Borehole Erosion Test: Some Improvements

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ABSTRACT

The borehole erosion test or BET is a simple field test to obtain the continuous erodibility profile of a soil deposit. It is to erosion what the cone penetration test is to soil strength profiling and stratigraphy. The BET consists of measuring with a borehole caliper the increase in diameter of a borehole when water is circulated in the borehole. The increase in borehole radius divided by the amount of time the water has been flowing gives the erosion rate and the test yields the erosion rate as a function depth. Repeating the tests for different water flow velocities gives the erosion function, erosion rate vs. velocity or erosion rate vs. shear stress, for each soil layer in the profile. This erosion function is the soil constitutive law for erosion problems much like the stress strain curve is for mechanical loading problems. As the use of the borehole erosion test is increasing worldwide, lessons are being learned and the procedures are being updated and refined while dos and don’ts are encountered. The paper describes the updated field procedure for optimizing the result of a BET and the updated procedure for data reduction. This is done in light of some recent BET results.

INTRODUCTION

A significant effort to develop laboratory soil erosion tests by several research centers started in the 1980s after some catastrophic events took place due to soil erosion including the Teton Dam internal erosion failure in 1976 (Chedid et al., 2018) and the Schoharie Creek bridge scour failure in 1987 (Govindasamy et al., 2010). These laboratory tests included the Erosion Function Apparatus (EFA, Briaud 2013), the Hole Erosion Test (Wan and Fell 2004), the Jet Erosion Test (Hanson et al., 2004), and the Pocket Erodometer Test, (Briaud et al., 2012). Some 30 years later, in the early 2010s, a similar development took place for soil erosion field tests. One of these tests is the Borehole Erosion Test or BET which is the topic of this paper. The BET was developed by Briaud and his colleagues at Texas A&M University. While two previous papers have been published on the BET (Briaud et al., 2016 and Briaud et al., 2017), the BET is progressing and new improvements have been made. This paper outlines these new developments including the proper field procedure for optimizing the result of a BET, the proper procedure for data reduction, the limitations of the BET, its advantages, and how to best use it. All this is done in light of some recent BET results.

BET FIELD TEST PROCEDURE

The Borehole Erosion Test (BET) is a field erosion test conducted in a borehole. Recent tests have led to modifying the BET procedure as follows:

1. Set a casing down to a small depth, say 0.6 m, with a known diameter, say 100 mm. This will serve as an additional calibration for the caliper as it passes the casing. Seal the casing so the fluid used for drilling returns to the mud pit.
2. Drill a hole, preferable 75 mm diameter to achieve in-situ testing of faster velocities, over the depth of interest by the wet rotary method. The rods should have an outer diameter of about 50 mm so that the annulus is about 12.5 mm wide. The inside diameter of the rods is not critical. The size of the annulus will have an impact on the velocity that can be generated by the pump on the drilling rig. These rigs typically have pumps that can generate a maximum flow of about 50 m^3/h. Do not "clean" the borehole by repeated passages of the drill bit.
3. Remove the drilling rods and drill bit from the borehole.
4. Lower the calibrated caliper device to the bottom of the hole. Some illustrations of the caliper are shown in the Figure 1 a and 1b. Measure the depth of the bottom of the hole precisely. The caliper should be able to measure the diameter within 1 mm or better so the erosion rate is known with sufficient precision. Keeping notes on how fast the borehole is drilled may give some indication about the erodibility of the soil.
5. Expand the caliper and pull it up the hole while recording the diameter profile; the caliper arms, three minimum, follow the hole and give a continuous record of its average diameter. This gives the initial profile (D_o). Repeat this caliper logging a couple of times for a better precision as the hole may not be completely circular.
6. Pull the caliper out of the hole.
7. Lower the drilling rods without the drilling bit down to a depth such that the bottom of the rods is 0.15 m from the bottom of the borehole. Start the flow of water at a chosen velocity (Figure 1c). In doing so, the discharge at the bottom of the rods is vertical downward. The bottom of the hole will be tested as a jet erosion test; this is why it is important to measure precisely the depth of the hole before and after the flow.
8. Start the pump and set it at a chosen flow rate. This flow rate should be calculated so that it corresponds to a chosen initial velocity V_1 in the annulus. The ability to generate velocities in the range of 0.5 to 4.0 m/s is desirable. Maintain the water flow for 10 minutes. A test in progress is shown in Figure 1c.
9. Stop the flow and remove the drilling rods from the borehole.
10. Repeat steps 4, 5, and 6. This gives the diameter profile after water flow number 1 (D_1).
11. Repeat steps 7 through 10 for different velocities. This gives data of velocities V_2, V_3, V_4 and so on corresponding to diameter profiles D_2, D_3, D_4 and so on.
12. Seal the borehole as required.

