertainties associated with in situ boundary conditions and test interpretation. For rocks, core drilling may disturb fractures, joints, and weak bedding planes, and damaged cores may underestimate the resistance of the natural rock mass. The available literature provides important qualitative guidance on these effects, but broadly applicable correction factors for translating sampling disturbance into changes in EFA, JET, RETA, BET, or modified slake durability results are not yet well established. Therefore, this review emphasizes the need for representative sampling and site-specific interpretation, while a quantitative comparison of sampling disturbance effects is identified as a future research topic.

For scour analysis of rock with either quarrying and plucking scour mode or abrasion mode, performing a lab test on undisturbed samples is recommended. For sampling undisturbed samples, the rotary corer is the most suitable option. Table 3 shows the rock sampling techniques recommended by Monnet [56]. A simple corer, a double corer, or a triple corer with the rotary coring technique can be used for collecting relatively undisturbed samples. A core drill usually needs to be cooled by water or by a mixture of water and slurry during the drilling process. Generally, the simple corer is not recommended unless for sound rock, since the drilling fluid must pass over the recovered sample in this sampling technique, which might cause disturbance to the sample. By contrast, the double corer is the most popular and widely used rock coring tool, which is good for loose ground, soft rock, and altered rock. The triple corer is recommended for any type of rock, since it can provide relatively undisturbed and quality samples [56,65].

Table 3. Recommended rock sampling techniques [56].

Sampling Tool	Fluid
Simple corer	Water or Water + slurry additive
Double corer	
Triple corer	

3.2. Erodibility Testing

The definition of erodibility of a cohesive soil bed or a rock bed in streams involves both the hydraulic action of water and the erosion resistivity of the geomaterial, which are analogous to the roles of loading and strength in solid mechanics respectively [13,41]. Therefore, erosion resistivity (or erodibility as defined oppositely) is one major material property in the consideration of bridge scour. What makes it even more complicated is that this material property, i.e., erodibility, is also related to the flow condition, i.e., flow rate. To quantify this material property for scour, a relationship between the erosion rate and shear stress of the stream bed has been widely adopted. Recent laboratory work has continued to examine the measurement of bed shear stress and erosion rate in cohesive soils, including the influence of unconfined compressive strength and water content on measured erosion behavior [66]. This relationship is much more significant in cohesive soils and scour-susceptible rocks than in sands due to the relatively slow erosion speed. Three types of devices have been widely adopted for the erodibility testing of soil or rock: piston type, rotating type, and submerged jet type (Figure 1). The piston-type and rotating types of devices are laboratory devices, whereas the submerged jet type of device can be used both in the field and laboratory. Data collected with all these devices can be used to develop a relationship between the erosion rate and shear stress for the tested sample [7,35]. The following subsections provide detailed information about popular erodibility tests.

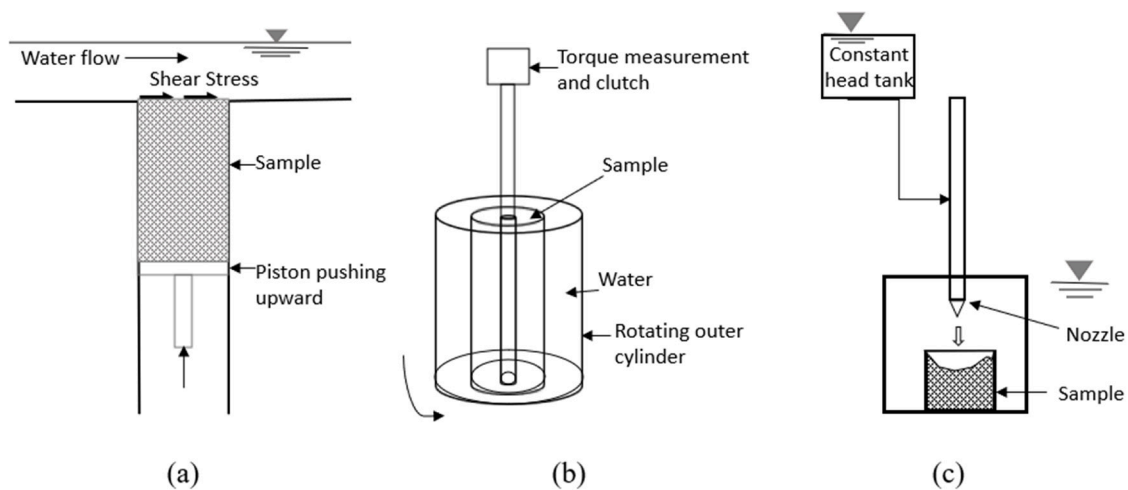


Figure 1. Schematics of common erosion rate test devices: (a) piston type, (b) rotating type, and (c) jet type [7].

3.2.1. In Situ Erosion Tests

In situ erosion tests can generally be categorized into jet-based methods, borehole circulation methods, and field flume methods depending on the testing mechanism and sample configuration.

The Field Jet Erosion Test (JET) [67,68] was developed by the Agricultural Research Service in the U.S. Department of Agriculture in 1990. In this test, water flows through a submerged, vertical jet (Figure 1c) at various velocities perpendicularly to the soil surface, and the variation of the depth of the hole made by the jet is recorded as a function of time. The In Situ Erosion Evaluation Probe (ISEEP) [69] was developed at North Carolina State University and also uses a vertical jet type device (Figure 1c) for measuring the erodibility of any soil at any depth. This test involves the flow of water through an impinging jet to the material at various velocities. The measurement is the rate of advancement of the jet probe versus the stream power developed due to the jet velocity. This test does not perform as effectively in clayey soils as it does in sandy soils [35]. Portable jet-based devices have also been developed for rapid field evaluation. The Pocket Erodrometer Test (PET) [57,58] uses a miniature jet type device to record the erosion depth created at the soil sample surface due to 20 impulses of water at a velocity of 8.0 m/s. The erosion depth is compared to a PET erosion chart proposed by Briaud, Bernhardt and Leclair [58] to obtain the erodibility category of the sample.

Borehole-based erosion tests evaluate erodibility by circulating water within drilled holes or casing systems at depth. The Borehole Erosion Test (BET) [60], which is suitable for any soil or rock that can be drilled, provides erodibility measurements as a function of depth. This test requires a hole to be drilled to the desired depth, where water is circulated down the drill rods, around the bottom of the drill bit, and up the annulus between the rods and the wall of the borehole at various velocities to record the erosion rate. A borehole caliper is used to determine the hole diameter before and after the water flow to determine erosion rate versus shear stress. The In Situ Scour Testing Device (ISTD) is capable of estimating the erodibility of soil at any depth [70]. The technology is currently being transitioned into engineering practice through FHWA-led pooled fund studies. It is designed for use in cohesive soil layers below the water table and can operate at depths of 10–40 ft or greater, though it works best in stiff, cohesive materials and requires precise insertion in a standard boring casing [35,71].

