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Note on the Evaluation of Solid-Blockage Corrections for Rectangular Wind Tunnels with Slotted Walls

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1. *Introduction.* During the preparation at the N.P.L. of a manual of tunnel interference the necessity arose for calculating additional values of the blockage-interference corrections for small bodies in incompressible flow in rectangular tunnels having longitudinally slotted roofs and floors. This consisted essentially of extending the work of Davis and Moore[1] to include a wider range of tunnel height/breadth ratio. In order to do this without excessive computation it was necessary to simplify the formulae given in Ref. 1, and this report is concerned with the manner of simplification and with the results of the calculations.

2. *Simplified Formulae for Blockage Interference.* The configuration considered is a rectangular tunnel with solid side walls of height H and longitudinally slotted roof and floor each containing N slots, each slot being of width d. The breadth of the tunnel is denoted by B. A small model placed symmetrically in the tunnel is represented by a doublet of strength m. In Ref. 1, Davis and Moore, using an equivalent homogeneous boundary condition, have derived the following expression for the longitudinal incremental velocity, u_2, at the position of the model

$$\frac{u_2 B^3}{8m} = \frac{1}{16\pi} \sum_{k=1}^{\infty} \frac{1}{k^3} + \frac{1}{\pi^2} \sum_{s=0}^{\infty} p(s) \int_0^{\infty} \frac{q^2[qc\lambda^2 H_1(\lambda, s, q) - H_0(\lambda, s, q)]}{C(\lambda, s, q) + cS(\lambda, s, q)}\, dq\,, \tag{1}$$

where

$$p(0) = \tfrac{1}{2} \text{ and } p(s) = 1 \text{ for } s \geqslant 1\,, \tag{2}$$

$$H_1 = \int_0^1 \sum_{k=-\infty}^{+\infty} \frac{K_1[q\sqrt{\{(\alpha+2k)^2 + \lambda^2\}}]}{\sqrt{\{(\alpha+2k)^2 + \lambda^2\}}} \cos(s\pi\alpha) d\alpha\,, \tag{3}$$

$$H_0 = \int_0^1 \sum_{k=-\infty}^{+\infty} K_0[q\sqrt{\{(\alpha+2k)^2 + \lambda^2\}}] \cos(s\pi\alpha) d\alpha\,, \tag{4}$$

$$C(\lambda, s, q) = \cosh\{\lambda\sqrt{(q^2+s^2\pi^2)}\}\,, \tag{5}$$

$$S(\lambda, s, q) = \lambda\sqrt{(q^2+s^2\pi^2)} \sinh\{\lambda\sqrt{(q^2+s^2\pi^2)}\}\,, \tag{6}$$

$$\lambda = H/B\,; \tag{7}$$

$$c = \frac{2}{\pi N\lambda} \log \operatorname{cosec} \frac{\pi N d}{2B}\,, \tag{8}$$

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and $K_0(x)$ and $K_1(x)$ are Bessel functions in the notation of Ref. 2. The parameter c represents the openness of the roof and floor of the tunnel; for a closed tunnel c tends to $+\infty$, and for a tunnel with completely open roof and floor $c = 0$.

For computing purposes some simplification of equations (1) to (6) is desirable. Consider first H_0 and H_1. Since $K_0(x)$ tends to zero exponentially as x tends to $+\infty$,

$$\begin{aligned} H_0 &= \sum_{k=-\infty}^{+\infty} \int_0^1 K_0[q\sqrt{\{(\alpha+2k)^2 + \lambda^2\}}] \cos(s\pi\alpha)d\alpha \\ &= \sum_{k=1}^{\infty} \int_0^1 K_0[q\sqrt{\{(\alpha-2k)^2 + \lambda^2\}}] \cos(s\pi\alpha)d\alpha + \\ &\quad + \int_0^1 K_0[q\sqrt{(\alpha^2+\lambda^2)}] \cos(s\pi\alpha)d\alpha + \\ &\quad + \sum_{k=1}^{\infty} \int_0^1 K_0[q\sqrt{\{(\alpha+2k)^2 + \lambda^2\}}] \cos(s\pi\alpha)d\alpha. \end{aligned} \tag{9}$$