Figure 1: Borehole Erosion Tests. a) Retraced caliper, b) Expanded caliper, c) Test in progress.

BET DATA REDUCTION PROCEDURE

Reference is made in the text below to the BET Excel Spreadsheet accompanying this report using the example of data reduction between the initial data and flow 1. The Borehole Erosion Test (BET) data reduction consists of the following procedure.

1. Input the field data in the spread sheet. This data includes the site location, the site elevation, the borehole number, the depths at which the caliper reading are taken, the corresponding borehole diameter (caliper reading), the flow rate as a function of time, the time duration of the flow, and the outside radius of the rods.
2. Calculate the average radius versus depth profile for the borehole before any flow takes place. This requires making an average of the caliper diameter profiles recorded right after drilling the borehole. The radius is used because the erosion rate is the increase in radius divided by the elapsed time of flow.
3. Calculate the average radius versus depth profile for the borehole after the first 10 minutes of flow. This requires making an average of the caliper diameter profiles recorded right after the 10 minutes of flow. Indeed, several caliper diameter profiles are typically recorded in the same borehole.
4. Calculate the difference in radius between the profiles of step 1 and 2 and record it as the radial erosion increment as a function depth.
5. Calculate the erosion rate at any depth by dividing the radial erosion increment by the duration of the flow (~10 minutes). This gives the erosion rate profile for the first flow velocity.
6. Repeat steps 2 to 5 for the other chosen flow rates.
7. During the first flow rate application, the flow rate varies somewhat, and an average value must be calculated. Calculate the average flow rate for the duration of the flow (~10 minutes).
8. Repeat step 6 for all flow rates applied during the BET.
9. For each one of the flow rates, calculate the associated velocity by dividing the flow rate

by the area available for the water to flow. This is taken as the area of the annulus between the outside diameter of the rods and the diameter of the borehole at that depth. The diameter of the borehole at a given depth during the 10 minutes of flow is taken as the average of the annulus area before the flow start and after the flow stops. This step gives the velocity profile for the first average flow rate.

$$v = \frac{Q}{\pi r^2}$$

Note that this is based on the assumption that no drilling fluid permeates into the soil and that all the fluid is going back to the ground surface in the mud pit.

10. Repeat step 9 for all other flow rates.

11. Calculate the shear stress associated with the velocity as described in the following steps. The computations which are described next make a number of assumptions.

12. The equation to go from the velocity to the shear stress is $\tau = \frac{1}{8} f \rho V^2$ (Munson, 2009) where τ is the hydraulic shear stress at the water soil interface, f is the friction factor, ρ is the density of water (1000 kg/m^3), and V is the velocity (m/s). The friction factor depends on the interface relative roughness ε/D_h and the Reynolds Number Re. The roughness ε is the mean depth of the asperities along the borehole wall. The parameter D_h is the hydraulic diameter associated with the annulus between the outside diameter of the rods and the diameter of the borehole. The Reynolds Number Re is

$$R_e = \frac{V D_h}{v}$$

where V is the velocity, D_h is the hydraulic diameter of the annulus space between the rods and the wall of the borehole and ν is the kinematic viscosity of water (10^{-6} m^2/s at 20^0C). The parameter D_h for an annulus is given by $D_h = D_o - D_i$ where D_o is the outside diameter and D_i the inside diameter. At any depth, the outside diameter D_o is taken as the average of 2 times the borehole radius before the flow and 2 times the borehole radius after the flow. The inside diameter D_i is equal to 2 times the outside radius of the rods.

13. Moody (1944) developed a chart which gives the friction factor as a function of the relative roughness and the Reynolds Number. This chart if for circular pipes and leads to the following equation proposed by Haaland:

$$\frac{1}{\sqrt{f}} = -1.8 log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]$$

Note that the viscosity of the fluid appears in the Reynolds number and should be corresponding to the fluid being used for the test (water, drilling mud or other).