Field flume methods provide another approach for evaluating erosion resistance under controlled hydraulic flow conditions. Field flume tests, or Sediment Erosion at Depth Flume

(SEDflume) [72], can measure the erodibility of field soil samples. A major advantage of this test is that site water can be used during testing. However, a noticeable drawback is that this test can only be used for disturbed samples.

3.2.2. Laboratory Erosion Tests

The traditional lab erosion tests include JET, RCT, and RETA. The Lab Jet Erosion Test (JET), as a lab version of JET [59,73], is similar to the field version except that it has an extra tank for the undisturbed soil sample, and the working procedure is also similar to the field JET [74]. The Rotating Cylinder Test (RCT) and improved versions, which originated from the work of Moore and Masch Jr [75] for developing RCT to record the critical shear stress under a rotating flow in cohesive soils, are also very common. In RCTs, a cylindrical soil sample is placed in the test cylinder, and water flows around the side of the cylinder. The rotational speed is gradually increased until erosion initiates, and the torque is recorded to find the shear stress. A major disadvantage of this test is that it requires remolded samples. Later, this test was improved by Chapuis and Gatién [76] to allow the use of intact samples. The Rotating Erosion Testing Apparatus (RETA) developed at the University of Florida is a rotary-type device (Figure 1b) for determining the relationship between the shear stress and erosion rate of stiff clays and hard rocks such as limestone and sandstone [77–80]. Although this test requires an undisturbed self-supporting sample, the sample is not usable unless a center hole is drilled through it [13,35,81]. Florida DOT reportedly achieved significant cost savings by using RETA results, which eliminated the need for scour protection of several bridge sites [82].

The Erosion Function Apparatus (EFA) and similar versions started with the work of Briaud, Ting, Chen, Cao, Han and Kwak [53] for developing EFA for a wide range of cohesive soils, non-cohesive soils, and soft rocks [35], which allows testing with minimal sample disturbance and is suitable for site-specific scour studies. This test requires a piston-type device (Figure 1a) to measure the relationship between the erosion rate and velocity/shear stress. A standard Shelby tube sample is used in this test. The Sediment Erosion Rate Flume (SERF) [83], Sediment Erosion at Depth Flume (SEDflume) [72], and Ex Situ Scour Testing Device (ESTD) [84] work similarly. SERF is no longer commonly used in practice because of operational inconvenience and costly setup requirements. Neither SEDflume nor ESTD can fully reproduce in situ erodibility conditions because they primarily rely on disturbed or reconstituted samples. Nicks et al. [85] further examined differences between EFA and ESTD measurements, noting that although the devices are conceptually similar, differences in geometry and testing procedures can affect results.

Besides the above tests for direct erodibility measurement, a few other lab methods also need to be mentioned. First, the erodibility index from the Erodibility Index Method [62], which is similar to the headcut erodibility index [86–88], measures the resistance of earth material to erosion based on Kirsten's rippability index [61]. The geological parameters needed for determining the erodibility index of rocks can be obtained by some sample tests including the UCS, the RQD, and visual inspection for the joints and dip condition [61,62]. Also, the slake durability test, especially the ASTM standard slake durability test [89], is usually performed to estimate the durability of weak rocks during wetting and drying cycles. In this test, a drum with the given specification is rotated in water with the specimen at a given speed. The test consists of multiple cycles and the slake durability index is determined based on the mass of the specimen retained in the drum after each cycle.

3.2.3. Erodibility Testing for Cohesive Soil

For cohesive soils, JET is accepted to be a standard test for determining erodibility [90]. Meanwhile, the EFA proposed by Briaud, Ting, Chen, Cao, Han and Kwak [53] has become

a widely used erodibility test for cohesive soils in bridge scour analysis [35]. However, the device used in this test is a relatively expensive laboratory device and is primarily available at research institutes [91]. Due to this reason, a pocket erodometer (PET) can be a quick and simple alternative option for determining the preliminary strength of in situ materials [57,58]. BET can be another alternative to EFA, except that it requires further testing on its functionality [60]. RETA is also used for the erodibility testing of cohesive soils by some DOTs such as the Florida DOT [92].

3.2.4. Erodibility Testing for Rock

Preliminary assessments of the scour susceptibility of rock can be conducted via visual inspections in weak zones of the rock bed and other field test results. Some researchers use core recovery techniques to characterize the scour resistivity of rock samples [93]. In particular, the Rock Quality Designation (RQD) [94] of cored samples is widely adopted in practice to estimate rock quality [7,95]. For example, in a shale or limestone channel bed with an RQD lower than 20%, scour can reach up to 6 inches below the foundation level [96]. However, this parameter might sometimes underestimate the erosion resistivity of the rock, especially for the quarrying and plucking mode of scour. That is, a rock with a low RQD value might not be susceptible to scour in all flow conditions [13,47,97]. This is because, if the rock core is damaged during the coring process, the RQD from that core will not be representative of the natural rock quality [55]. Besides the RQD, the Slake Durability Index test (SDI), Jar Slake Test, and Cone Penetration Test (CPT) are also frequently used in practice [19,88,93,98].

On top of preliminary assessments, the erodibility of rock can be obtained more accurately with direct and indirect methods. Among the erodibility tests described in the previous section, RETA has been the most widely used erodibility test for directly measuring the erodibility of rock. By contrast, the Erodibility Index Method [62] is used to indirectly determine the erodibility of rocks. Instead of using any erodibility testing device, this method determines the erodibility index of the rock material based on other testing results and observations on the rock quality. The Erodibility Index Method incorporates both hydraulics and engineering geology to determine the critical erosion threshold.

Special attention was paid to the erodibility testing of rock in the abrasion mode to quantify rock's response under submerged tumbling action. Dickenson and Bailie [99] modified the standard slake durability test [89] for continuous abrasion and suggested the abrasion number. Keaton and Mishra [100] further modified this test into the "modified slake durability test" for determining the Geotechnical Scour Number (GSN) and proposed to use the GSN as a potential parameter in rock scour depth calculations [13].