In the first term in equation (9) put $\alpha - 2k = -\theta$, and in the third $\alpha + 2k = \theta$. Then, since s is an integer,

$$\begin{aligned} H_0 &= \sum_{k=1}^{\infty} \int_{2k-1}^{2k} K_0[q\sqrt{(\theta^2+\lambda^2)}] \cos(s\pi\theta)d\theta + \\ &\quad + \int_0^1 K_0[q\sqrt{(\alpha^2+\lambda^2)}] \cos(s\pi\alpha)d\alpha + \\ &\quad + \sum_{k=1}^{\infty} \int_{2k}^{2k+1} K_0[q\sqrt{(\theta^2+\lambda^2)}] \cos(s\pi\theta)d\theta. \end{aligned} \tag{10}$$

Thus

$$H_0 = \int_0^{\infty} K_0[q\sqrt{(\theta^2+\lambda^2)}] \cos(s\pi\theta)d\theta. \tag{11}$$

Similarly

$$H_1 = \int_0^{\infty} \frac{K_1[q\sqrt{(\theta^2+\lambda^2)}]}{\sqrt{(\theta^2+\lambda^2)}} \cos(s\pi\theta)d\theta. \tag{12}$$

Now by Ref. 2 (p. 55)

$$J_{-1/2}(z) \equiv \left(\frac{2}{\pi z}\right)^{1/2} \cos z,$$

so that

$$\cos(s\pi\theta) = J_{-1/2}(s\pi\theta)\pi\left(\frac{s\theta}{2}\right)^{1/2},$$

and by equation (11)

$$H_0 = \pi\sqrt{\left(\frac{s}{2}\right)} \int_0^{\infty} K_0[q\sqrt{(\theta^2+\lambda^2)}] J_{-1/2}(s\pi\theta)\theta^{1/2}d\theta. \tag{13}$$

Since by Ref. 2 (p. 416),

$$\begin{aligned} &\int_0^{\infty} K_0[q\sqrt{(\theta^2+\lambda^2)}] J_{-1/2}(s\pi\theta)\theta^{1/2}d\theta \\ &= (s\pi)^{-1/2}\left\{\frac{\sqrt{(q^2+s^2\pi^2)}}{\lambda}\right\}^{-1/2} K_{-1/2}[\lambda\sqrt{(q^2+s^2\pi^2)}], \end{aligned}$$

then

$$H_0 = \sqrt{\left(\frac{\pi}{2}\right)} (q^2+s^2\pi^2)^{-1/4} \lambda^{1/2} K_{-1/2}[\lambda\sqrt{(q^2+s^2\pi^2)}]; \tag{14}$$

or, since (Ref. 2, p. 80)

$$K_{-1/2}(z) \equiv K_{1/2}(z) \equiv \left(\frac{\pi}{2z}\right)^{1/2} e^{-z},$$

$$H_0 = \frac{\pi}{2} \frac{e^{-\lambda\sqrt{(q^2+s^2\pi^2)}}}{\sqrt{(q^2+s^2\pi^2)}}. \tag{15}$$

Similarly (Ref. 2, p. 416),

$$\int_0^\infty \frac{K_1[q\sqrt{(\theta^2+\lambda^2)}]}{\sqrt{(\theta^2+\lambda^2)}} J_{-1/2}(s\pi\theta)\, \theta^{1/2} d\theta = \frac{(s\pi)^{-1/2}}{q} \left\{\frac{\sqrt{(q^2+s^2\pi^2)}}{\lambda}\right\}^{1/2} K_{1/2}(\lambda\sqrt{(q^2+s^2\pi^2)}),$$

and it follows from equation (12) that

$$H_1 = \frac{\pi}{2} \frac{1}{\lambda q} e^{-\lambda\sqrt{(q^2+s^2\pi^2)}}. \tag{16}$$

