International Scientific Conference *People, Buildings and Environment 2016* (PBE2016)
29 September – 1 October, 2016, Luhacovice, Czech Republic, www.fce.vutbr.cz/ekr/PBE

# TIME OF SCOUR AT ELLIPTICAL GUIDE BANKS

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## Abstract

The differential equation of the bed sediment movement in clear water was used and the method for computing equilibrium time of scour was elaborated. New hydraulic criterion is proposed to find equilibrium time of scour near elliptical guide banks. According to the method presented the equilibrium time of scour is depending on: Froude number, contraction rate of the flow, bed layering, grain size diameter, local flow velocity, and ratio of local velocity to critical one. The test results of scour evaluation in time with duration of 7 hours were prolonged till the equilibrium stage of scour [1] and compared with equilibrium time of scour calculated by the method presented, and they were in good agreement.

## Key words

contraction rate of the flow; equilibrium time; guide bank; local scour

To cite this paper: *Gjunsburgs, B., Lauva, O., Jaudzems G., Vilnitis, M. (2016). Time of scour at elliptical guide banks, In conference proceedings of People, Buildings and Environment 2016, an international scientific conference, vol. 4, Luhačovice, Czech Republic, pp. 47-56, ISSN: 1805-6784.*

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# 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 equilibrium time of scour is as 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 were studied, among others, 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], and Ghani et al. [10].

Scour evaluation at clear water conditions never cease completely, so threshold criteria has to be found when scour development in time has reduced to a negligible value. The various threshold criteria proposed in literature usually are assumed that equilibrium has been reached when the depth of scour evaluation is less than 5% of the pier diameter within a period of 24 hours [11] 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 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 equilibrium time of scour near elliptical guide banks at clear water conditions, while in the available formulas for calculating 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 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 equilibrium time.

New hydraulic criterion is proposed to determine the equilibrium time of scour. It is found that equilibrium time of scour is depending 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 relative depth of scour.

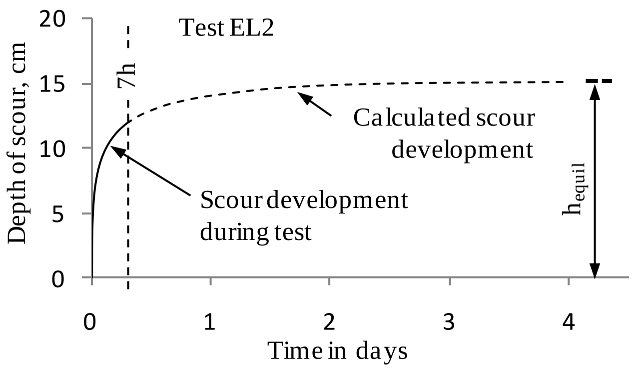


*Fig. 1: Scour depth development in time: test and calculation results; test EL2*

The equilibrium time of scour in tests is calculated by using grain size diameter $d_{50}$, which is found from uniform sand grain-size distribution curve. The test results of scour evaluation in time with duration of 7 hours were prolonged till the equilibrium stage of scour (Fig. 1). Computer modeling of equilibrium depth and time of scour by early proposed method [1] was made and compared with equilibrium time of scour at the elliptical guide bank calculated by the presented method.

The equilibrium time of scour in tests is calculated by using grain size diameter $d_{50}$, which is found from uniform sand grain-size distribution 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.

## 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. Experimental data for the open-flow conditions are presented in Table 1.

The fixed bed tests were performed for different flow contractions and Froude numbers in order to investigate the velocity and the water level changes in the vicinity of the guide banks and along it.

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, the flow contraction rate, the grain size, stratification of the model bed and the scour development in time.