3.2.5. Summary of Erodibility Testing

Overall, erodibility testing methods differ significantly in terms of applicability, representativeness, and required assumptions. Laboratory-based methods such as EFA provide controlled conditions and repeatable measurements but may not fully capture in situ variability. In contrast, field-based methods such as JET offer more representative conditions but are subject to higher uncertainty and variability. For rock materials, erodibility assessments rely heavily on indirect characterization through indices and geological observations. These differences highlight the importance of selecting appropriate testing methods based on material type, project scale, and required accuracy for scour prediction.

4. Scour Calculation Approaches

Most of the scour analysis studies before the late 1990s were for non-cohesive soils, and the scour depth calculations were conducted mostly using the HEC-18 Sand Equations

published by Richardson and Davis [31,101]. Since the late 1990s, many groups including some state DOTs have investigated the HEC-18 Sand Equations for cohesive soils and/or scour-susceptible rocks and found that these equations tend to overpredict the scour depth in these two materials and consequently lead to costly over-conservative designs [21–27]. This finding has been prompting researchers to study scour analysis in these fields individually [7,18,24,44,91,102]. The available scour analysis approaches for cohesive soils and scour-susceptible rocks are summarized in the following sub-sections.

4.1. Scour Calculation for Cohesive Soils

Hosny [103] was the first to conduct a systematic investigation into bridge scour in a cohesive soil bed and a channel bed consisting of a mixture of cohesive and non-cohesive soils, in which an equation was proposed for predicting the scour depth at a bridge pier in a cohesive soil based on several flume experiments. However, the prediction results were not verified in either the laboratory or the field. Gudavalli [104] proposed another equation containing pier and flow properties based on laboratory flume tests but excluding soil properties [105]. One way to consider all field variables is to simulate the field conditions in a small-scale lab model for scour monitoring and scale up the recorded erosion rate and depth to obtain relationships that can be used in the field [23,106]. This is, however, not always feasible. Ansari, Kothyari and Ranga Raju [30] developed a mathematical model to compute the temporal variation of the scour depth in cohesive soils. Several flume tests with cohesive bed were carried out at Texas A&M University, and equations (Equations (1)–(4)) were proposed for calculating the maximum pier scour depth [46,105], maximum contraction scour depth [46,105,107,108], and maximum abutment scour depth [46,109], which consider the bed critical velocity along with other variables.

$$\frac{y_{s(\text{pier})}}{a'} = 2.2K_w K_1 K_L K_{sp} \left(2.6Fr_{(\text{pier})} - Fr_{c(\text{pier})} \right)^{0.7} \quad (1)$$

where $y_{s(\text{pier})}$ is the maximum complex pier scour depth, a' is the projected pier width determined by the pier length, pier width, and attack angle of water flow, K_w is the water depth correction factor, K_1 is the pier nose correction factor, K_L is the aspect ratio correction factor for a rectangular pier, K_{sp} is the pier spacing correction factor, $Fr_{(\text{pier})}$ is the Froude number based on the approaching velocity, and $Fr_{c(\text{pier})}$ is the Froude number determined by the critical velocity.

$$\frac{y_{s(\text{contraction})}}{y_{m1}} = 1.27(1.83Fr_{m2} - Fr_{mc}) \text{ in the transition zone} \quad (2)$$

$$\frac{y_{s(\text{contraction})}}{y_{m1}} = 0.94(1.83Fr_{m2} - Fr_{mc}) \text{ far from the transition zone} \quad (3)$$

where $y_{s(\text{contraction})}$ is the maximum contraction scour depth, y_{m1} is the main channel depth in the approaching section, and Fr_{m2} and Fr_{mc} are the Froude number and the critical Froude number of the main channel at the bridge section, respectively.

$$\frac{y_{s(\text{abutment})}}{y_{f1}} = K_1 K_2 K_L K_G K_p 243Re_{f2}^{-0.28} (1.65Fr_{f2} - Fr_{fc}) \quad (4)$$

where $y_{s(\text{abutment})}$ is the maximum abutment scour depth, K_1 is the abutment shape correction factor, K_2 is the abutment skew correction factor, K_L is the abutment location correction factor, K_G is the channel geometry correction factor, K_p is the pressure-flow correction factor, Re_{f2} is the Reynolds number at the tow of the abutment, Fr_{f2} is the Froude number around the toe of the abutment, and Fr_{fc} is the critical Froude number around the toe of the

abutment. The values of all the correction factors (K) in the above equations can be obtained from Briaud, Chen, Chang, Oh, Chen, Wang, Li, Kwak, Nartjaho and Gudaralli [46].

The equilibrium scour depth has also attracted many researchers' attention. This is generally related to the scour depth in a sand-bed stream with a dune bed configuration. In such a stream bed condition, the live-bed pier scour depth fluctuates in the vicinity of the equilibrium scour depth due to variability in bed material transport in the approaching flow. It is assumed that the equilibrium live bed pier scour depth is 10% less than the maximum clear water pier scour depth [7]. A schematic of the equilibrium live bed pier scour depth and the maximum clear water pier scour depth is shown in Figure 2. Kho et al. [110] proposed an equation for calculating the equilibrium pier scour depth in cohesive/non-cohesive soil mixtures in terms of Reynolds number and clay content from their flume test results and also concluded that the proposed equation underestimated the scour depth at higher flow velocities. Debnath and Chaudhuri [41] proposed equations (Equations (5)–(9)) for the maximum equilibrium scour depth at cylindrical piers embedded in clay-sand mixtures in terms of Froude's number, clay content, and water content. Jain et al. [111] further investigated the influence of cohesion on scour at piers founded in clay-sand-gravel mixtures. These equations' performance was later verified by Najafzadeh and Barani [112].

$$y_s = 2.05F_{rp}^{1.72}C^{-1.29}\tau_s^{-0.37} \text{ for } W_c = 20 - 23.22\% \text{ \& } 20\% \leq C_p \leq 85\% \quad (5)$$

$$y_s = 3.64F_{rp}^{0.22}C^{-1.01}\tau_s^{-0.69} \text{ for } W_c = 27.95 - 33.55\% \text{ \& } 20\% \leq C_p \leq 50\% \quad (6)$$

$$y_s = 20.52F_{rp}^{1.28}C^{0.19}\tau_s^{-0.89} \text{ for } W_c = 27.95 - 33.55\% \text{ \& } 50\% \leq C_p \leq 100\% \quad (7)$$

$$y_s = 3.32F_{rp}^{0.72}C^{-0.62}W_c^{0.36}\tau_s^{-0.29} \text{ for } W_c = 33.60 - 45.92\% \text{ \& } 20\% \leq C_p \leq 70\% \quad (8)$$

$$y_s = 8F_{rp}^{0.61}C^{0.58}W_c^{1.24}\tau_s^{-0.19} \text{ for } W_c = 33.60 - 45.92\% \text{ \& } 70\% \leq C_p \leq 100\% \quad (9)$$

where y_s is the non-dimensional equilibrium scour depth, which is defined as the ratio of equilibrium scour depth to pier diameter, F_{rp} is the pier's Froude number, C is the clay fraction, C_p is the clay percentage, τ_s is the bed shear strength, and W_c is the water content (of the sediment).