Substituting equations (15) and (16) in equation (1), we have

$$\frac{u_2 B^3}{8m} = \frac{1}{16\pi} \sum_{k=1}^{\infty} \frac{1}{k^3} + \frac{1}{2\pi} \sum_{s=0}^{\infty} p(s) \int_{q=0}^{\infty} \frac{q^2 e^{-\lambda\sqrt{(q^2+s^2\pi^2)}} [c\lambda - (q^2+s^2\pi^2)^{-1/2}] dq}{\cosh\{\lambda\sqrt{(q^2+s^2\pi^2)}\} + c\lambda\sqrt{(q^2+s^2\pi^2)} \sinh\{\lambda\sqrt{(q^2+s^2\pi^2)}\}}. \tag{17}$$

Equation (17) may be written in the alternative form

$$\frac{u_2 B^3}{8m} = \frac{1}{16\pi} \sum_{k=1}^{\infty} \frac{1}{k^3} + \frac{1}{2\pi\lambda^2} \sum_{s=0}^{\infty} p(s) \int_{t=\lambda\pi s}^{\infty} \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)} e^{-t}(ct-1)}{\cosh t + ct \sinh t} dt. \tag{18}$$

The expression given by Maeder[3] is equivalent to equation (18) with the terms corresponding to $s \geqslant 1$ omitted.

Now consider the term of equation (18) corresponding to any particular value of s greater than one,

$$\alpha_s(c, \lambda) = \frac{1}{2\pi\lambda^2} \int_{t=\lambda\pi s}^{\infty} \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)} e^{-t}(ct-1)}{\cosh t + ct \sinh t} dt. \tag{19}$$

Since

$$\frac{\partial}{\partial c} \left\{\frac{ct-1}{\cosh t + ct \sinh t}\right\} = \frac{t(\cosh t + \sinh t)}{(\cosh t + ct \sinh t)^2}, \tag{20}$$

it follows that $\alpha_s(c, \lambda)$ is an increasing function of c, and for $0 < c < \infty$

$$\alpha_s(0, \lambda) < \alpha_s(c, \lambda) < \alpha_s(\infty, \lambda). \tag{21}$$

Now

$$\alpha_s(0, \lambda) = -\frac{1}{2\pi\lambda^2} \int_{t=\lambda\pi s}^{\infty} \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)}}{\cosh t} e^{-t} dt > -\frac{1}{\pi\lambda^2} \int_{\lambda\pi s}^{\infty} e^{-2t} \sqrt{(t^2-\lambda^2\pi^2 s^2)} dt,$$

and

$$\alpha_s(\infty, \lambda) = \frac{1}{2\pi\lambda^2} \int_{t=\lambda\pi s}^{\infty} \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)}}{\sinh t} e^{-t} dt < \frac{1}{\pi\lambda^2} \int_{\lambda\pi s}^{\infty} e^{-2t} \sqrt{(t^2-\lambda^2\pi^2 s^2)} dt,$$

so that

$$|\alpha_s(c, \lambda)| < \frac{1}{\pi\lambda^2} \int_{\lambda\pi s}^{\infty} e^{-2t} \sqrt{(t^2-\lambda^2\pi^2 s^2)} dt, \tag{22}$$

or

$$|\alpha_s(c, \lambda)| < \frac{s}{2\lambda} K_1(2\lambda\pi s) \tag{23}$$

by Ref. 2, p. 172. Since

$$K_1(x) \simeq \sqrt{\left(\frac{\pi}{2x}\right)}\, e^{-x} \text{ for large } x,$$

the successive terms in s tend rapidly to zero, unless λ is small. Equation (18) is therefore a suitable form for computation.

For the special case of a closed tunnel, c tends to $+\infty$ and equation (18) becomes

$$\begin{aligned}\frac{u_2 B^3}{8m} &= \frac{1}{16\pi}\sum_1^\infty \frac{1}{k^3} + \frac{1}{2\pi\lambda^2}\sum_{s=0}^\infty p(s)\int_{t=\lambda\pi s}^\infty \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)}e^{-t}}{\sinh t}\,dt \\ &= \frac{1}{16\pi}\sum_1^\infty \frac{1}{k^3} + \frac{\pi}{48\lambda^2} + \frac{1}{2\lambda}\sum_{s=1}^\infty s\{K_1(2\lambda\pi s) + \tfrac{1}{2}K_1(4\lambda\pi s) + \tfrac{1}{3}K_1(6\lambda\pi s) + \ldots\}; \end{aligned} \tag{24}$$

