Evaluation of Time of Scour at Guide Banks in Plain Rivers

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Abstract. Analysis of the literature shows that there are no methods or formulas to calculate the equilibrium time of scour near elliptical guide banks. In the formulas used in calculating the equilibrium time of scour at piers or abutments, different parameters are not taken into consideration. The differential equation of the bed sediment movement in clear-water was used and the method for computing the equilibrium time of scour near elliptical guide banks was elaborated. New hydraulic threshold criterion is proposed for the calculation of equilibrium time of scour. Analysis of the proposed method shows the influence of the following parameters on the equilibrium time of scour: contraction rate of the flow, Froude number, bed layering, sediment movement parameters, local flow modification, relative local and critical velocities ratio, and relative depth. Computer modeling results were compared with the equilibrium times of scour which were calculated by the presented method and they were in good agreement.

1. Introduction

Different authors in order to predict the depth of the bridge foundations (calculate how deep the foundation will be in the river bed) use formulas where the equilibrium time of scour is one of the main parameters. Incorrect prediction of the depth of scour and, consequently, the level of the foundation for abutments, piers, guide banks or spur dikes may lead to severe damages of the bridge structures and cause considerable economic and financial losses.

The equilibrium time of scour at bridge piers, abutments and spur dikes was studied, among others, by Melville & Chiew [1], Ballio & Orsi [2], Lauchlan et al. [3], Coleman et al. [4], Gjunsburgs & Neilands [5], Dey & Barbhuiya [6], Grimaldi et al. [7], Cardoso & Fael [8], Gjunsburgs et al. [9], Ghani et al. [10], Mohammadpour et al. [11], Abou-Seida et al. [12], Gjunsburgs et al. [13].

Scour evaluation at clear-water conditions never ceases completely, so threshold criteria have to be found when the scour development in time has reduced to a negligible value. Various threshold criteria proposed in the literature usually assume that the equilibrium has been reached when the depth of

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scour evaluation is less than 5% of the pier diameter within a period of 24 hours [1] or less than 5% of the flow depth or abutments length [4], or again less than 5% of the 1/3 of the pier diameter [7]. All these criteria for the equilibrium time of scour reference only on the geometrical size of the bridge structures.

Analysis of the literature shows that today there are no methods or formulas to predict the equilibrium time of scour near elliptical guide banks at clear-water conditions, while in the available formulas for calculating the equilibrium time of scour at piers and abutments some important parameters of the flow and river bed are not taken into consideration.

The aim of this paper is to find the equilibrium time of scour near elliptical guide banks in clear-water conditions by using the differential equation of the bed sediment movement in clear-water. Solution of that equation, which describes scour development in time, allows easily finding the equilibrium time.

New hydraulic criterion is proposed to determine the equilibrium time of scour. It has been found that equilibrium time of scour depends on the following parameters: contraction rate of the flow, Froude number, bed layering, grain size diameter, local flow velocity near structure, ratio of local velocity to critical one, and are changing with the relative depth of scour.

The equilibrium time of scour in tests is calculated by using grain size diameter d_{50}, which is found from the uniform sand granulometric curve. The test results of scour evaluation in time with duration of 7 hours were prolonged till the equilibrium stage of scour. Computer modeling of the equilibrium depth and time of scour by early proposed method by Gjunsburgs et al. [13] was done and compared with the equilibrium time of scour at the elliptical guide bank calculated by the presented method.

2. Experimental setup
The tests were carried out in a flume 3.5 m wide and 21 m long. The tests were carried out under open-flow conditions, while studying the flow distribution between the channel and the floodplain.
The fixed bed tests were performed for different flow contractions and Froude numbers in order to investigate the local velocity and the water level changes in the vicinity of the guide bank and along it [14].

The aim of the sand bed tests was to study the scour process, the changes in the local velocity, the effect of different hydraulic parameters, flow contraction rate, grain size, stratification of the model bed and scour development in time.

The openings of the bridge model were 50, 80, 120, and 200 cm. Flow contraction rate Q/Q_b (where Q is flow discharge and Q_b is discharge in the bridge opening under open-flow conditions) varied respectively from 1.56 to 5.69. The depth of water on the floodplain was 7 cm and 13 cm, while the Froude numbers varied from 0.078 to 0.124. The tests were carried out under clear-water conditions. The sand was placed 1 m up and down of the contraction of the flume. The mean grain size was 0.24 mm and 0.67 mm.

