Elastic Design Charts for the Rapid Selection of Web Bolts for Composite Steel Bridge Splices

FIRAS I. SHEIKH-IBRAHIM

ABSTRACT

Selection of the web bolts for steel bridge girder splices requires a trial and error procedure. A group of bolts is initially selected, and its resistance is checked against the required resistance. If the provided resistance is less than required, a new group of bolts is selected and the procedure is repeated until an acceptable design is achieved.

In this paper, elastic design charts for the rapid selection of web bolts are presented along with three design examples. The charts are developed to be used for composite bridge girder splices at either the strength limit state or the service limit state, but can be used for any other eccentric shear connection. The charts can be used for connections with bolted depths ranging from 900 mm to 2000 mm, eccentricity-to-bolted-depth ratios up to 1.5, design forces applied at 0° to 80° from the vertical axis, a uniform vertical bolt spacing, and a horizontal bolt spacing of 75 mm. The required bolt pattern can be determined directly from the charts for a known bolted depth, eccentricity, vertical design shear, angle of the design force line of action, and factored resistance of one bolt.

BACKGROUND AND DEVELOPMENT OF DESIGN CHARTS

The design forces for the web splice bolts of composite bridge girders are shown in Figure 1a. The web bolts must be designed for the vertical design shear for the web (V_{uw}), design moment resisted by the web applied at the mid-depth of the web (M_{uw}), and moment due to the eccentricity of the design shear ($V_{uw} \times e_g$). The eccentricity of the design shear (e_g) is the distance from the centerline of the splice to the centroid of the web bolts on the side of the splice under consideration. For composite girder splices, the web bolts must also be designed for the horizontal design force resultant applied at the mid-depth of the web (H_{uw}). The latter is caused by the shift in the neutral axis due to the presence of the concrete deck when the splice is subjected to positive flexure, or due to the presence of the longitudinal reinforcement when the splice is subjected to negative flexure. As shown in Figure 1a, the presence of the horizontal design force causes the design force resultant (P_{uw}) to be inclined with respect to the vertical axis.

As shown in Figure 1b, equivalent web splice design forces can be used by shifting the inclined force line of action. These forces include the vertical design shear (V_{uw}), moment due to the effective eccentricity of the design shear ($V_{uw} \times e$), and the horizontal design force applied at the mid-depth of the web (H_{uw}). The effective eccentricity of the design shear (e) is the horizontal distance from the inclined force shifted line of action to the centroid of the web bolts on the side of the splice under consideration, which can be determined from Equation 1.

$$e = e_g + \frac{M_{uw}}{V_{uw}} \tag{1}$$

Currently, one of two methods can be used to determine the resistance of bolts subjected to an eccentric, inclined shear. These are the elastic method and the ultimate strength method (AISC, 1994). Regardless of the analysis method used, selection of the web bolts is iterative. A known bolt pattern is required before the resistance of the bolts can be checked.

The C coefficient tables listed in the AISC *Manual of Steel Construction* (AISC, 1994) were developed to help

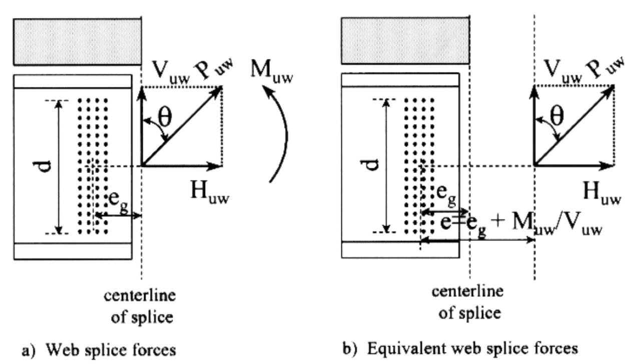

Fig. 1. The design forces for web splice bolts of composite girders.

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designers in the rapid selection of eccentrically loaded bolt groups. Given the actual eccentricity to the centroid of the bolts and the required *C* coefficient, which is equal to the design force resultant divided by the factored resistance of one bolt, the number of bolts can be determined from the tables.