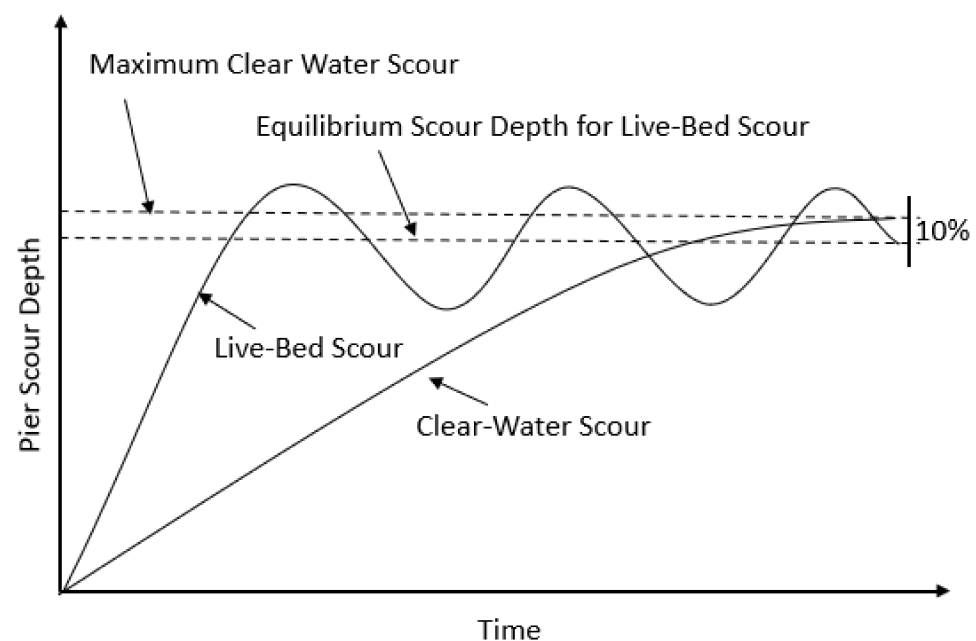


Figure 2. Schematic of maximum scour depth and equilibrium scour depth (after Arneson, Zevenbergen, Lagasse and Clopper [7]).

Abou-Seida et al. [113] proposed an equation for calculating the equilibrium scour depth at the vertical wall abutment in cohesive soil beds as a function of the clay content, soil compaction, and liquidity index. Debnath et al. [114] proposed equations for both the vertical wall and wing wall abutments in terms of the clay content, water content, Froude number, and shear stress. Danish [115] applied gene expression programming to the data set used by Debnath, Chaudhuri and Manik [114] and proposed a single equation for calculating the abutment scour depth in cohesive soils. Chaudhuri et al. [116] proposed an equation for predicting the contraction scour depth in cohesive soil beds as a function of the contraction ratio, clay fraction, flow depth, shear stress, and water content, which applies only to the contraction of a natural stream in the presence of a man-made rigid guide bank. It is noted that these equations were not verified against other data sets.

The rate of scour is an important factor for cohesive soils. The maximum scour depth, which is reached within a short time in non-cohesive soils, might not be reached for structures founded on cohesive soils within a single event [101]. Briaud, Ting, Chen, Gudavalli, Perugu and Wei [5] for the first time discussed the importance of the rate of scour in cohesive soils. They proposed a method named SRICOS (Scour Rate in Cohesive Soil) and a hyperbolic function for determining the scour depth in cohesive soils. Ting et al. [117] concluded from their flume test results that ignoring the rate of scour at bridges in cohesive soils might result in over-predictions of scour depths. Later, Rambabu et al. [118] verified the hyperbolic behavior of the erodibility of cohesive soils. For applying the SRICOS method, the erosion rate of the soil is an important input parameter. To measure the erosion rate of cohesive soils, Briaud, Ting, Chen, Cao, Han and Kwak [53] proposed EFA. It was included in the SRICOS method and was combined and called SRICOS-EFA, which was used to obtain the scour depth over time for a cylindrical pier founded on cohesive soils [119]. SRICOS-EFA was further developed for contraction scour, complex pier scour, abutment scour, varying velocity, and multilayered soil strata [6,46,57,105,107,109,119,120]. Once the maximum scour depth at a pier, a contracted section, or an abutment is obtained with its corresponding equation from Equations (1)–(4), the design scour depth can be calculated with Equation (10) [5]:

$$y_s(t) = \frac{t}{\frac{1}{z_i} + \frac{t}{y_{s(max)}}} \quad (10)$$

where $y_s(t)$ is the scour depth after a storm of duration t , z_i is the initial rate of scour, and t is the duration of the flow.

The development of a computer program for automatically implementing the SRICOS-EFA method [119,120] made it easier to consider all the factors associated with bridge scour. Many researchers have used SRICOS-EFA for the calculation of the bridge scour in cohesive soils and found this method can predict a reasonable 'localized scour depth' [20,45,121–123], though incorporating a probabilistic model in this scour prediction model could further improve the results [124]. SRICOS-EFA needs daily flow data, which forms a hydrograph, to develop a series of hyperbolic functions to represent a continuous scour history and yields the final scour depth at the end of the hydrograph. Ting and Kidd [125] further examined flood-hydrograph generation for predicting bridge scour in cohesive soils using the SRICOS method. The SRICOS-EFA computer program can be used to predict future scour depths where a synthetic hydrograph is developed by sampling from a log-normal distribution. In the absence of daily flow data, the peak discharge, rainfall distributions, and drainage-area characteristics can be used [126]. By contrast, stochastic flow analysis coupled with a scour model could provide a synthetic stream flow history along with the scour depth at any time within the life span of the bridge [127–129]. In addition, Najafzadeh et al. [130] applied the Group Method of Data Handling with a Back Propagation algorithm

(GMDH-BP) as a soft computing technique to predict the scour depth around bridge piers embedded in a cohesive soil bed and showed its better performance compared with many traditional equations including Rambabu, Rao and Sundar [118], Molinas and Hosny [131], Najafzadeh [132], and Debnath and Chaudhuri [41].