for the tunnel with open roof and floor, $c = 0$, and

$$\frac{u_2 B^3}{8m} = \frac{1}{16\pi}\sum_1^\infty \frac{1}{k^3} - \frac{\pi}{96\lambda^2} - \frac{1}{2\lambda}\sum_{s=1}^\infty s\{K_1(2\lambda\pi s) - \tfrac{1}{2}K_1(4\lambda\pi s) + \tfrac{1}{3}K_1(6\lambda\pi s) - \ldots\}. \tag{25}$$

For the purpose of assessing the effect of varying c and λ it is more convenient to use the ratio of the interference for the slotted tunnel to the interference for a closed tunnel of the same shape,

$$\Omega(\lambda, c) = \frac{\dfrac{1}{16\pi}\displaystyle\sum_1^\infty \frac{1}{k^3} + \frac{1}{2\pi\lambda^2}\sum_{s=0}^\infty p(s)\int_{t=\lambda\pi s}^\infty \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)}e^{-t}(ct-1)}{\cosh t + ct\sinh t}\,dt}{\dfrac{1}{16\pi}\displaystyle\sum_1^\infty \frac{1}{k^3} + \frac{1}{2\pi\lambda^2}\sum_{s=0}^\infty p(s)\int_{t=\lambda\pi s}^\infty \frac{\sqrt{(t^2-\lambda^2\pi^2 s^2)}e^{-t}}{\sinh t}\,dt}. \tag{26}$$

As $\lambda \to \infty$, $\Omega \to 1$ for all c. As $\lambda \to 0$ both numerator and denominator tend to infinity. However, the limiting ratio may be determined by multiplying both by $2\lambda^3\pi^2$. Thus

$$\lim_{\lambda\to 0} \Omega(\lambda, c) = \frac{\dfrac{\pi}{8}\lambda^3\displaystyle\sum_1^\infty \frac{1}{k^3} + \pi\lambda\sum_{s=0}^\infty p(s) f_1(s\pi\lambda)}{\dfrac{\pi}{8}\lambda^3\displaystyle\sum_1^\infty \frac{1}{k^3} + \pi\lambda\sum_{s=0}^\infty p(s) f_2(s\pi\lambda)}, \tag{27}$$

when

$$f_1(x) = \int_x^\infty \frac{\sqrt{(t^2-x^2)}e^{-t}(ct-1)}{\cosh t + ct\sinh t}\,dt, \tag{28}$$

and

$$f_2(x) = \int_x^\infty \frac{\sqrt{(t^2-x^2)}e^{-t}}{\sinh t}\,dt. \tag{29}$$

It follows that

$$\lim_{\lambda\to 0} \Omega(\lambda, c) = \frac{\displaystyle\int_{x=0}^\infty \int_{t=x}^\infty \frac{\sqrt{(t^2-x^2)}e^{-t}(ct-1)}{\cosh t + ct\sinh t}\,dt\,dx}{\displaystyle\int_{x=0}^\infty \int_{t=x}^\infty \frac{\sqrt{(t^2-x^2)}e^{-t}dt}{\sinh t}\,dx}, \tag{30}$$

or, by inverting the order of integration,

$$\lim_{\lambda\to 0} \Omega(\lambda, c) = \int_{t=0}^\infty \frac{t^2 e^{-t}(ct-1)}{\cosh t + ct\sinh t}\,dt \Bigg/ \int_{t=0}^\infty \frac{t^2 e^{-t}}{\sinh t}\,dt. \tag{31}$$

3. *Calculation of Blockage Correction.* Although in a few special cases the integrals arising in equation (26) can be expressed in closed form, no simple expression was found for the general case and recourse was made to numerical integration. For λ greater than about one the terms with s greater than zero were negligible, but for the smaller values of λ more had to be included. In such cases the approximation of Ref. 3 is unacceptable.

