Research Article

Spoke Model for Calculating Reliability Index and Safety Factor of Slopes

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Received 4 December 2012; Revised 7 March 2013; Accepted 14 March 2013

Academic Editor: Panos Liatsis

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Considering the disadvantages of the slice method commonly employed in reliability analysis of slopes, a novel method (Spoke model) was proposed for reliability analysis and safety factor calculation of slopes in this work based on geometrical relationship among slices. The safety factor and the coefficients of limit state function of slopes could be achieved with the Gaussian integral method. The minimum safety factor and the minimum reliability index, as well as their corresponding coordinates on the slip surface, can be calculated with the improved JC method and the searching method. A novel and practical method for reliability analysis of slopes has been achieved. With this method the slice process could be avoided, which helps to eliminate some calculation errors caused by oversimplified assumption. Moreover, the explicit expression of safety factor in this method requires no repeated iterative solution, which is employed in traditional slice methods, as well as can be developed into a limit state function required by calculation of the reliability index. It is demonstrated that this method works efficiently and succinctly in evaluation of reliability index and safety factor for soil slopes.

1. Introduction

Each slope (including stable and unstable slopes) possesses an inherent tendency to degrade to a more stable form and eventually make the slope tend to horizontal. Mass movement (slope rupture, landslide, etc.) may take place as a result of the shear failure. The Spoke model proposed in this work is mainly focused on the stability analysis and reliability analysis of simple slopes, where the concept of simple slope discussed in this work is of the slope morphology as shown in Figure 1, and the concept includes the following aspects: (1) the soil is homogeneous, and considering its geotechnical parameters it only includes weight density " w ", cohesion " c ", and internal friction angle " φ "; (2) the underground water are not taken into consideration.

2. Literature Review

There are many methods to determine a slope slip surface. The center coordinate and the radius of a sliding circle were

employed to determine the slip surface in one method [1, 2], while the center coordinate and the height of a sliding circle were introduced in another method [3]. A variety of methods have been applied to analyze the reliability of slopes. Based on traditional slice methods (such as Bishop method [3], Spencer model, Sarma model, and Janbu model [4, 5]), the reliability index can be achieved with the calculated safety factor F and the limit state function $Z = F - 1$. In other cases the minimum reliability index was obtained with the limit state function on the slip surface where the safety factor reaches its minimum value [6]. These approaches are approximate methods for calculation of the reliability index, because all the expressions of safety factor in the slide methods are implicit, which require complicated iterative process when solving. Moreover, the slip surface corresponding to the minimum reliability index may not be the slip surface corresponding to the minimum safety factor [7].

The parallel slide method was employed to analyze the stability of slopes in Bishop method. The safety factor F_s is

FIGURE 1: Illustration of a simple slope.

expressed as follows:

$$F_s = \frac{\sum (1/m_{ai}) [c_i b_i + (W_i - u_i b_i) \tan \varphi_i]}{\sum W_i \sin \alpha_i}. \quad (1)$$

Obviously, the equation is implicit where the parameter m_a contains F_s as well; therefore, it can be solved only with the iterative method. Since the F_s expression is implicit, the corresponding limit state function cannot be achieved when analyzing the stability of slopes with traditional slice methods.

3. Spoke Model

To achieve the limit state equation, a novel slide model (the Spoke model) is proposed in this work. With this model we can get the limit state equation from which the reliability index of slopes can be obtained.

Assuming that a slope is homogeneous, the height, slope angle, slope weight, angle of internal friction, and cohesion are H_0 , α_0 , w , φ , and c , respectively. The slip surface is supposed to be a circular arc surface (Figure 2). Point O is the center of the slope line. Points O , M , and N are on the same line. The angle between line NM and the slope line is ψ . Since $OO' \perp MN$ and $OO' = h$, the arc NM is the slip line. Translate left the center O' , the arc NM , segments, and intersections with a distance of l . The coordinates (ψ, l, h) correspond to all possible slip surfaces, respectively.