As shown in Figure 2, the eccentricity (e) with respect to the centroid of the bolts is dependent on the number of vertical rows of bolts (v), which is not known until the bolt pattern is determined. On the other hand, the eccentricity (e_o) from the inclined force shifted line of action to the first vertical row of bolts adjacent to the force can be determined before the required bolt pattern is known. Therefore, to expedite the selection of bolts, design charts were developed using the eccentricity with respect to the first vertical row of bolts adjacent to the force (e_o).

The charts were developed using the elastic method because it was adopted by AASHTO (1999) as the preferred method of analysis. According to the elastic method, the factored resistance of a group of bolts subjected to an eccentric, inclined force can be determined as (Iwankiw, 1987):

$$P_{rw} = \frac{R_r}{\sqrt{\cos^2\theta\left[\frac{1}{(nv)^2}+\frac{2ex_{max}}{nv\sum d_i^2}+\left(\frac{e\,d_{max}}{\sum d_i^2}\right)^2\right]+\frac{\sin^2\theta}{(nv)^2}+\sin\theta\cos\theta\left(\frac{2ey_{max}}{nv\sum d_i^2}\right)}} \geq P_{uw} \tag{2}$$

where

- P_{uw} = inclined design force for the web bolts
- P_{rw} = inclined factored resistance of the web bolts
- R_r = factored resistance of one bolt
- n = number of bolts in a vertical row
- v = number of vertical rows of bolts
- e = horizontal distance from the center of gravity of the bolts to the design force shifted line of action
- x_{max} = horizontal distance from the critical bolt to the center of gravity of the bolts
- y_{max} = vertical distance from the critical bolt to the center of gravity of the bolts
- d_{max} = radial distance from the critical bolt to the center of gravity of the bolts
- d_i = radial distance from the bolt under consideration to the center of gravity of the bolts
- θ = angle between the design force line of action and the vertical axis, which can be computed from Equation 3.

$$\theta = \tan^{-1}\left(\frac{H_{uw}}{V_{uw}}\right) \tag{3}$$

Equation 2 can be rearranged to produce a *C* coefficient, which is defined as the vertical design shear for the web normalized with respect to the factored resistance of one bolt. This *C* coefficient is different from that defined by AISC and is equal to the vertical component of the AISC elastic coefficient. The *C* coefficient was determined using the vertical design shear to avoid the unnecessary determination of the inclined design force (P_{uw}).

$$\frac{P_{uw}\cos\theta}{R_r} \leq C = \frac{\cos\theta}{\sqrt{\frac{1}{(nv)^2}+\frac{e\left(2x_{max}\cos^2\theta+2y_{max}\sin\theta\cos\theta\right)}{nv\sum d_i^2}+\left(\frac{e\,d_{max}\cos\theta}{\sum d_i^2}\right)^2}} \tag{4}$$

Equation 4 can be rearranged further to produce:

$$\frac{V_{uw}}{R_r} \leq C = \frac{1}{\sqrt{\frac{1}{(nv\cos\theta)^2}+\frac{2e\left(x_{max}+y_{max}\tan\theta\right)}{nv\sum d_i^2}+\left(\frac{e\,d_{max}}{\sum d_i^2}\right)^2}} \tag{5}$$

For a group of bolts with a uniform bolt spacing and gage, the term $\sum d_i^2$ in Equation 5 can be calculated as follows (AISC, 1963):

$$\sum d_i^2 = \frac{vn}{12}\left[s^2\left(n^2-1\right)+g^2\left(v^2-1\right)\right] \tag{6}$$

where s is the vertical spacing of the bolts, and g is the horizontal spacing of the bolts.

Equation 5 was rearranged into Equation 7, which was used in plotting the charts, to produce the *C* coefficient as a function of the eccentricity-to-bolted-depth ratio (e_o/d).