The condition that $Fr_R = Fr_f$ was fulfilled; where Fr_R and Fr_f are the Froude numbers for the plain river and for the flume, respectively. The tests in the flume lasted for 7 hours, the length scale was 50 and the time scale was 7.

The tests were carried out with one floodplain model and one side contraction of the flow. The dimension of the upper part of an elliptical guide bank, particularly the length, was calculated according to the Latishenkov [15] method and was found to be dependent on the flow contraction rate and the main channel width. The length of the lower part of the guide bank was assumed to be half of the upper part.

3. Method

The differential equation of equilibrium for the bed sediment movement in clear-water conditions has the form:

$$\frac{dW}{dt} = Q_s \tag{1}$$

where: W = volume of the scour hole at the elliptical guide bank, which, according to the test results, is equal to $1/5\pi m^2 h_s^3$; t = time; and Q_s = sediment discharge out of the scour hole.

The volume and shape of the scour hole are independent of the contraction rate of the flow [16]. The left-hand part of Eq. (1) can be written as:

$$\frac{dW}{dt} = \frac{3}{5}\pi n^2 h_s^2 \frac{dh_s}{dt} = ah_s^2 \frac{dh_s}{dt} \tag{2}$$

where: h_s = scour depth; m = steepness of the scour hole; $a = 3/5\pi m^2$.

Sediment discharge was determined by the Levi [17] formula:

$$Q_s = AB \cdot V_{l\,el}^4 \tag{3}$$

where: $B = mh_s$ describes the width of the scour hole; V_{lel} = local velocity at the elliptical guide bank with a plain bed; and A = a parameter in the Levi [17] formula.

The discharge across the width of a scour hole before and after the scour is determined as follows [15]:

$$Q_f = Q_{sc} \tag{4}$$

where: Q_f = discharge across the width of the scour hole with a plain bed; Q_{sc} = discharge across the scour hole with scour depth h_s.

Now we have:

$$mh_s h_f V_{l\,el} = \left(mh_s h_f + \frac{mh_s}{2} h_s \right) \cdot V_{lt\,el} \tag{5}$$

where: mh_s = width of the scour hole; h_f = water depth in the floodplain; h_s = scour depth; and V_{ltel} = local flow velocity at the elliptical guide bank with a plain bed at scour depth h_s.

From Eq. (5), the local velocity for any depth of scour is:

$$V_{lt\,el} = V_{l\,el}\left(1 + \frac{h_s}{2h_f} \right)^{-1} \tag{6}$$

The critical velocity at the plain bed V_0 can be determined by the Studenicnikov [18] formula $V_0 = 3.6 d_i^{0.25} h_f^{0.25}$, where: d_i = grain size of the bed materials.

The critical velocity V_{0t} for any depth of scour h_s and for the flow bended by the bridge crossing embankment is:

$$V_{0t} = \beta \cdot 3.6 \cdot d_i^{0.25} \cdot h_f^{0.25} \left(1 + \frac{h_s}{2h_f}\right)^{0.25} \tag{7}$$

where: β = coefficient of critical velocity reduction near the elliptical guide bank, because of flow circulation, determined using the Rozovskyi [19] approach.

At a plain river bed the formula for $A = A_1$ is presented as (Eq. 3)

$$A = \frac{5.62}{\gamma}\left(1 - \frac{\beta V_0}{V_{lel}}\right)\frac{1}{d_i^{0.25} \cdot h_f^{0.25}}, \tag{8}$$

where: γ = specific weight of the sediments.

Parameter A depends on the scour, local velocity V_{lel}, critical velocity V_0 and grain size of the bed material which changes during the floods:

$$A_i = \frac{5.62}{\gamma}\left[1 - \frac{\beta V_0}{V_{lel}}\left(1 + \frac{h_s}{2h_f}\right)^{1.25}\right] \cdot d_i^{-0.25} \cdot h_f^{-0.25}\left(1 + \frac{h_s}{2h_f}\right)^{-0.25} \tag{9}$$

where: $\dfrac{\beta V_{0t}}{V_{lt\,el}} = \dfrac{\beta V_0}{V_{lel}}\left(1 + \dfrac{h_s}{2h_f}\right)^{1.25}$.