The Florida DOT has developed its own method for pier scour calculations, which applies to both clear water scour and live bed scour. The continued practical relevance of this topic is also reflected in the FDOT Bridge Scour Manual, which includes discussion of scour at structures founded in cohesive sediments or erodible rock [92]. This method considers the median particle size of the bed material (D_{50}) along with the pier geometry and flow conditions [92,133]. The fifth edition of HEC-18 has included the FDOT methodology as an alternative to the HEC-18 Sand Equation for pier scour, especially for wide piers founded on cohesive soil beds with a shallow water depth [7].

FDOT equations (Equations (11)–(16)) are given below.

$$\frac{y_s}{a^*} = 2.5f_1f_2f_3 \text{ for } 0.4 \leq \frac{V_1}{V_c} < 1.0 \quad (11)$$

$$\frac{y_s}{a^*} = f_1 \left[2.2 \left\{ \frac{\frac{V_1}{V_c} - 1}{\frac{V_{lp}}{V_c} - 1} \right\} \right] + 2.5f_3 \left\{ \frac{\frac{V_{lp}}{V_c} - \frac{V_1}{V_c}}{\frac{V_{lp}}{V_c} - 1} \right\} \text{ for } 1.0 \leq \frac{V_1}{V_c} \leq \frac{V_{lp}}{V_c} \quad (12)$$

$$\frac{y_s}{a^*} = 2.2f_1 \text{ for } \frac{y_s}{a^*} = 2.2f_1 \quad (13)$$

$$f_1 = \tanh \left[\left(\frac{y_1}{a^*} \right)^{0.4} \right] \quad (14)$$

$$f_2 = \left[1 - 1.2 \left\{ \ln \left(\frac{V_1}{V_c} \right) \right\}^2 \right] \quad (15)$$

$$f_3 = \left[\frac{\left(\frac{a^*}{D_{50}} \right)^{1.13}}{10.6 + 0.4 \left(\frac{a^*}{D_{50}} \right)^{1.33}} \right] \quad (16)$$

where y_s is the pier scour depth; $y_{sa}^* = y_s/a^*$ is the normalized scour depth; a^* is the effective pier width or effective pier diameter in feet; y_1 is the approach flow depth; V_1 is the mean approach velocity in ft/s; V_c is the critical velocity of the bed material characterized by the median particle size D_{50} ; V_{lp} is the live-bed peak velocity; F_1 , F_2 , and F_3 are dimensionless functions representing flow depth, flow intensity, and sediment size effects, respectively; and D_{50} is the median particle size. The equations for determining V_c and V_{lp} , together with the dimensional requirements for the variables, are provided in the FDOT Bridge Scour Manual [133].

4.2. Scour Calculation for Scour-Susceptible Rocks

The erosion of rock in the presence of water depends on both the flow conditions and rock properties [134,135]. The erosion capacity of flowing water is termed as the erosive power, which quantifies the stream power for producing scour. Erosion occurs when this erosive power exceeds the relative scour resistivity of the earth material [134]. To characterize the ability of rocks to resist erosion, a geomechanical classification system together with an erosion threshold, i.e., the erodibility index, was proposed by Annandale [62]. In this method, the erodibility index is a function of the rock mass strength based on the UCS, shear strength, block size, joint orientation, and shape. Based on this understanding, the erosion threshold was proposed to indicate the stream power required for initiating the erosion of the bed material with a certain erodibility. Smith [136] applied Annandale's [62] findings to bridge scour analysis and outlined a preliminary procedure to predict contrac-

tion scour depth and pier scour depth in bedrock. However, this procedure required further refinement and calibration. Later, the Erodibility Index Method was used in clear-water scour predictions for bridge piers founded on rocks [22,137–139]. The erodibility index of any earth material including rock can be calculated using Equation (17), in which all the parameters can be determined from tables provided by Kirsten [7,61,62]:

$$K = M_s K_b K_d J_s \quad (17)$$

where K is the erodibility index, M_s is the intact rock mass strength parameter depending on the UCS (Table 4), K_b is the block size parameter depending on RQD and joint separation (Equation (18)), K_d is the shear strength parameter depending on the condition of joint and joint separation (Equation (19)), and J_s is the relative orientation parameter depending on the dip angle, dip direction, and joint spacing (Table 5).

$$K_b = \frac{RQD}{J_n} \quad (18)$$

$$K_d = \frac{J_r}{J_a} \quad (19)$$

where RQD is the rock quality designation number, J_n is the number of joint sets (Table 6), J_r is the joint roughness number depending on the condition of the joint (Table 7), and J_a is the joint alteration number depending on the type of gouge and the joint separation (Table 8).

Table 4. Mass strength number for rock (M_s) [61,62].

Hardness	UCS (MPa)	Mass Strength Number (M_s)
Very soft rock	<1.7	0.87
	1.7–3.3	1.86
Soft rock	3.3–6.6	3.95
	6.6–13.2	8.39
Hard rock	13.2–26.4	17.70
Very hard rock	26.4–53.0	35.0
	53.0–106.0	70.0
Extremely hard rock	>212	280.0

Erosion begins when water flows around bridge piers and the corresponding stream power increases above the critical stream power. Annandale [140] proposed the following four equations (Equations (20)–(23)) as a part of the Erodibility Index Method for determining the scour depth for piers founded in scour-susceptible rocks.

$$P_c = K^{0.75} \text{ for } K > 0.1 \quad (20)$$

$$P_c = 0.48K^{0.44} \text{ for } K \leq 0.1 \quad (21)$$

$$P_a = 7.853\rho \left(\frac{\tau}{\rho} \right)^{3/2} \quad (22)$$

$$\frac{P}{P_a} = 8.42e^{-0.712(\frac{y_s}{b})} \quad (23)$$

where P_c is the critical or required stream power below which there is no erosion, K is the erodibility index determined from Equation (17), P_a is the stream power of the approaching flow, τ is the shear stress, P stands for the stream power at the bottom of the scour hole,

or in other words, the available stream power at the pier, y_s is the depth of the scour hole, and b is the pier width perpendicular to the flow direction. According to the research conducted by the FHWA [141], the erosive power of water around a bridge pier decreases as the scour hole deepens. Erosion ceases when the stream power at the bottom of the scour hole reaches the critical stream power of the channel bed.