The slip soil can be divided into three parts S_1 , S_2 , and S_3 . Taking the second part S_2 , for example, the center angle $\Delta\theta_i$ has crossing points AFDG with the slip line and slope line. The area of the i th AFDG is $\Delta S_2 = S_{AFDG}$. The radius of slip circle is R_0 which can be expressed in

$$R_0 = \left\{ h^2 + \left[\frac{H_0}{2 \sin(\alpha_0 - \psi)} \right]^2 \right\}^{1/2}. \quad (2)$$

Considering $\Delta\theta_i$ is a small value,

$$S_{AFDG} = \left(R_0^2 - \overline{O'D}^2 \right) \frac{\Delta\theta_i}{2}, \quad (3)$$

$$\overline{O'D} = \overline{O'B} - \overline{BC} - \overline{CD}. \quad (4)$$

Assume that

$$r = \angle OO'C = \theta - (\alpha_0 - \psi) = \theta + \psi - \alpha_0, \quad (5)$$

$$\overline{O'B} = \frac{h}{\cos r} = \frac{h}{\cos(\theta + \psi - \alpha_0)}. \quad (6)$$

In triangle $\triangle OBC$, according to Sine theorem, it can be achieved that

$$\frac{\overline{BC}}{\sin \psi} = \frac{h \tan r}{\sin(r + 90^\circ - \psi)} = \frac{h \tan r}{\cos(\psi - r)}. \quad (7)$$

Combining (5) and (7),

$$\overline{BC} = \frac{h \tan(\theta + \psi - \alpha_0) \sin \psi}{\cos(\theta - \alpha_0)}. \quad (8)$$

Similarly, in triangle $\triangle OBC$,

$$\overline{CD} = \frac{\overline{CP}}{\cos(\theta - \alpha_0)} \frac{l \sin \alpha_0}{\cos(\theta - \alpha_0)}. \quad (9)$$

Combining (6), (8), (9), and (4),

$$\begin{aligned} \overline{O'D} &= \frac{h}{\cos(\theta + \psi - \alpha_0)} - \frac{h \tan(\theta + \psi - \alpha_0) \sin \psi}{\cos(\theta - \alpha_0)} \\ &\quad - \frac{l \sin \alpha_0}{\cos(\theta - \alpha_0)}. \end{aligned} \quad (10)$$

Combining (3) and (10),

$$\begin{aligned} S_{AFDG} &= \frac{\Delta\theta_i}{2} \left\{ R_0^2 - \left[\frac{h}{\cos(\theta + \psi - \alpha_0)} - \frac{h \tan(\theta + \psi - \alpha_0) \sin \psi}{\cos(\theta - \alpha_0)} \right. \right. \\ &\quad \left. \left. - \frac{l \sin \alpha_0}{\cos(\theta - \alpha_0)} \right]^2 \right\}. \end{aligned} \quad (11)$$

Assuming that the area of the i th slice is S_i , bulk density and weight of the soil are w_i and W_i , respectively, as follows:

$$W_i = w_i S_i. \quad (12)$$

In the second part, S_i is determined by (11).

$$S_i = S_{AFDG}. \quad (13)$$

Similarly, the S_i expression of the first and third parts can be achieved, respectively, as follows:

$$S_i = \frac{\Delta\theta_i}{2} \left\{ R_0^2 - \frac{R_0 \sin[\arcsin(h/R) + \alpha_0 - \psi]}{\cos \theta} \right\}, \quad (14)$$

$$S_i = \frac{\Delta\theta_i}{2} \left\{ R_0^2 - \frac{R_0 \cos[\arccos(h/R) + \alpha_0 - \psi]}{\cos \theta} \right\}. \quad (15)$$

Shear forces X_i and X_{i+1} pass through center O' , perpendicular to the slip surface. The sideward normal forces are E_i and E_{i+1} , respectively. According to the balance condition along the direction of each radial line,

$$\begin{aligned} W_i \cos \theta_i + X_{i+1} \cos\left(\frac{\Delta\theta_i}{2}\right) - X_i \cos\left(\frac{\Delta\theta_i}{2}\right) \\ + E_i \sin\left(\frac{\Delta\theta_i}{2}\right) + E_{i+1} \sin\left(\frac{\Delta\theta_i}{2}\right) - N_i = 0. \end{aligned} \quad (16)$$

$$\cos\left(\frac{\Delta\theta_i}{2}\right) = 1, \quad (17)$$

where the sum of all the force moments of the slide friction forces on the center of the circle resulting from shear stresses should be zero. Therefore,