Then we replace V_{lel} in Eq. (3) with the local velocity at any depth of scour V_{ltel} from Eq. (6). The parameter A in Eq. (3) is replaced with the parameter A_i from Eq. (9). The sediment discharge upon the development of the scour is:

$$Q_s = A_i \cdot mh_s \cdot V_{lt\,el}^4 = b \cdot h_s\left(1 + \frac{h_s}{2h_f}\right)^{-4} \tag{10}$$

where: $b = A_i m V_{l\,el}^{\,4}$.

The hydraulic characteristics, such as contraction rate of the flow, the recalculated critical velocity βV_0 and local velocity V_{lel}, grain size in different bed layers, sediment discharge, and the depth, width and volume of the scour hole, varied during the floods.

Taking into account Eq. (2) and Eq. (10), the differential Eq. (1) can be written in the form:

$$ah_s^2 \frac{dh_s}{dt} = b \cdot h_s\left(1 + \frac{h_s}{2h_f}\right)^{-4} \tag{11}$$

After separating the variables and integrating Eq. (11), we have:

$$t = D_i \int_{x_1}^{x_2} h_s \left(1 + \frac{h_s}{2h_f}\right)^4 dh_s \tag{12}$$

$$D_i = \frac{a}{b} = \frac{3}{5} \frac{\pi \cdot m \cdot}{A_i \cdot V_{l\,el}^4} \tag{13}$$

where: $x_1 = 1 + h_{s1} / 2h_f$ and $x_2 = 1 + h_{s2} / 2h_f$ are relative depths of scour.

After integration with new variables $x = 1 + h_s / 2h_f$, $h_s = 2h_f(x-1)$ and $dh_s = 2h_f dx$ we obtain:

$$t = 4D_i h_f^2 \left(N_i - N_{i-1}\right) \tag{14}$$

where: $N_i = 1/6x_i^6 - 1/5x_i^5$, $N_{i-1} = 1/6x_{i-1}^6 - 1/5x_{i-1}^5$, and $x = 1 + h_s/2h_f$ are the relative depths of scour. Using Eqs. (9), (13) and (14), which contain the equilibrium depth of scour, it is therefore possible to find the equilibrium time of scour near elliptical guide banks:

$$t_{equil} = 4D_{equil.} \cdot h_f^2 \left(N_{equil.} - N_1\right) \tag{15}$$

The sequence to calculate the equilibrium time of scour is the following:
The equilibrium depth of scour at elliptical guide banks is found [14]:

$$h_{equil} = 2h_f \left[\left(\frac{V_{lel}}{\beta V_0}\right)^{0.8} - 1\right] \cdot k_\alpha \cdot k_m \tag{16}$$

where: $V_0 = 3.6 d_i^{0.25} h_f^{0.25}$ = critical velocity at the plain bed; k_α = a coefficient depending on the flow crossing angle; and k_m = a coefficient depending on the side-wall slope of guide banks.
Using value h_{equil}, hydraulic threshold criterion, it is possible to find values A, D, N_{equil} and finally t_{equil}. When local velocity V_{lt} becomes equal to the recalculated critical velocity βV_{0t}, then $A_{equil} = 0$, $D_{equil} = \infty$ and $t_{equil} = \infty$. Criterion to evaluate the threshold is needed to appoint to calculate the equilibrium time of scour.

4. Analysis of the method
To analyze the method, Equations (14) and (15) are transformed to a form that shows clearly that they contain dimensionless parameters and characteristics of the flow and riverbed:

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} \tag{17}$$

Eq. (17) is transformed in to a more detailed form, expressing the parameters for value D_i:

$$N_i = \frac{2t_i A \varphi^4 g^2}{\pi m} \frac{\Delta h^2}{h_f^2} + N_{i-1} \tag{18}$$

From Eq. (18) value t_i is expressed and it reads as follows:

$$t_i = \frac{(N_i - N_{i-1})(\pi m h_f^2)}{2A\varphi^4 g^2 \Delta h^2} \tag{19}$$

In the general form Eq. (18) can be written as:

$$N_i = \frac{2A_1 \varphi^4 g^2}{\pi n} \frac{h^2}{h_f^2} \left(\frac{d}{h_f}\right)^{-0.25} \left\{\frac{P_k}{2}\left[\left(\frac{Q}{Q_b}\right)^2 - 1\right] + \frac{1}{2}P_{kb}\left(\frac{Fr}{i}\right)^{-0.5}\left[\left(\frac{Q}{Q_b}\right)^2 + 1\right] + P_{kb}\right\}^2 \cdot t_i + N_{i-1} \tag{20}$$