Table 5. Relative ground structure number (J_s) for rock [61,62].

Dip Direction of Closer Spaced Joint Set (Degrees)	Dip Angle of Closer Spaced Joint Set (Degrees)	Ratio of Joint Spacing, r			
		1:1	1:2	1:4	1:8
180/0	90	1.14	1.20	1.24	1.26
	89	0.78	0.71	0.65	0.61
	85	0.73	0.66	0.61	0.57
	80	0.67	0.60	0.55	0.52
	70	0.56	0.50	0.46	0.43
	60	0.50	0.46	0.42	0.40
	50	0.49	0.46	0.43	0.41
	40	0.53	0.49	0.46	0.45
	30	0.63	0.59	0.55	0.53
	20	0.84	0.77	0.71	0.67
	10	1.25	1.10	0.98	0.90
	5	1.39	1.23	1.09	1.01
	1	1.50	1.33	1.19	1.10
0/180	0	1.14	1.09	1.05	1.02
	−1	0.78	0.85	0.90	0.94
	−5	0.73	0.79	0.84	0.88
	−10	0.67	0.72	0.78	0.81
	−20	0.56	0.62	0.66	0.69
	−30	0.50	0.55	0.58	0.60
	−40	0.49	0.52	0.55	0.57
	−50	0.53	0.56	0.59	0.61
	−60	0.63	0.68	0.71	0.73
	−70	1.84	0.91	0.97	1.01
	−80	1.26	1.41	1.53	1.61
	−85	1.39	1.55	1.69	1.77
	−89	1.50	1.68	1.82	1.91
180/0	−90	1.14	1.20	1.24	1.26

Note: 1. For intact material like massive rocks or fine-grained massive clays, $J_s = 1$. 2. For r greater than 8, take J_s as if $r = 8$. 3. If the flow direction FD is not in the direction of the true dip TD, the effective dip ED = AD + GS, where AD is the apparent dip and GS is the ground slope.

Table 6. Joint set number (J_n) for rock [61,62].

Number of Joint Sets	Joint Set Number (J_n)
Intact, no or few joints/fissures	1.00
One joint/fissure set	1.22
One joint/fissure set plus random	1.50
Two joint/fissure sets	1.83
Two joint/fissure sets plus random	2.24
Three joint/fissure sets	2.73
Three joint/fissure sets plus random	3.34
Four joint/fissure sets	4.09
Multiple joint/fissure sets	5.00

Table 7. Joint roughness number (J_r) for rock [61,62].

Joint Separation	Condition of Joint	Joint Roughness Number (J_r)
Joints/fissures tight or closing during excavation	Stepped joints/fissures	4.0
	Rough or irregular, undulating	3.0
	Smooth undulating	2.0
	Slickensided undulating	1.5
	Rough or irregular, planar	1.5
	Smooth planar	1.0
	Slickensided planar	0.5
Joints/fissures open and remain open during excavation	Joints/fissures either open or containing relatively soft gouge of sufficient thickness to prevent joint/fissure wall contact upon excavation	1.0
	Shattered or micro-shattered clays	1.0

Table 8. Joint alteration number (J_a) for rock [61,62].

Description of Gouge	Joint Alteration Number (J_a) for Joint Separation (mm)		
	1.0 ¹	1.0–5.0 ²	5.0 ³
Tightly healed, hard, non-softening impermeable filling	0.75	-	-
Unaltered joint walls, surface staining only	1.0	-	-
Slightly altered, non-softening, non-cohesive rock mineral or crushed rock filling	2.0	2.0	4.0
Non-softening, slightly clayey non-cohesive filling	3.0	6.0	10.0
Non-softening, strongly over-consolidated clay mineral filling, with or without crushed rock	3.0	6.0 *	10.0
Softening or low friction clay mineral coatings and small quantities of swelling clays	4.0	8.0	13.0
Softening moderately over-consolidated clay mineral filling, with or without crushed rock	4.0	8.0 *	13.0
Shattered or micro-shattered (swelling) clay gouge, with or without crushed rock	5.0	10.0 *	18.0

Note: ¹ Joint walls effectively in contact. ² Joint walls come into contact after approximately 100 mm shear. ³ Joint walls do not come into contact at all upon shear. * Also applies when crushed rock occurs in clay gouge without rock wall contact.

Unfortunately, this Erodibility Index Method did not account for protruding rocks [142,143] and the continuous movement of water and bedload over the rock-bed channel [99]. Bollaert [144] proposed a set of threshold velocities for rock plucking in terms of the shape, thickness, and protrusion of the rock block. Numerical modeling of threshold flow velocities was performed using the Comprehensive Scour Model (CSM) [135,145,146] for predicting the scour depth with respect to the pier diameter. Both the Erodibility Index Method and the method developed by Bollaert [144] were capable of determining the maximum scour depth, especially for the quarrying and plucking mode of scour [50,147]. However, structures founded on degradable rocks may experience a different scour mode, e.g., abrasion, and may not reach the maximum scour depth within their life spans. Therefore, the time rate of scour is an important parameter for the abrasion mode of rock scour. A modification of the Erodibility Index Method was proposed by Huang et al. [148] for soft bedrock erosion. The rate of submerged rock erosion was claimed to depend on (1) the lithology, (2) frequency, character, and orientation of the rock discontinuities, (3) degree of weathering and induration of sedimentary rock, (4) rock density, strength, abrasion resistance, and slake durability, (5) channel geometry, (6) year-round flow characteristics such as intensity and duration of flood events, and (7) energy gradient and bedload

characteristics [7]. Keaton, Mishra and Clopper [51] suggested a probability-weighted approach to represent the channel annual average scour condition and hydraulic loading for predicting rock scour. Hydraulic loading represents the accumulated stream power over the life cycle of a bridge structure. Stream power is a function of the shear stress and stream velocity and is also representative of the rate of energy dissipation per unit width of flow [136,149–151]. The relationship between the observed scour depth over a certain period and the stream power accumulated over the same time can provide an important index of relative erodibility called the Scour Number (SN) [151]. This index can also be used to estimate future scour depths using Equation (24) if the future hydraulic loading is known for the same channel section [13].

$$y_s = K_s \Omega_{\text{future}} \quad (24)$$

where y_s is the scour depth, K_s is the SN, and Ω_{future} is the future cumulative hydraulic loading. The SN can also be used for other structures founded on similar rock formations and similar flow properties [28]. In the absence of historical data for scour depth, the modified slake durability test [100,152] results can be used to derive GSN (Equation (25)) as an alternative to empirical SN [13,50,151,153]. Calibration of the GSN was conducted for two samples of siltstones from the Sacramento River in Redding, California [50]. The following equations (Equations (25) and (26)) can be used to predict the scour depth due to the abrasion mode of scour [13,50,100].

$$\text{GSN} = \frac{\text{ESD}}{\text{ESP}} \quad (25)$$

$$y_s = \text{GSN} \times \Omega \quad (26)$$

where ESD is the Equivalent Scour Depth, ESP is the Equivalent Stream Power derived from the modified slake durability test, and Ω is the cumulative stream power.