For $\lambda > 1$, with an error less than 5×10^{-4},

$$\frac{u_2 B^3}{8m} = 0 \cdot 023914 + \frac{I}{4\pi\lambda^2} \tag{32}$$

where

$$I = \int_{t=0}^{\infty} \frac{te^{-t}(ct-1)dt}{\cosh t + ct \sinh t} . \tag{33}$$

Some values of the integral in equation (33) are given in Table 1, which also contains values of $u_2 B^3/8m$ calculated from equation (18) including terms in $s = 1, 2, 3, \ldots$ where necessary. The limiting ratio $\Omega(0, c)$ from equation (31) is also tabulated.

Fig. 1 contains curves of the corresponding values of Ω plotted against $(1+c)^{-1/2}$. In practice the open/closed ratio is such that c is small, and the left-hand side of Fig. 1 is only of academic interest. In the practical range, say $0 \cdot 8 < (1+c)^{-1/2} < 1$, Ω is a monotonic function of both λ and c. It should be noted that for λ greater than about $1 \cdot 17$ zero blockage cannot be obtained even for a tunnel with completely open roof and floor. This confirms the prediction of Wieselberger[4].

4. *Acknowledgements.* The calculation of the numerical values given in Table 1 was carried out by Mrs. B. Armour and Miss B. A. Foster.

LIST OF SYMBOLS

B	Breadth of tunnel
c	Slotted-wall parameter, defined in equation (8)
C	Function defined in equation (5)
d	Width of a slot
$\left.\begin{matrix} f_1 \\ f_2 \end{matrix}\right\}$	Functions defined in equations (28) and (29)
H	Height of tunnel
$\left.\begin{matrix} H_0 \\ H_1 \end{matrix}\right\}$	Functions defined in equations (3) and (4)
I	Function defined in equation (33)
m	Strength of doublet used to represent model, m = (Volume of Model) × (Free-Stream Speed)
N	Number of slots in the roof or in the floor
p	Function defined in equation (2)
S	Function defined in equation (6)
u_2	Increment in longitudinal velocity due to tunnel blockage effect
α_s	Function defined in equation (19)
λ	$= H/B$
Ω	Ratio of solid blockage in slotted tunnel to the solid blockage in a solid-walled tunnel of the same cross-section.

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TABLE 1

Blockage Interference for a Rectangular Tunnel with Solid Side Walls and Longitudinally Slotted Roof and Floor

c	$(1+c)^{-1/2}$	I {equation(33)}	Values of $u_2B^3/8m$									$\Omega(0, c)$
			$\lambda = \frac{1}{4}$	$\lambda = \frac{1}{2}$	$\lambda = \frac{3}{4}$	$\lambda = 1$	$\lambda = 1\frac{1}{4}$	$\lambda = 1\frac{1}{2}$	$\lambda = 1\frac{3}{4}$	$\lambda = 2$	$\lambda = \infty$	
0	1·0000	−0·411234	−1·148	−0·1424	−0·0380	−0·0093	+0·0030	+0·0094	+0·0132	+0·0157	+0·0239	−0·7500
0·1	0·9535	−0·339270	−0·864	−0·1061	−0·0265	−0·0034	+0·0066	+0·0119	+0·0151	+0·0172	+0·0239	−0·5612
0·2	0·9129	−0·282208	−0·653	−0·0792	−0·0174	+0·0013	+0·0095	+0·0139	+0·0166	+0·0183	+0·0239	−0·4216
0·4	0·8452	−0·194817	−0·335	−0·0399	−0·0034	+0·0083	+0·0140	+0·0170	+0·0189	+0·0200	+0·0239	−0·2230
1·0	0·7071	−0·033852	+0·150	+0·0268	+0·0210	+0·0213	+0·0222	+0·0227	+0·0230	+0·0232	+0·0239	+0·1003
3·0	0·5000	+0·192506	+0·728	+0·1122	+0·0541	+0·0396	+0·0337	+0·0307	+0·0289	+0·0277	+0·0239	+0·4729
15·0	0·2500	+0·478661	+1·290	+0·2106	+0·0952	+0·0624	+0·0483	+0·0408	+0·0364	+0·0334	+0·0239	+0·8134
∞	0	+0·822468	+1·794	+0·3220	+0·1440	+0·0899	+0·0658	+0·0530	+0·0453	+0·0403	+0·0239	1·0000