From Eq. (20) value t_i is expressed and it reads as follows:

$$t_i = (N_i - N_{i-1})(\pi m h_f^2)\left(\frac{d}{h_f}\right)^{0.25}$$
$$\cdot \left(\left\{\frac{P_k}{2}\left[\left(\frac{Q}{Q_b}\right)^2 - 1\right] + \frac{1}{2}P_{kb}\left(\frac{Fr}{i}\right)^{-0.5}\left[\left(\frac{Q}{Q_b}\right)^2 + 1\right] + P_{kb}\right\}^2 \cdot 2A_1 \varphi^4 g^2 h^2\right)^{-1} \tag{21}$$

where: Q/Q_b – flow contraction rate; $P_k = V_k^2/gh$ – kinetic parameter of the flow in contraction in open-flow conditions; V_k – flow velocity in contraction (under the bridge); $P_{kb} = V^2/gh_f$ – kinetic parameter of the open flow in natural conditions; V – approach flow velocity; Fr/i – ratio of the Froude number to the river slope; h/h_f – relative depth of the flow; h – average depth of the flow in the contracted section; and h_f – water depth in the floodplain.

In the general form, the equilibrium time of scour is a function of the following parameters:

$$t_i = f\left(\frac{Q}{Q_b}; P_k; P_{kb}; \frac{Fr}{i}; \frac{d}{h_f}; \frac{\beta V_0}{V_{lel}}; \frac{h}{h_f}; \frac{h_s}{h_f}; N_{i-1}\right) \tag{22}$$

where: Q/Q_b – flow contraction rate; P_k – kinetic parameter of the flow in contraction in open-flow conditions; P_{kb} – kinetic parameter of the open flow; Fr/i – ratio of the Froude number to the river slope; d/h_f – dimensionless grain size; $\beta V_0/V_{lel}$ – ratio of the recalculated critical velocity at which the sediment movement starts to the local velocity; β – coefficient of critical velocity reduction near the elliptical guide bank, because of flow circulation; h/h_f – relative flow depth; h_s/h_f – relative scour depth; N_{i-1} – calculated parameter, which is taking into account depth of scour in previous time step.

5. Results
At the head of the elliptical guide bank, we observe a concentration of streamlines, a sharp drop in water level, and a local increase in velocity. Locally modified flow near the guide banks forms the scour hole. With the scour depth increase, the local velocity is reducing and the critical one is increasing.

The ratio of the recalculated critical velocity to the local one at the head of the elliptical guide bank is accepted as the threshold criterion in the equilibrium time of scour calculation. According to the computer modeling results, the scour stops when the local velocity V_{ltel} becomes equal to the recalculated critical velocity βV_{0t} or the ratio of those velocities becomes equal to 1, and the equilibrium is equal to infinity. The threshold criterion for equilibrium time of scour calculation was checked and accepted equal to:

$$\frac{\beta V_{0t}}{V_{lt\,el}} = \frac{\beta V_0}{V_{lel}} \left(1 + \frac{h_{equil.}}{2h_f} \right)^{1.25} = 0.985222 \tag{23}$$

Analysis of the method presented and the test results confirmed the influence of the contraction rate of the flow, Froude number, bed grain size diameter, relative local and critical velocities ratio, as well as relative depth of scour on the equilibrium time of scour.
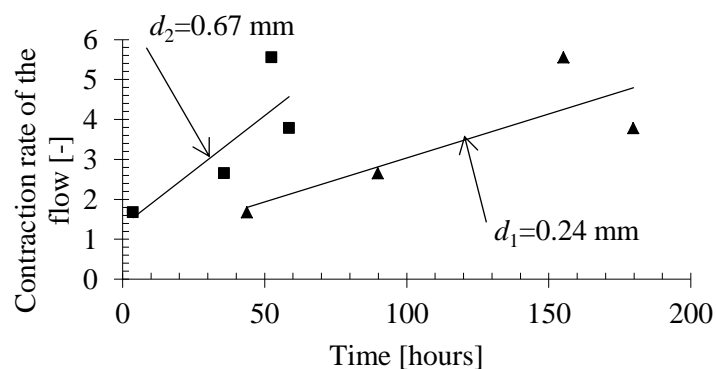
Figure 1. Contraction rate of the flow influence on the equilibrium time of scour. Tests EL3, EL6, EL9, & EL12 with two different sand grain sizes d_1=0.24 mm and d_2=0.67 mm.