*Tab. 1: Test data for open flow conditions*

| **Test** | ***L*** (cm) | ***h*** (cm) | ***V*** (cm/s) | ***Q*** (l/s) | ***Fr*** | ***Re$_c$*** | ***Re$_f$*** |
|---|---|---|---|---|---|---|---|
| L1 | 350 | 7 | 6.47 | 16.60 | 0.078 | 7500 | 4390 |
| L2 | 350 | 7 | 8.58 | 22.70 | 0.103 | 10010 | 6060 |
| L3 | 350 | 7 | 10.3 | 23.60 | 0.124 | 12280 | 7190 |
| L7 | 350 | 13 | 7.51 | 35.48 | 0.066 | 13700 | 9740 |
| L8 | 350 | 13 | 8.74 | 41.38 | 0.075 | 16010 | 11395 |

The openings of the bridge model were 50, 80, 120, and 200 cm. The flow contraction rate $Q/Q_b$ (where $Q$ is the flow discharge and $Q_b$ is the discharge in the bridge opening under open-flow conditions) varied respectively from 1.56 to 5.69. The depth of water on floodplain was 7 cm and 13 cm, while the Froude numbers varied from 0.078 to 0.134. The tests were carried out under clear-water conditions. The sand was placed 1 m up and down the contraction of the flume. The mean grain size was 0.24 mm and 0.67 mm. The tests with stratified bed conditions were performed for contraction rate $Q/Q_b$= 3.66-4.05. The thickness of the layers with different grain sizes of 0.24 mm and 0.67 mm were equal to 4, 7 and 10 cm.

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 [12] 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:

$$(1-p)\frac{dW}{dt} = Q_S \tag{1}$$

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

According to Gjunsburgs et.al [1] the volume and shape of the scour hole are independent of the contraction rate of the flow.

The left-hand part of Eq. (1) can be written as

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

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

The sediment discharge was determined by the Levi [13] formula:

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

where: $B = mh_s$ describes the width of the scour hole; $V_l$ = the local velocity at the elliptical guide banks with a plain bed; and $A$ = a parameter in the Levi [13] formula.

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

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

where: $Q_f$ = is the discharge across the width of the scour hole with a plain bed; $Q_{sc}$ = the discharge across the scour hole with a 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: $m_h$ = the width of the scour hole; $h_f$ = water depth in the floodplain; $h_s$ = the scour depth; and $V_{lt}$ = the local flow velocity at scour depth $h_s$.

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

$$V_{lt_{el}} = \frac{V_l}{1+\dfrac{h_s}{2h_f}} \tag{6}$$

The critical velocity at the plain bed $V_0$ can be determined by the Studenitcnikov [14] formula $V_0=3.6d_i^{0.25}h_f^{0.25}$, where: $d_i$ = the 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: $\beta$ = coefficient of critical velocity reduction near the structure, because of flow circulation.

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

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

where: $\gamma$ = specific weight of the sediments.

The parameter $A$ depends on the scour, local velocity $V_l$, critical velocity $\beta V_0$ and grain size of the bed material which changes during the floods:

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

where: $\dfrac{\beta V_{ot}}{V_{ltel}} = \dfrac{\beta V_o}{V_{l\,el}}\left(1+\dfrac{h_s}{2h_f}\right)^{1.25}$.

Then we replace $V_l$ in Eq. (3) with the local velocity at any depth of scour $V_{lt}$ 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

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

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

The hydraulic characteristics, such as the contraction rate of the flow, the velocities $\beta V_0$ and $V_l$, the grain size in different bed layers, the 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

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

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

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

where:
$$D_i = \frac{a}{b} = \frac{3}{5}\frac{\pi \cdot m \cdot}{A_i \cdot V_l^4{}_{el}} \tag{13}$$

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 $x=1+h_s /2h_s$ 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 equilibrium time of scour near elliptical guide banks

$$t_{equil} = 4D_{equil.}.h_f^2 \left(N_{equil.} - N_{i-1}\right) \tag{15}$$

The sequence to calculate the equilibrium time of scour is following. The equilibrium depth of scour at elliptical guide banks is found [1]:

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

where: $V_0=3.6d_i^{0.25}h_f^{0.25}$ = the critical velocity at the plain bed; $k_\alpha$ = a coefficient depending on the flow crossing angle; and $k_m$ = a coefficient depending on the side-wall slope of guide banks.

Using value $h_{equil}$, it is possible to find values $A_{equil}$, $D_{equil}$, $N_{equil}$ and finally $t_{equil}$. When local velocity $V_{lt}$ becomes equal to critical velocity $\beta V_{0t}$, $A_{equil}$= 0, $D_{equil}$=∞ and $t_{equil}$=∞ . Criteria to evaluate threshold is needed to appoint to calculate equilibrium time of scour.