$$l_i = R_0 \Delta \theta_i,$$

Combining (16), (17), and (18),

$$W_i \cos \theta_i + X_{i+1} - X_i + E_i \Delta \theta_i - N_i = 0. \quad (19)$$

$$\sum W_i R_i \sin \theta_i - \sum T_i R_0 + \sum Q_i e_i = 0, \quad (20)$$

Compared with the F_s expression in Bishop method, (23) possesses three obvious advantages as follows: (i) the shear stress between the soil strips is not involved in (23); (ii) it is an absolute expression without F_s in its right part, which requires no repeated iterative solution; (iii) (23) has a clear physical meaning. F_s is the ratio of the total resisting moment to the total sliding moment.

When the slope is sliced infinitely, as well as the interstitial pressure and the seismic inertial force are not taken into consideration, the safety factor can be expressed in the integration form. Combining (13), (16), and (23),

$$T_i = \tau l_i = \frac{\tau_f}{F_s} l_i = \frac{c_i l_i}{F_s} + (N_i - u_i l_i) \frac{\tan \varphi_i}{F_s}. \quad (21)$$

$$F_s = \frac{R_0 \sum [c_i l_i + (W_i \cos \theta_i + X_{i+1} - X_i + E_i \Delta \theta_i - u_i l_i) \tan \varphi_i]}{\sum W_i R_i \sin \theta_i + \sum Q_i e_i}, \quad (22)$$

$$F_s = \frac{(cR_0^2/w) \int_{\theta_0}^{\theta_3} d\theta + R_0 \tan \varphi \times T}{\int_{\theta_0}^{\theta_1} S_1 R_1 \sin \theta d\theta + \int_{\theta_1}^{\theta_2} S_2 R_2 \sin \theta d\theta + \int_{\theta_2}^{\theta_3} S_3 R_3 \sin \theta d\theta}, \quad (24)$$

$$\text{where } T = \int_{\theta_0}^{\theta_1} [S_1 \cos \theta + E_1(\theta)] d\theta + \int_{\theta_1}^{\theta_2} [S_2 \cos \theta + E_2(\theta)] d\theta + \int_{\theta_2}^{\theta_3} [S_3 \cos \theta + E_3(\theta)] d\theta.$$

Therefore,

$$\begin{aligned}
 f &= \frac{cR_0^2}{w} \int_{\theta_0}^{\theta_3} d\theta + R_0 \tan \varphi \\
 &\times \left\{ \int_{\theta_0}^{\theta_1} [S_1 \cos \theta + E_1(\theta)] d\theta \right. \\
 &\quad \left. + \int_{\theta_1}^{\theta_2} [S_2 \cos \theta + E_2(\theta)] d\theta + \int_{\theta_2}^{\theta_3} [S_3 \cos \theta + E_3(\theta)] d\theta \right\} \\
 &\div \left(\int_{\theta_0}^{\theta_1} S_1 R_1 \sin \theta d\theta \right. \\
 &\quad \left. + \int_{\theta_1}^{\theta_2} S_2 R_2 \sin \theta d\theta + \int_{\theta_2}^{\theta_3} S_3 R_3 \sin \theta d\theta \right), \quad (25)
 \end{aligned}$$

where $S_j d\theta$ ($j = 1, 2, 3$) in (24) and (25) is the integrated area element, R_j ($j = 1, 2, 3$) is the distance between the slice center and the center of the circle, and $S_j R_j d\theta$ ($j = 1, 2, 3$) represents the quadrature. Combining (11)–(15), they could be expressed as the functions of the parameters H_0 , α_0 , ψ , l , and h as follows:

$$\begin{aligned}
 S_j d\theta &= (R_0^2 - r_j^2) \frac{d\theta}{2}, \\
 R_j &= \frac{2(R_0^2 + R_0 r_j + r_j^2)}{3(R_0 + r_j)}, \quad (26) \\
 S_j R_j d\theta &= (R_0^3 - r_j^3) \frac{d\theta}{3}, \\
 (j &= 1, 2, 3),
 \end{aligned}$$

where

$$\begin{aligned}
 r_1 &= \frac{R_0 \sin [\arcsin (h/R_0) + \alpha_0 - \psi]}{\cos \theta}, \\
 r_2 &= \frac{h}{\cos (\theta + \psi - \alpha_0)} \\
 &\quad - \frac{h \tan (\theta + \psi - \alpha_0) \sin \psi}{\cos (\theta - \alpha_0)} - \frac{l \sin \alpha_0}{\cos (\theta - \alpha_0)}, \\
 r_3 &= \frac{R_0 \cos [\arccos (h/R_0) + \alpha_0 - \psi]}{\cos \theta}. \quad (27)
 \end{aligned}$$