14. Applying this equation to pipes with an annulus cross section requires a modification of the value of f as follows (Munson, 2009): $f_{annulus} = 1.5 f_{pipe}$

15. The roughness ε is generated as a profile by considering a rolling depth equal to 0.1 m of the eroded radius profile and calculating for each one of those 0.1 m depth the mean depth of the asperities.

16. Now all the elements are set to calculate the shear stress from the velocity as follows. At

any depth, obtain the velocity from step 8, then the fluid density, then the roughness, then the hydraulic diameter of the annulus, then Reynolds Number, then the friction factor, and then the hydraulic shear stress.

17. Prepare a profile of shear stress versus depth.

18. Use the profiles of erosion rate vs depth, velocity vs depth, and shear stress vs depth to generate for each stratigraphic layer the erosion functions of erosion rate vs velocity and erosion rate vs. shear stress.

EXAMPLE OF RECENT BET TESTS

These tests were conducted as part of an NCHRP project on soil erodibility (Briaud et al., 2019) at the two National Sites for Geotechnical Experimentation at Texas A&M University (Briaud, 1997).

BET at Clay Site

One borehole was drilled down to the depth of 4.3 m. The borehole was located at the coordinates: N 30º.38.104’, W 096º.29.348’. The soil was classified as predominantly high plasticity clay (CH). As described earlier in the BET procedure, the zero reading was measured after 1 minute of flushing at 36 gpm (0.002271 m^3/s) flow. After that, three different flows of 35 gpm (0.002208 m^3/s), 21 gpm (0.001325 m^3/s), and 33 gpm (0.002082 m^3/s) were generated in the borehole and maintained for 10 minutes each. The radius profile was obtained after each flow using the mechanical caliper. Fig. 2 shows the caliper readings at five different stages:

1) Before flushing: right after the borehole was drilled and before doing the 1-minute flushing
2) After flushing: readings were made after 1-minute flushing
3) Reading 1: the borehole radius profile was obtained after 10 minutes of 35 gpm flow
4) Reading 2: the borehole radius profile after 10 minutes of 21 gpm flow
5) Reading 3: the borehole radius profile after 10 minutes of 33 gpm flow

It should be noted that the caliper readings at each of the aforementioned stages were obtained in two runs in order to make sure that the readings were repeatable. In all cases, an acceptable overlay was observed, and the repeatability of the caliper readings was confirmed. The borehole radius profiles shown in Fig. 2 portray the averaged radius profile between the first and second runs at each stage. Fig. 2 clearly shows that there is a more erodible layer between 2.3 and 2.6 m which leads to a much higher radius. This is an example of one of the most important advantages of the BET compared to many other erosion tests in obtaining a continuous erodibility profile. The erosion function curves (i.e. “erosion rate vs. fluid velocity” plots) were constructed for each 0.6 m intervals separately. Table 1 gives the flow rates, velocities, and time of application of each velocity for the BET at the clay site. Fig. 3 shows the erosion function curves for each of the 0.6 m intervals placed on top of the erosion classification chart (Briaud, 2013).

Table 1. Flow, velocity, and time for the BET at clay site

Depth (m)	Flow (m^3/s)	Velocity (m/s)	Duration (min)	Change in profile
0.61 – 1.21	0.002271	1.967	1	before flushing to after flushing
	0.002208	1.308	10	After flushing to reading 1
	0.001325	0.773	10	Reading 1 to reading 2
	0.002082	1.063	10	Reading 2 to reading 3
1.21 – 1.81	0.002271	2.639	1	before flushing to after flushing
	0.002208	1.444	10	After flushing to reading 1
	0.001325	0.967	10	Reading 1 to reading 2
	0.002082	1.431	10	Reading 2 to reading 3
1.81 – 2.41	0.002271	2.450	1	before flushing to after flushing
	0.002208	1.280	10	After flushing to reading 1
	0.001325	0.669	10	Reading 1 to reading 2
	0.002082	0.687	10	Reading 2 to reading 3
2.41 – 3.01	0.002271	N/A	1	before flushing to after flushing
	0.002208	0.596	10	After flushing to reading 1
	0.001325	0.418	10	Reading 1 to reading 2
	0.002082	0.433	10	Reading 2 to reading 3
3.01 – 3.61	0.002271	2.242	1	before flushing to after flushing
	0.002208	1.188	10	After flushing to reading 1
	0.001325	0.621	10	Reading 1 to reading 2
	0.002082	0.712	10	Reading 2 to reading 3