Flow contraction creates a series of events that also has an impact on the equilibrium time of scour, thereby if the flow contraction rate Q/Q_b increases, this leads to an increased equilibrium time of scour, consequently, the greater the contraction rate of the flow Q/Q_b value is, the greater the equilibrium time of scour value becomes. Since fine (d_1=0.24 mm) sand particles are more easily scoured away, it takes longer time to achieve the equilibrium stage than in the case with coarse (d_2=0.67 mm) sand.

The ratio of the recalculated critical velocity to the local one $\beta V_0/V_{ltel}$ depends on the contraction rate of the flow Q/Q_b, therefore with an increase of the contraction rate of the flow the equilibrium time of scour is increasing (figure 1).

With an increase in the Froude number Fr, there is also an increase in the equilibrium time of scour, the greater the Froude number Fr value becomes, the further the scouring process continues in the scour hole, resulting also in an increased equilibrium time of scour. With finer sand the equilibrium time is greater, the scouring process takes longer to achieve the equilibrium stage; with coarser sand, on the other hand, the scouring process ends more quickly, resulting in a lesser

equilibrium time of scour value. The greater the grain size diameter of the river bed is, the shorter is the equilibrium time of scour.

Flow velocity is one of the fundamental scouring agents; when the local flow velocity V_{lel} at the elliptical guide bank exceeds the critical value of sediments, the scouring process begins. Since coarser sand particles are heavier, it is more difficult to scour them away, so with an increase of the relative velocity of the flow $V_{ltel}/\beta V_{0t}$ the increase in the equilibrium time of scour is medium, however for the finer sand the increase in the equilibrium time is accelerating with the increase of the relative velocity of the flow $V_{ltel}/\beta V_{0t}$. So the greater the local flow velocity V_{ltel} is and, at the same time, the smaller the recalculated critical flow velocity βV_{0t} for the finer sand is, the greater the equilibrium time of scour will become.

When the scouring process continues in the scour hole, it takes longer time to achieve the time to equilibrium scour. In case of coarser sand (d_2=0.67 mm), the depth of scour is achieved faster, thus resulting in lesser relative depth of scour and at the same time lesser time to equilibrium scour, however, with finer sand (d_1=0.24 mm), on the contrary, it takes more time to achieve the equilibrium scour depth, since also the scour depth increases, consequently increasing the relative depth of scour $h_{equil.}/h_f$. When the relative depth of scour $h_{equil.}/h_f$ becomes greater, the equilibrium time of scour increases as well (figure 2).
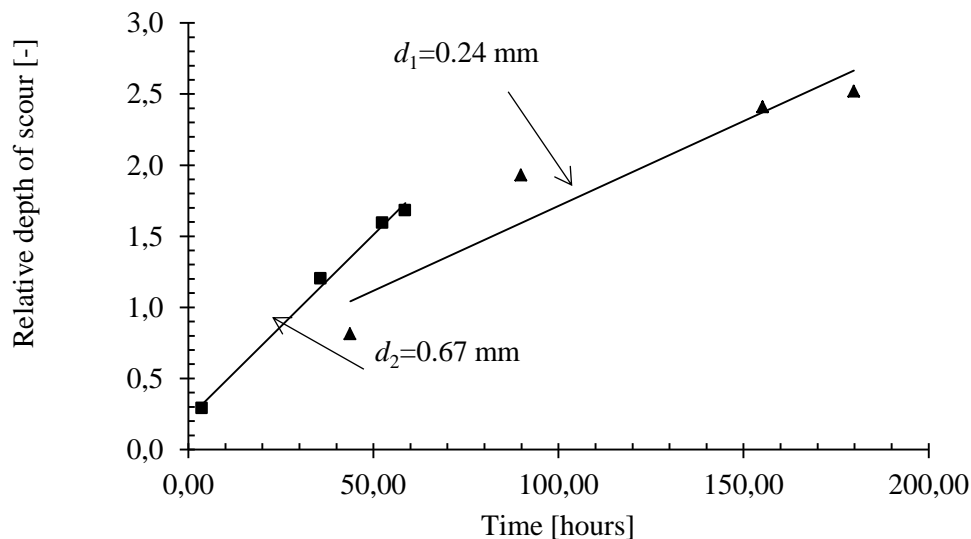
Figure 2. Equilibrium time versus the relative equilibrium depth of scour with sand particle sizes d_1=0.24 mm and d_2=0.67 mm.