In (24) and (25), the upper/lower limit of integral θ_i ($i = 0, 1, 2, 3$) represents the central angle between the line $O'H$ and another segment whose two endpoints are the center of circle and the endpoint of the slide slope segment in the circle

arc, which can be expressed as the functions of the parameters H_0 , α_0 , ψ , l , and h as follows:

$$\begin{aligned}
 \theta_0 &= -\arccos \left(\frac{h}{R_0} \right) + \alpha_0 - \psi, \\
 \theta_1 &= -\arcsin \frac{R_0 \cos [\arcsin (h/R_0) + \alpha_0 - \psi] - (s - l)}{\{R_0^2 + (s - l)^2 - 2R_0 (s - l) \cos [\arcsin (h/R_0) + \alpha_0 - \psi]\}^{1/2}}, \\
 \theta_2 &= \arcsin \frac{R_0 \sin [\arccos (h/R_0) + \alpha_0 - \psi] - (s + l)}{\{R_0^2 + (s + l)^2 - 2R_0 (s + l) \cos [\arcsin (h/R_0) - \alpha_0 + \psi]\}^{1/2}}, \\
 \theta_3 &= \arccos \left(\frac{h}{R_0} \right) + \alpha_0 - \psi. \quad (28)
 \end{aligned}$$

In (26), (27), and (28),

$$R_0 = \left\{ h^2 + \left[\frac{H_0}{2 \sin (\alpha_0 - \psi)} \right]^2 \right\}^{1/2}, \quad (29)$$

$$s = \frac{H_0 \sin \psi}{2 \sin (\alpha_0 - \psi) \sin \alpha_0}. \quad (30)$$

In (24) and (25), $E(\theta)$ can be achieved by solving differential equations. The differential equation in the tangential direction of the i th slice slope can be expressed as follows:

$$\Delta E_i = -W_i \sin \theta + N_i \tan \varphi. \quad (31)$$

Combining (20) and (31),

$$\Delta E_i = -W_i \sin \theta_i + (W_i \cos \theta_i + E_i \Delta \theta_i) \tan \varphi + \Delta X_i \tan \varphi. \quad (32)$$

To simplify the calculation, let $\Delta X_i = \Delta E_i \tan \varphi$, $\mu = \tan \varphi$, and (32) can be developed into a differential equation:

$$dE(\theta) - \frac{\mu}{1 - \mu^2} E(\theta) d\theta = w(\mu \cos \theta - \sin \theta) f(\theta) d\theta, \quad (33)$$

where $f(\theta) d\theta$ is the area element, which can be expressed as follows with (26):

$$f(\theta) d\theta = S_j d\theta = (R_0^2 - r_j^2) \frac{d\theta}{2}. \quad (34)$$

Let $\alpha = \mu/(1 - \mu^2)$. The general solution of the linear differential (33) is

$$E(\theta) = e^{\alpha \theta} \left[\int w(\mu \cos \theta - \sin \theta) f(\theta) e^{-\alpha \theta} d\theta + C \right], \quad (35)$$

where C is an arbitrary constant. Considering the complexity of $f(\theta)$, it is definitely complicated to solve the indefinite integral of the transcendental function. To simplify the calculation, $f(\theta)$ is replaced with a proper constant M . Within the interval $\theta > 0$ in (26), r_j is replaced with $\overline{OO'}$. Equation (32) can be developed into

$$E(\theta) = e^{\alpha \theta} M \left[\int w(\mu \cos \theta - \sin \theta) e^{-\alpha \theta} d\theta + C \right]. \quad (36)$$

With

$$\begin{aligned} \int e^{-\alpha\theta} \cos \theta d\theta &= \frac{1}{1+\alpha^2} e^{-\alpha\theta} (-\alpha \cos \theta + \sin \theta) + C_1, \\ \int e^{-\alpha\theta} \sin \theta d\theta &= \frac{1}{1+\alpha^2} e^{-\alpha\theta} (-\alpha \sin \theta - \cos \theta) + C_2, \end{aligned} \quad (37)$$