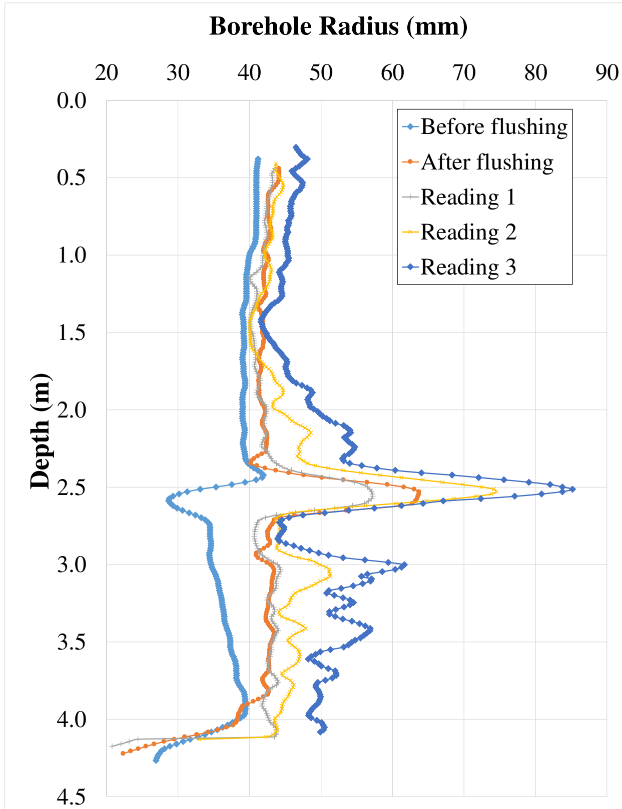

Fig. 2 - Clay borehole radius profile at different stages during the BET (Briaud et al., 2019).

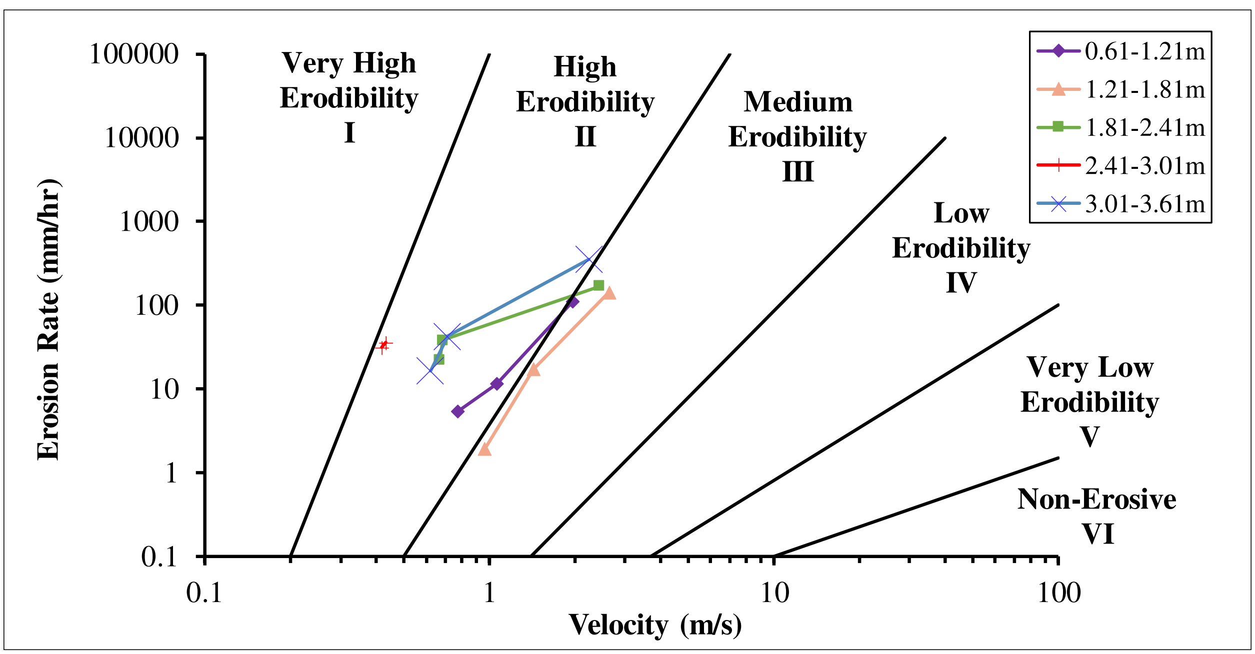

Fig. 3 - BET Results - erosion function curves for each of the 0.6 m intervals in the clay site