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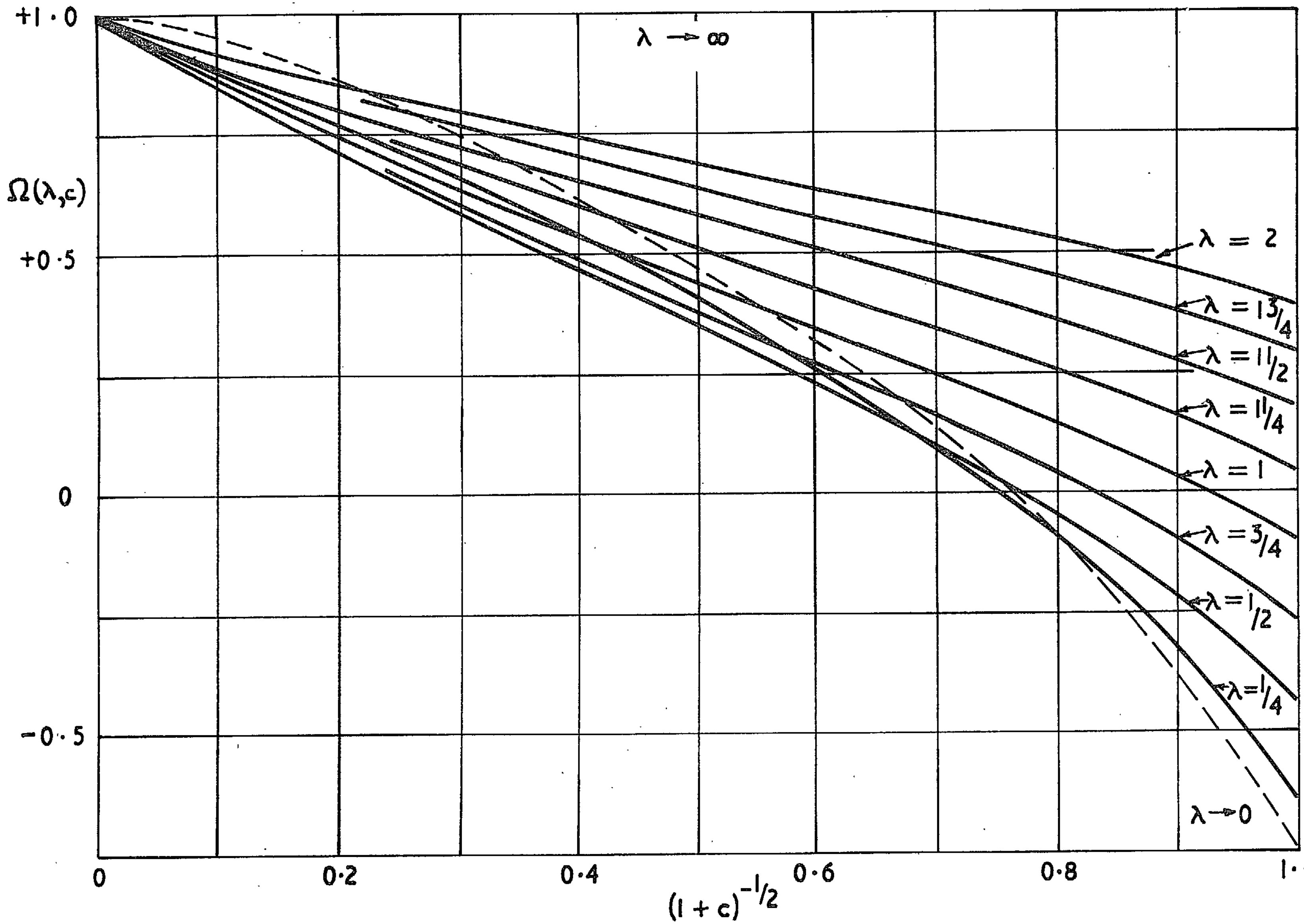

FIG. 1. Solid-blockage interference for rectangular tunnels with slotted roof and floor.

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