Using the threshold criteria (Eq. 23), the equilibrium depth of scour h_{equil} (Eq. 16), A, D, N_{equil} and finally the equilibrium time t_{equil} (Eq. 15) is calculated.

Table 1. Comparison of equilibrium time of scour calculated by computer modeling and by the proposed method for d_{50}=0.24 mm.

TEST	Q/Q_b	D	N_i-N_{i-1}	$t_{comp.}$ [hours]	$t_{form.}$ [hours]	t_c/t_f	V_{0t}/V_{lt}	Fr
EL1	5.27	104.71	1.89	96.0	93.33	1.03	0.985	0.078
EL4	3.66	166.54	1.37	92.1	107.42	0.86	0.985	0.078
EL7	2.60	450.47	0.20	45.0	42.96	1.05	0.985	0.078
EL10	1.56	957.28	0.04	18.0	18.89	0.95	0.985	0.078
EL2	5.69	52.28	5.46	132.0	134.25	0.98	0.985	0.103
EL5	3.87	47.49	4.09	100.8	91.36	1.10	0.985	0.103
EL8	2.69	130.76	1.55	90.0	95.57	0.94	0.985	0.103
EL11	1.66	619.50	0.10	30.5	29.96	1.02	0.985	0.103
EL3	5.55	40.54	8.14	153.6	155.18	0.99	0.985	0.124
EL6	3.78	39.32	9.72	151.2	179.83	0.84	0.985	0.124
EL9	2.65	55.08	3.47	84.0	89.87	0.93	0.985	0.124
EL12	1.67	467.54	0.20	45.0	43.76	1.03	0.985	0.124

Comparison of some results of the equilibrium time of scour calculated by the method presented and found by the computer modeling for d_{50}=0.24 mm are presented in table 1.
Computer modeling of the scour evaluation in time near elliptical guide banks at clear-water conditions was used [14] to prolong the test results to the equilibrium depth and time of scour.
Comparison of the equilibrium times of scour calculated by the computer modeling and by the Eq. (15) has been made; the results are in good agreement (table 1).

6. Conclusions
The flow pattern at the head of the elliptical guide bank was modified, a concentration of streamlines, a sharp drop in water level, local increase in the velocity, circulation and scour hole were observed. Locally modified flow near the head of the guide bank forms a scour hole.
The equilibrium depth of scour development under steady flow conditions can be reached in equilibrium time.

Analysis of the literature shows that there are no methods or formulas to calculate the equilibrium time of scour near elliptical guide banks.
The differential equation of the bed sediment movement in clear-water was used and the method for computing the equilibrium time of scour near elliptical guide banks was elaborated. The test results in the flume with duration of 7 hours were prolonged till the equilibrium stage by scour evaluation in time calculations [16].

It has been confirmed by the method elaborated that the equilibrium time of scour depends on the contraction rate of the flow, Froude number, grain size diameter, local flow velocity near the elliptical guide bank, and the ratio of local velocity to critical one, and is changing with different relative depth of scour. Dependence of the equilibrium time of scour on some parameters is presented in figures (1-2).

With the scour depth increase, the local velocity is reducing and the critical one is increasing. According to Gjunsburgs et al. [14], the scour evaluation stops when the local velocity V_{ltel} becomes equal to the recalculated critical velocity βV_{0t} and the ratio of those velocities becomes equal to 1. In

that case the parameters become equal to $A_{equil} = 0$, $D_{equil} = \infty$ and the equilibrium time goes to infinity $t_{equil} = \infty$.

The equilibrium time of scour in tests is calculated by using grain size diameter d_{50}, which is found from the uniform sand granulometric curve. The equilibrium time for other grain size diameters, for example, d_{10}, d_{16}, d_{84}, d_{90} of the same uniform sand will be very different.

As scour evaluation at clear-water conditions never ceases completely, the threshold criterion is needed to be accepted, when the scour development in time has reduced to a negligible value. The new criterion as $\beta V_{0t}/V_{lt\ el} = 0.985222$ is checked and accepted for the equilibrium time of scour calculations.

The threshold criteria and the values h_{equil}, A, D, N and finally the equilibrium time of scour t_{equil} can be calculated with Eq. (15).

Computer modeling results were compared with the equilibrium time of scour for grain size d_{50} calculated by the method presented (Eq. 15) and they were in good agreement (table 1).

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