BET at Sand Site

One borehole was drilled down to a depth of 3.66 m. The borehole was located at the coordinates: N 30º.38.301', W 096º.27.606'. The soil was classified as predominantly clayey sand (SC). The borehole was flushed for almost 30 seconds at 37 gpm (0.002334 m^3/s) flow. After that, two different flows of 34 gpm (0.002145 m^3/s) and 38 gpm (0.002397 m^3/s) were generated in the borehole and maintained for 7 minutes each. The borehole radius profile was obtained after each flow using a mechanical caliper. Fig. 4 shows the caliper readings at four different stages during the test:

1) Before flushing: right after the borehole was drilled and before doing the 30-seconds flushing
2) After flushing: readings were made after 30 seconds flushing
3) Reading 1: the borehole radius profile after 7 minutes of 34 gpm flow
4) Reading 2: the borehole radius profile after 7 minutes of 38 gpm flow

Similar to the BET at the clay site, the caliper readings at each of the aforementioned stages were obtained in two runs in order to make sure that the readings were repeatable. For all the cases, an acceptable overlay was observed, and the repeatability of the caliper readings was confirmed. The borehole radius profiles shown in Fig. 4 show the averaged radius profile between the first and second runs at each stage. The increase in radius at depths close to the ground surface (0-0.9 m) was significantly larger than at other depths. The erosion function curves (i.e. "erosion rate vs. fluid velocity" plots) were constructed for each 0.6 m intervals separately. Table 2 gives the flow rates, velocities, and time of application of each velocity for the BET at the sand site. Fig. 5 shows the erosion function curves for each of the 0.6 m intervals.