## 4 RESULTS

At the head of the elliptical guide bank, we observe the concentration of streamlines, a sharp drop in water level, and a local increase in the velocity. Locally modified flow near the guide banks is forming the scour hole. Figure 2 illustrates the scour depth $h_s$, respective variations in the local $V_{lt}$ and the critical $\beta V_{0t}$ velocities, as measured experimentally and calculated in steady flow including the layer with uniform sand. With the scour depth increase, the local velocity is reducing and the critical one is increasing (Figure 2).

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

$$\frac{\beta V_{ot}}{V_{lt_{el}}} = \frac{\beta V_o}{V_{lel}}\left(1+\frac{h_{equil.}}{2h_f}\right)^{1.25} = 0.985 \tag{17}$$

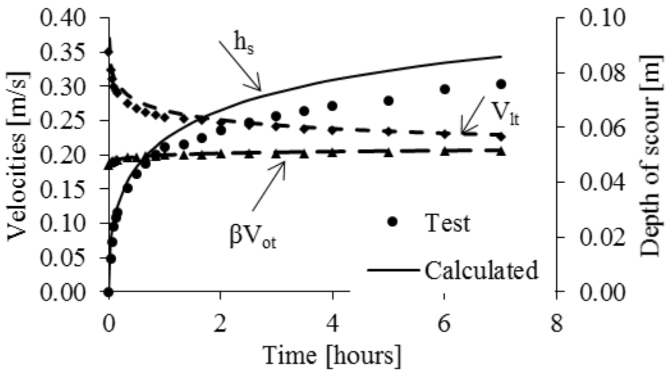


*Fig. 2: Changes in scour depth and in the local and critical velocities $V_{lt}$ and $\beta V_{0t}$ varying with time under steady flow with one-sand layer $d_{50}$=0.24 mm; test EL 6*

Analysis of the method presented and test results confirmed the influence of 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 equilibrium time of scour.

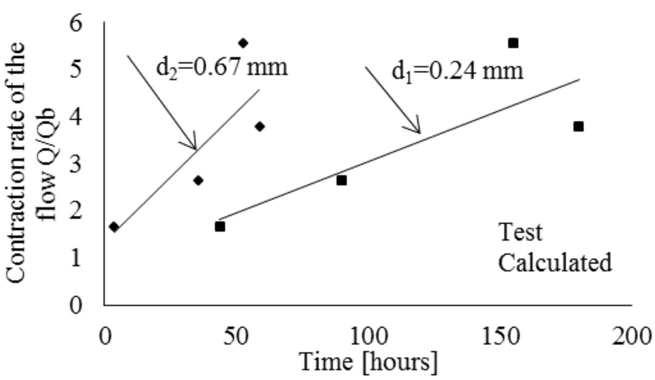


*Fig. 3: Equilibrium time of scour dependence from contraction rate of the flow $Q/Q_b$ with Fr=0.124 and sand particle sizes $d_1$=0.24 mm, and $d_2$=0.67 mm*

The ratio of the critical velocity to local one $\beta V_0/V_l$ is depending on contraction rate of the flow $Q/Q_b$ and then with increase of contraction rate of the flow the equilibrium time of scour is increasing (Figure 3).

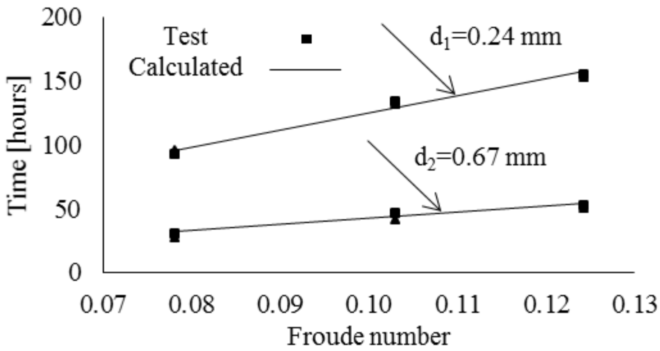


*Fig. 4: Froude number influence on equilibrium time of scour with sand particle sizes $d_1$=0.24 mm and $d_2$=0.67 mm*

With increase of the Froude number of the flow, the equilibrium time of scour is increasing (Fig. 4).The greater the grain size diameter of the river bed is, the less the equilibrium time of scour becomes.