(36) can be developed into

$$\begin{aligned} E(\theta) &= \frac{wM}{1+\alpha^2} \\ &\times \left\{ [(1-\alpha\mu) \cos \theta + (\alpha + \mu) \sin \theta] + C_3 e^{-\alpha\theta} + C_4 \right\}. \end{aligned} \quad (38)$$

Assuming $E(\theta) = 0$ when $\theta = \theta_3$,

$$\begin{aligned} E(\theta) &= \frac{wM}{1+\alpha^2} \left\{ [(1-\alpha\mu) \cos \theta + (\alpha + \mu) \sin \theta] \right. \\ &\quad \left. - e^{\alpha(\theta-\theta_3)} [(1-\alpha\mu) \cos \theta_3 + (\alpha + \mu) \sin \theta_3] \right\}. \end{aligned} \quad (39)$$

When $\partial E(\theta)/\partial \theta = 0$, we can obtain the maximum value of broadside normal stress $E_m(\theta)$ and its corresponding angle $\theta = \theta_m$. The normal stress would reduce to zero gradually from the cut-off point toward both directions. It can be analyzed that θ_m is in the interval $\theta > 0$. Combining $E = E(\theta_m)/2$ and (24), (25), the safety factor can be calculated, and the limit state function can be determined.

Subsequently, combine (24)–(30). As for a certain slope (i.e., α_0 and H_0 are fixed.), each group of (ψ, l, h) would result in its corresponding safety factor and limit state function. Namely, safety factor and limit state function can be expressed as a function containing variables ψ , l , and h , respectively as follows:

$$\begin{aligned} F_s &= g_1(\psi, l, h), \\ f &= g_2(\psi, l, h, c, \varphi, w). \end{aligned} \quad (40)$$

Considering the random variability of soil parameters, we could obtain the reliability index of each group of (ψ, l, h) . By varying the numerical values of (ψ, l, h) , the minimum values of reliability index and safety factor can both be obtained. The calculation of structure reliability index has been discussed in many reported works [9–13]. In a typical failure mode of a slope (Figure 3), the slip surface passes through both the top plane and bottom plane. Based on geometrical condition and the constraint relationship among ψ , l , and h , inequalities (41) can be obtained theoretically as follows:

$$\begin{aligned} 0 &\leq \psi < \alpha_0, \\ |l| &\leq \frac{H_0 \sin \psi}{2 \sin \alpha_0 \sin(\alpha_0 - \psi)}, \\ \frac{H_0}{2 \cos(\alpha_0 - \psi)} &\leq h \\ &\leq \frac{(H_0 / \sin \alpha_0) - ((s-l) / \cos(\alpha_0 - \psi))}{2 \tan(\alpha_0 - \psi)}. \end{aligned} \quad (41)$$

FIGURE 3: Area of most possible slip surface.

TABLE 1: Calculation Results for Example (II).

		Corresponding coordinate		
		x (m)	y (m)	r (m)
Result achieved in [8]	$K_{s \min} = 1.28$	59.21	-84.72	152.13
		Corresponding coordinate		
		ψ (°)	l (m)	h (m)
Result in this work	$K_{s \min} = 1.31$	2.18	6.35	115.22

Pan Jia-zheng has stated that the center of critical slip surface is in the area formed by two circulars with radius of $H_0/2 \tan \alpha_0$ and $3H_0/4 \tan \alpha_0$, respectively, central normal line and perpendicular bisector of the slope surface (Figure 3) [14]. By varying the values of ψ , l , and h within this area, we can achieve the minimum values of reliability index $\beta_{\min}$, and safety factor $K_{s \min}$, and their corresponding (ψ, l, h) .

3.1. Example Analysis

Example (I) (see [15]). There is a slope whose height and slope angle are 4.5 m and 20° , respectively, with a sand bed beneath which helps to drain water away adequately. The natural unit weight of soil is $\gamma = 16 \text{ kN/m}^3$. The average efficacious shear strength and variation coefficient are $\mu'_c = 2.159 \text{ kPa}$, $\delta'_c = 30\%$, $\mu_{\tan \varphi'} = 0.312$, and $\delta_{\tan \varphi'} = 2.5\%$, respectively. Find out the failure probability of the given slid surface. The safety factor was calculated approximately to be $K_s = 1.25$ with a vertical slice method in [15]. The failure probability was calculated to be $P_f = 0.002$ ($\beta = 2.901$) with statistics formulas.