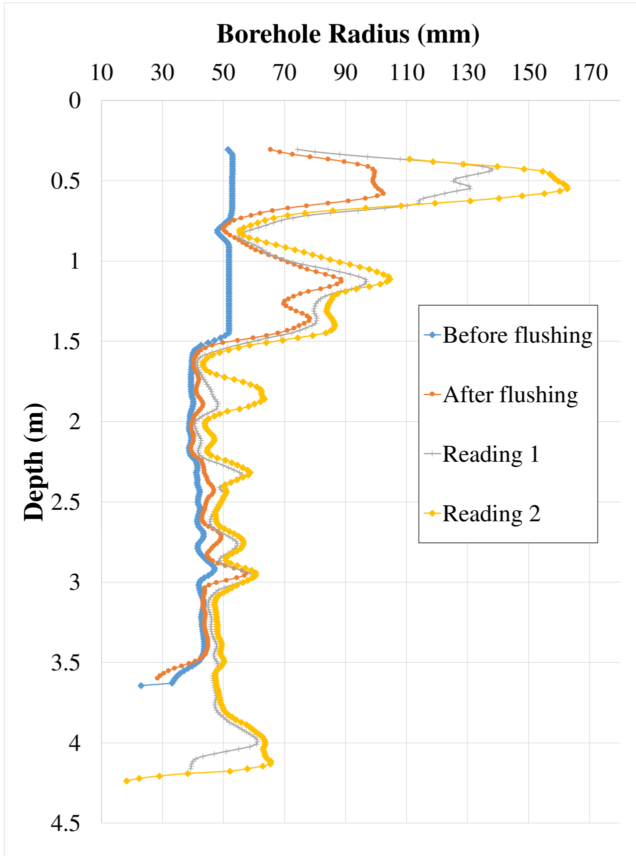

Fig. 4 - Sand borehole radius profile at different stages during the BET

Table 2 - Flow, velocity, and time for the BET at sand site

Depth (m)	Flow (m^3/s)	Velocity (m/s)	Duration (min)	Change in profile
0.31 – 0.91	0.002334	0.518	0.5	before flushing to after flushing
	0.002145	0.147	7	After flushing to reading 1
	0.002397	0.102	7	Reading 1 to reading 2
0.91 – 1.51	0.002334	0.548	0.5	before flushing to after flushing
	0.002145	0.179	7	After flushing to reading 1
	0.002397	0.162	7	Reading 1 to reading 2
1.51 – 2.11	0.002334	2.453	0.5	before flushing to after flushing
	0.002145	1.555	7	After flushing to reading 1
	0.002397	1.191	7	Reading 1 to reading 2
2.11 – 2.71	0.002334	1.652	0.5	before flushing to after flushing
	0.002145	0.988	7	After flushing to reading 1
	0.002397	0.721	7	Reading 1 to reading 2
2.71 – 3.31	0.002334	1.207	0.5	before flushing to after flushing
	0.002145	0.769	7	After flushing to reading 1
	0.002397	0.647	7	Reading 1 to reading 2

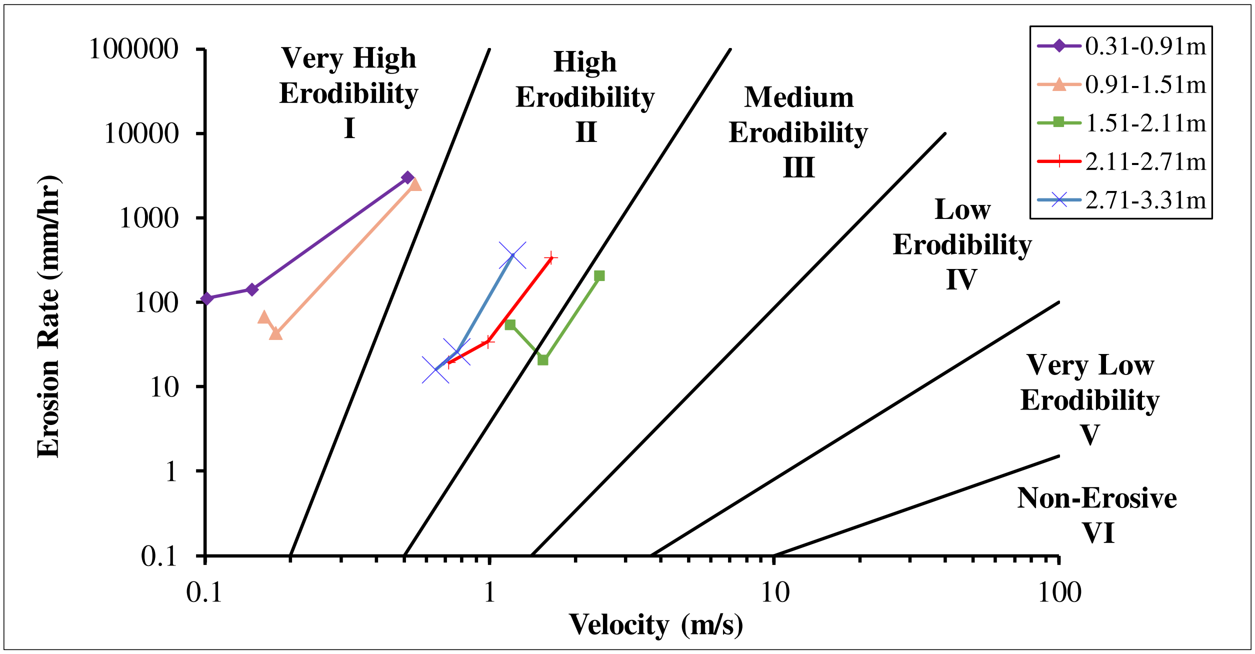

Fig. 5 - BET Results - erosion function curves for each of the 0.6 m intervals at the sand site

CONCLUSIONS

The Borehole Erosion Test or BET is developing as it is increasingly used in practice. The test procedure and the data reduction has been updated, improved, and extended as a result of those field tests. The BET gives a continuous erodibility profile of the borehole tested. It is to erosion what the cone penetrometer test is to strength profiling. It identifies more or less erodible layers through the profile and gives quantified erosion rate at any depth and is very efficient in providing such results. The drawback is the possible sloughing of the walls but such sloughing can typically be identified through a study of the results. The applications include levees, dams, bridge scour, meander migration, river diversions, and many other soil and rock erosion problems. Future development of the BET includes studying the results of the bottom jet test associated with a BET, improved precision on the caliper measurements, more advanced calculation of the shear stress, comparison with other erosion and other soil tests.

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