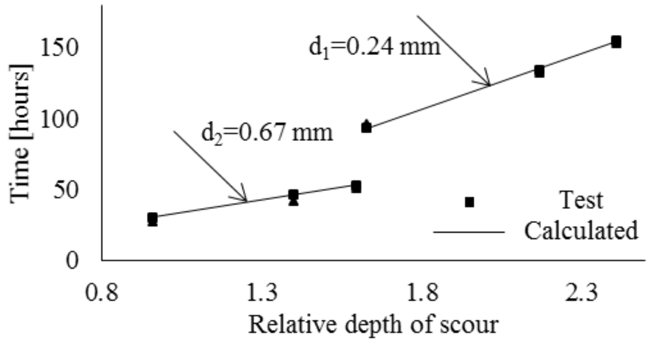


*Fig. 5: Equilibrium time versus relative equilibrium depth of scour with sand particle sizes $d_1$=0.24 mm and $d_2$=0.67 mm*

To reach greater relative equilibrium depth of scour greater equilibrium time is required (Fig. 5).

Using threshold criteria (Eq. 17), equilibrium depth of scour $h_{equil}$ (Eq. 16), *A*, *D*, *N* and finally the equilibrium time $t_{equil}$ (Eq. 15) is calculated.

Comparison of some results of equilibrium time of scour calculated by method presented and found by computer modeling for $d_{50}$=0.24 mm is presented in Table 2.

Computer modeling of scour evaluation in time near elliptical guide banks at clear water conditions was used [1] to prolong test results to equilibrium depth and time of scour.

Comparison of equilibrium times of scour calculated by computer modeling and by Eq. (15) has been made; results are in good agreement (Table 2).

*Tab. 2: Comparison equilibrium time of scour calculated by computer modeling and by proposed methods for $d_{50}$=0.24 mm*

| Test | $Q/Q_b$ | D | $N_i$-$N_{i-1}$ | $t_{comp}$ (hours) | $t_{form}$ (hors) | $t_c/t_f$ | $\beta V_{0t}/V_{lt}$ | *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 |

## 5 CONLUSIONS

The flow pattern at the head of the elliptical guide banks is modified, the 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 banks is forming the scour hole.

The equilibrium depth of scour development under steady flow can be reached in equilibrium time. An analysis of the literature shows that there are no methods or formulas to calculate 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 equilibrium time of scour near elliptical guide banks was considerably elaborated. The test results in flume with duration of 7 hours were prolonged till the equilibrium stage by calculation of scour evaluation in time [1].

It is confirmed by method elaborated that equilibrium time of scour is depending on contraction rate of the flow, Froude number, grain size diameter, local flow velocity near structure, and ratio of local velocity to critical one, and is changing with different relative depth of scour. Dependence of equilibrium time of scour from those parameters is presented in Figures.

With the scour depth increase, the local velocity is reducing and the critical one is increasing. According to Gjunsburgs et al. [1], the scour evaluation stops when local velocity $V_{lt}$ becomes equal to critical velocity $\beta V_{0t}$ and the ratio of those velocities becomes equal to 1. In that case parameters become equal: $A_{equil}$= 0, $D_{equil} = \infty$ and 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 uniform sand grain-size distribution 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 cease completely, the threshold criterion is needed to accept when scour development in time has reduced to a negligible value. The new criterion as $\beta V_{0t}/V_{lt}$ = 0.985222 is checked and accepted for equilibrium time of scour calculation.

The threshold criteria and values $h_{equil}$, $A$, $D$, $N$ and finally $t_{equil}$ can be calculated with Equation (15).

Computer modeling results were compared with equilibrium time of scour for grain size $d_{50}$ calculated by the method presented (Eq. 15) and they were in good agreement (Table 2).

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