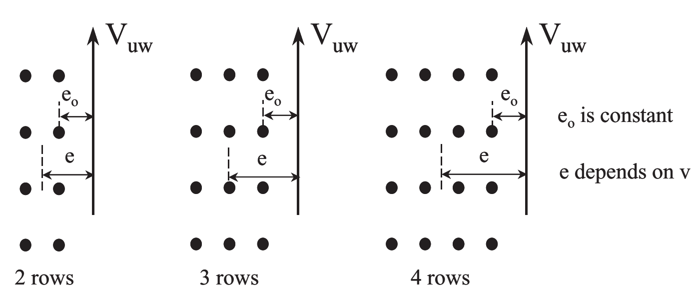

Fig. 2. Comparison between the eccentricity with respect to the centroid of bolts and first row of bolts adjacent to the force.

$$C = \frac{1}{\sqrt{\left(\frac{1}{(nv\cos\theta)^2} + \frac{2d\left(\frac{e_o}{d} + \frac{(v-1)g}{2d}\right)(x_{max} + y_{max}\tan\theta)}{nv\sum d_i^2}\right) + \left(\frac{d\left(\frac{e_o}{d} + \frac{(v-1)g}{2d}\right)d_{max}}{\sum d_i^2}\right)^2}}$$

in which d is the bolted depth between the centerline of the outermost top and bottom web bolts, and g is taken as 75 mm for all charts.

As shown in Appendix I, eight charts are plotted for each of the bolted depths ranging from 900 mm to 2000 mm at a 100 mm interval. The first four charts correspond to eccentricity-to-bolted-depth ratios up to 0.5, and the second four charts correspond to bolted-depth ratios up to 1.5. Each chart includes two vertical axes, which correspond to different angles of the applied force line of action. The curves in the charts intersect only with one of the two vertical axes and should only be used with that axis. The charts are developed for forces applied at 0°, 10°, 20°, 30°, 40°, 50°, 65°, and 80° from the vertical axis. Since they are developed using the normalized C coefficient, the charts can be used to determine the bolt pattern required to resist the design forces at either the strength limit state or the service limit state.

USE OF CHARTS

Use of the design charts is illustrated in Figures 3 and 4. To use the charts, go to the chart containing the required bolted depth, appropriate range of eccentricity-to-bolted-depth ratio, and angle of force. Enter the chart with the required C coefficient, as defined in this paper, and horizontal eccentricity-to-bolted-depth ratio (e_o/d). The required bolt pattern is given by the curve that lies at or immediately adjacent to the intersection point of the two lines drawn from the required C coefficient and horizontal eccentricity-to-bolted-depth ratio. The curve adjacent to the intersection point should be taken in the positive direction of the appropriate vertical axis; that is, above the intersection point when using the left vertical axis, and below the intersection point when using the right vertical axis. The number of vertical rows of bolts can be determined from the curve style.

EXAMPLE 1

Given:

Determine the required bolt pattern assuming d = 1000 mm, e_o = 900 mm, θ = 30°, and $C_{required} = \frac{V_{uw}}{R_r} = 4$.

Solution:

Determine the required eccentricity-to-bolted-depth ratio:

$$\frac{e_o}{d} = \frac{900}{1000} = 0.9$$

Go to the chart containing

$$d = 1000 \text{ mm},\ 0.5 < \frac{e_o}{d} \leq 1.5,\ \text{and}\ \theta = 30^\circ$$

Enter the chart with

$$C_{required} = 4 \text{ and } \frac{e_o}{d} = 0.9$$

As shown in Figure 5, use two vertical rows of eleven bolts at 100 mm vertical spacing and 75 mm horizontal spacing.

Note that there is no need to check the resistance of the bolts once the required bolt pattern is determined from the charts. However, to verify the validity of the charts, the resistance of the bolts will be checked in this example.