This method was published in NCHRP 717 [13] and later included in the fifth edition of HEC-18 [7] as the calculation method for pier scour depth for the abrasion mode of rock scour. The validity of this method for the prediction of the abrasion mode of scour has been tested in the bedrock of West Virginia [52] and Wisconsin [28]. Niemann, Wait and Keaton [47] concluded that this method provides good predictions of the scour depth for the abrasion mode of rock scour but is not suitable for considering the quarrying and plucking mode.

The available rock-scour methods should be interpreted according to their intended mechanisms and data requirements. The Erodibility Index Method is most suitable for evaluating threshold-type erosion associated with quarrying and plucking in jointed or fractured rock, but it depends strongly on rock-mass characterization and does not explicitly represent protruding blocks, continuous bedload abrasion, or time-dependent degradation. The Comprehensive Scour Model provides a more process-oriented framework for block plucking and pressure transmission in rock joints, but it requires detailed hydraulic and rock-block information and has not been adopted as broadly in routine DOT bridge-scour practice. NCHRP 717 addresses time-dependent abrasion and degradation of erodible rock through hydraulic loading and modified slake durability testing, but it is primarily applicable to pier scour and requires site-specific testing and stream-power histories. Probabilistic and machine-learning-based approaches represent promising research directions for uncertainty quantification, monitoring, and data-driven prediction, but they are not yet routine design methods for state DOT bridge-scour evaluation in cohesive soils and rock. Therefore, the present review emphasizes traditional and agency-implemented methods while identifying probabilistic and data-driven approaches as future research needs.

4.3. Summary

The available scour prediction approaches differ in their underlying assumptions and applicability. Empirical equations developed for non-cohesive sediments are often conservative when applied to cohesive materials because they do not explicitly account for interparticle bonding and time-dependent erosion. Erodibility-based methods, such as SRICOS-EFA, incorporate erosion resistance and hydrograph effects, making them more suitable for cohesive soils where scour evolves over time. For scour-susceptible rocks, methods based on the erodibility index and hydraulic loading provide a physically informed framework; however, their reliability depends strongly on accurate characterization of geological discontinuities and field conditions. Despite these developments, most methods focus on pier scour, while contraction and abutment scour in cohesive soils and rock remain less well established.

5. State DOT Practices

Together with the literature review, efforts were made to understand bridge scour evaluation practices adopted by state DOTs in the United States in order to capture practical implementation trends in addition to the research developments discussed previously. The practice review was based on thirty DOT response summaries that contained sufficient information to classify each agency's use of HEC-18 and its treatment of cohesive soils and/or scour-susceptible rock. The questionnaire and follow-up communications focused on practical scour-analysis topics, including the methods used for pier scour, abutment scour, and contraction scour; the edition of HEC-18 followed by the agency; whether special considerations were used for rock scour or cohesive soils; and whether hydraulic and geotechnical personnel were involved in the evaluation. In many cases, questionnaire responses were supplemented by phone or email communications with hydraulics and/or geotechnical personnel. Because the information was compiled from questionnaire responses, follow-up communications, and earlier AASHTO survey materials, a conventional response rate cannot be reconstructed reliably from the available records. Therefore, the DOT survey results should be interpreted as a state-of-practice summary of thirty classifiable DOT responses rather than a statistically stratified national survey. Potential biases may exist because agency practices are influenced by regional geology, hydrology, bridge inventory, availability of erodibility testing, funding, staff experience, and the timing of HEC-18 edition adoption. Figure 3 illustrates the key findings extracted from the thirty summaries generated based on the communications with each state DOT and an AASHTO survey conducted earlier.

Most state DOTs continue to follow the guidance framework provided in HEC-18 for bridge scour evaluation, although considerable variability still exists regarding the treatment of cohesive soils and scour-susceptible rock formations. Several agencies updated their scour evaluation procedures in recent years. For example, TxDOT released an updated Scour Evaluation Guide in 2023 that expanded and clarified scour analysis procedures for bridge design and evaluation [154]. In addition, many DOTs adapt the HEC-18 procedures to account for the geologic, hydrologic, and operational conditions specific to their states. SRICOS-EFA for cohesive soils, together with the Erodibility Index Method and NCHRP 717 procedures for rock beds, are included in the fifth edition of HEC-18; however, these approaches are still not implemented as broadly as the traditional HEC-18 sand-bed scour equations.

Among the thirty contacted DOTs, 50% primarily use the fourth edition of HEC-18 for scour depth evaluation, 30% primarily follow the fifth edition, 17% reported using HEC-18 without specifying the edition, and the remaining 3% indicated that both editions are used within their agencies (Figure 3a). Overall, most participating DOTs reported at least

some level of consideration, supplemental guidance, agency modification, or engineering judgment for cohesive soils and/or scour-susceptible rock formations, although the level of implementation varies substantially among agencies.

Among the DOTs that primarily follow the fourth edition of HEC-18, 27% use NCHRP 717 procedures for rock beds and/or have conducted related research, 13% reported past or ongoing work associated with SRICOS-EFA for cohesive soils, 6% reported previous work related to the Erodibility Index Method for rock beds, another 7% use agency-developed procedures for rock quarrying and plucking mechanisms, 7% rely on countermeasures when cohesive beds are encountered, another 7% coordinate with geotechnical personnel when cohesive or rock formations are present, 13% do not conduct scour depth calculations for rock beds, and the remaining 20% reported no special consideration for cohesive or rock beds (Figure 3b).