With the novel method (Spoke model) proposed in this work, the safety factor is calculated to be $K_s = 1.252$. If c and $\tan \varphi'$ are regarded as normal random variables, and they are not interrelated, the corresponding reliability index is calculated to be 2.883 with the Spoke model.

TABLE 2: Calculation Results for Example (III).

		Corresponding coordinates of the minimum value		
		ψ (°)	l (m)	h (m)
Safety index (variation coefficients of c and $\tan \varphi$ are 0.2 and 0.275, resp.)	$K_{s\min} = 1.38$	7.4	1.32	11.09
	$\beta_{\min} = 1.60$	7.6	1.34	11.13
Safety index (variation coefficients of c and $\tan \varphi$ are both 0.15)	$K_{s\min} = 1.38$	7.4	1.32	11.09
	$\beta_{\min} = 2.37$	6.4	1.45	10.98

Example (II) (see [8]). There is a homogeneous simple slope whose height (h) is 50 m, slope proportion (m) is 3.25, bulk density of soil (r) is 19.62 kNm^{-3} , coefficient of friction is $\tan \varphi = 0.2$, and adhesion stress (c) is 58.66 kPa. Work out the location of the most dangerous slide arc and minimum value of safety factor.

The calculated results with the Spoke model proposed in this work and the corresponding results in [8] are listed in Table 1.

Example (III) (see [7]). There is a clay slope whose height is 10.0 m, and the proportion of slope is 1:2. The average value and standard deviation of c and $\tan \varphi$ are 20 kPa, 0.1817 and 4.0 kPa, 0.05, respectively, and all of them are considered to be of normal distribution and not interrelated. The unit weight of soil is 16.0 kNm^{-3} , considered as a fixed value. Find out the minimum value of safety factor and reliability index of the slope.

With the Spoke model in this work, we take $\Delta\psi = 0.2^\circ$, $\Delta l = 0.05 \times H_0 \sin \psi / 2 \sin \alpha_0 \sin(\alpha_0 - \psi)$, and $\Delta h = 0.05 \times [(H_0 / \sin \alpha_0 - (s-l) / \cos(\alpha_0 - \psi)) / \tan(\alpha_0 - \psi) - H_0 / \cos(\alpha_0 - \psi)]$ as the step length to search solution. The results are listed in Table 2.

According to the analysis of Examples (I) and (II), the calculated results with Spoke model and traditional slice methods are subequal. Example (III) indicates that minimum safety factor and minimum reliability index are not achieved on the same slip surface. In addition, the variability of soil parameters affects the minimum reliability index and the position of its corresponding slip surface but possesses little influence on the minimum safety factor and the position of its corresponding slip surface.

It is worth noting that the expression of safety factor has a clear physical meaning in this work. With the calculation program built, it is convenient for data input, and the calculation process is quick. With this method for reliability analysis of slopes, the limit state function can be achieved which directly results in the reliability index.

4. Conclusion

The explicit expression of safety factor in Spoke model proposed in this work requires no repeated iterative solution, as well as can be developed into a limit state function required by calculation of the reliability index. The Spoke model avoids complicated repeated iterative solution as required in traditional slice methods as well as eliminates the errors arising from oversimplified assumption.

According to the example analysis, the slip surface with minimum reliability index is not in coincidence with, but similar to, the one with minimum safety factor. We can find out the minimum safety factor and its corresponding coordinates first, then search the minimum reliability index nearby.

The minimum reliability index and location of its corresponding slip surface are related with soil parameters such as weight density “ G ,” cohesion “ c ,” and internal friction angle “ φ .” The minimum safety factor and location of its corresponding slip surface have no relation with variability of soil parameters.

This work only discusses the calculation analysis of reliability of simple slopes. The failure surface is supposed as a circular arc, and some simplifications are utilized on the resistance calculation of slip surface caused by the stress between slices. The influence of simplified treatment in this work on calculation results could be a direction of further research.

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