Among the DOTs that primarily follow the fifth edition of HEC-18, 11% use NCHRP 717 procedures for rock beds, another 11% use the Erodibility Index Method for rock beds together with previous or ongoing work related to SRICOS-EFA for cohesive soils, another 11% use the Erodibility Index Method together with a modified version of the fifth edition adapted for state-specific conditions, another 11% use the Erodibility Index Method for cohesive-bed evaluations, 23% employ agency-developed scour evaluation procedures, 11% adopted portions of the fifth edition guidance, another 11% coordinate with geotechnical personnel for cohesive or rock-bed conditions, and the remaining 11% reported no special consideration for cohesive or rock beds (Figure 3c).

Among the state DOTs that did not specify the edition of HEC-18 used within the agency, 20% reported using SRICOS-EFA for cohesive soils, another 20% use agency-developed scour evaluation procedures, and the remaining 60% reported no special consideration for either cohesive soils or scour-susceptible rock formations. The DOT that reported using both HEC-18 editions indicated no special consideration for cohesive or rock-bed conditions (Figure 3d).

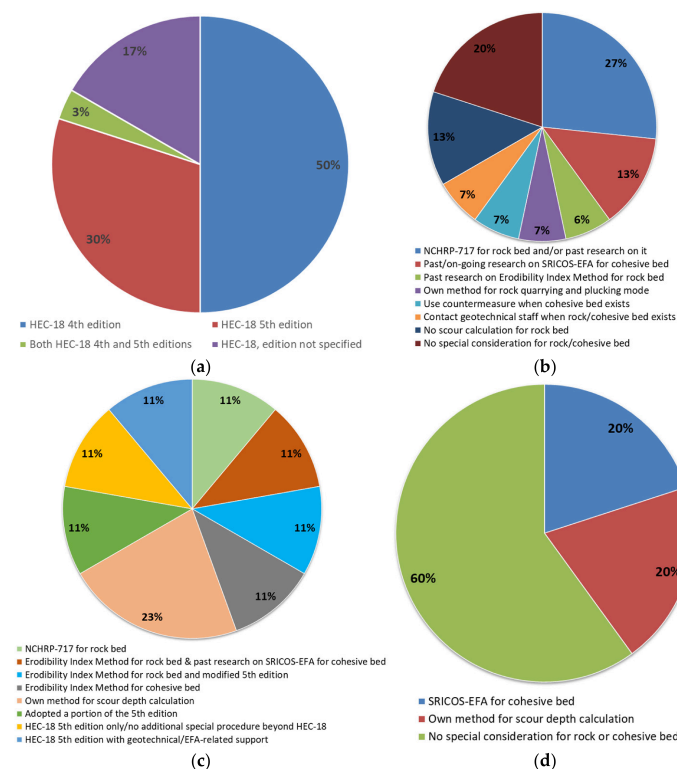


Figure 3. State DOT practices for bridge scour analysis in cohesive soils and scour-susceptible rock based on thirty classifiable DOT response summaries: (a) HEC-18 edition used for scour-depth

calculation, $n = 30$; (b) cohesive/rock-bed considerations among DOTs classified as HEC-18 fourth-edition users, $n = 15$; (c) cohesive/rock-bed considerations among DOTs classified as HEC-18 fifth-edition users, $n = 9$; and (d) cohesive/rock-bed considerations among DOTs that follow HEC-18 but did not specify the edition, $n = 5$. Percentages are calculated relative to the corresponding panel-specific sample size and rounded to the nearest integer considering the sample sizes.

6. Conclusions

This study primarily consists of a review of the relevant literature together with interviews and questionnaires involving state DOTs in the United States to better understand the current state of practice for bridge scour analysis in cohesive soils and scour-susceptible rocks. This review covers the major aspects of the field, including basic concepts, sampling approaches, erodibility testing, scour depth calculation methods, and current state DOT practices. Based on the findings from this study, the following conclusions can be drawn.

1. Bridge scour analysis in cohesive soils and scour-susceptible rocks remains an active area requiring further research and engineering development in the United States.
2. Undisturbed core-drilled samples are generally preferred for scour evaluations involving cohesive soils and scour-susceptible rocks because they better preserve in situ material characteristics. Shelby tube samples remain necessary for EFA testing.
3. Numerous erodibility testing methods are available; however, only a limited number have gained broad acceptance for bridge scour evaluation and DOT implementation.
4. For cohesive soils, SRICOS-EFA remains the most commonly implemented method in practical bridge scour evaluations despite the availability of additional research on pier, contraction, and abutment scour.
5. Research on scour-susceptible rocks remains relatively limited and continues to focus primarily on pier scour, with comparatively little work addressing contraction and abutment scour.
6. The governing scour mechanism is critical for scour analysis in rock formations. The Erodibility Index Method remains the most widely implemented practical approach, while NCHRP 717 has gained increasing acceptance among transportation agencies.
7. All contacted DOTs follow the general HEC-18 framework for bridge scour evaluation; however, considerable variability exists regarding cohesive-soil and rock-scour procedures. Among the contacted DOTs, 50.0% primarily use the fourth edition of HEC-18, 30.0% primarily use the fifth edition, 16.7% use HEC-18 without specifying the edition, and 3.3% use both editions.
8. Many DOTs incorporate SRICOS-EFA, the Erodibility Index Method, NCHRP 717, agency-developed procedures, and/or geotechnical consultation workflows for cohesive and rock-bed conditions, while others still rely on simplified assumptions or limited special consideration. Recent FHWA NextScour studies further indicate movement toward approaches that integrate hydraulic loading, erosion characterization, decay functions, and site-specific risk assessment.

Overall, although significant progress has been made in understanding scour processes in cohesive soils and scour-susceptible rocks, substantial challenges remain in integrating erosion mechanisms, material characterization, hydraulic loading, and predictive modeling into routine engineering practice. Based on the literature review and DOT practice summary, several specific research needs can be identified: (1) paired laboratory and field datasets are needed to evaluate how EFA, JET, RETA, BET, and modified slake durability results can be scaled to field scour conditions; (2) standardized sampling and testing protocols are needed for transitional geomaterials such as cemented soils, weak rock, weathered shale, and highly indurated glacial till; (3) time-dependent scour models require better integration of hydrograph duration, cumulative stream power, critical shear stress, erosion rate, and

material degradation; (4) contraction and abutment scour in scour-susceptible rock remain underdeveloped compared with pier scour; (5) uncertainty quantification, probabilistic assessment, and data-driven or machine-learning methods should be further evaluated, but with attention to interpretability and DOT implementation; and (6) practical guidance is needed to help agencies select cost-effective levels of testing and analysis based on material type, project importance, and risk. These needs are consistent with the DOT practice review, which shows that implementation remains variable even though all surveyed agencies operate within the general HEC-18 framework.

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