From Equation 6, with s = 100 mm, g = 75 mm, n = 11, and v = 2:

$$\sum d_i^2 = \frac{2\times 11}{12}\left[100^2\left(11^2-1\right) + 75^2\left(2^2-1\right)\right] = 2.23\times 10^6 \text{ mm}^2$$

From Equation 5, with

$x_{max} = 37.5$ mm, $y_{max} = 500$ mm, $d_{max} = \sqrt{37.5^2 + 500^2}$ = 501.4 mm, $e = 900 + 37.5 = 937.5$ mm, $\Sigma d_i^2 = 2.23\times 10^6$ mm², $\theta = 30^\circ$, $n = 11$, and $v = 2$:

$$C_{provided} = \frac{1}{\sqrt{\left(\frac{1}{(22\cos 30)^2} + \frac{2\times 937.5(37.5 + 500\tan 30)}{22\times 2.23\times 10^6}\right) + \left(\frac{937.5\times 501.4}{2.23\times 10^6}\right)^2}} = 4.1$$

$$C_{required} = 4.0 < C_{provided} = 4.1 \quad \text{o.k.}$$

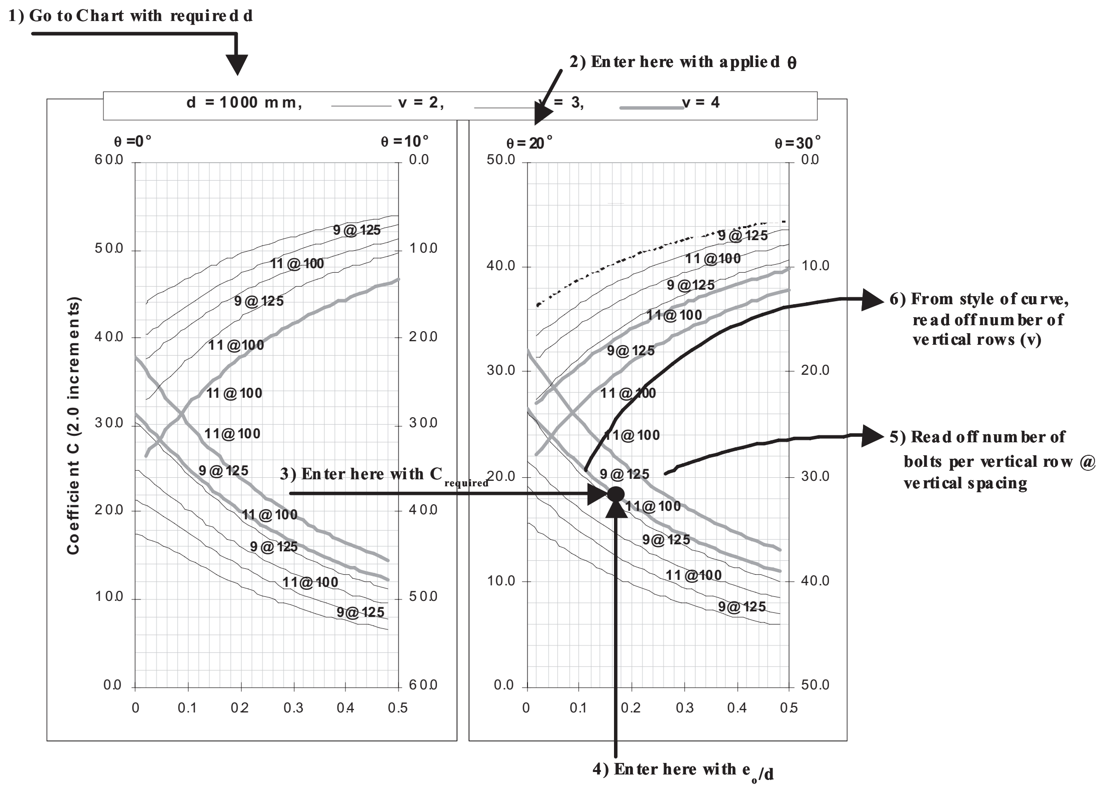

Fig. 3. Use of the design charts by reading off left vertical axis.

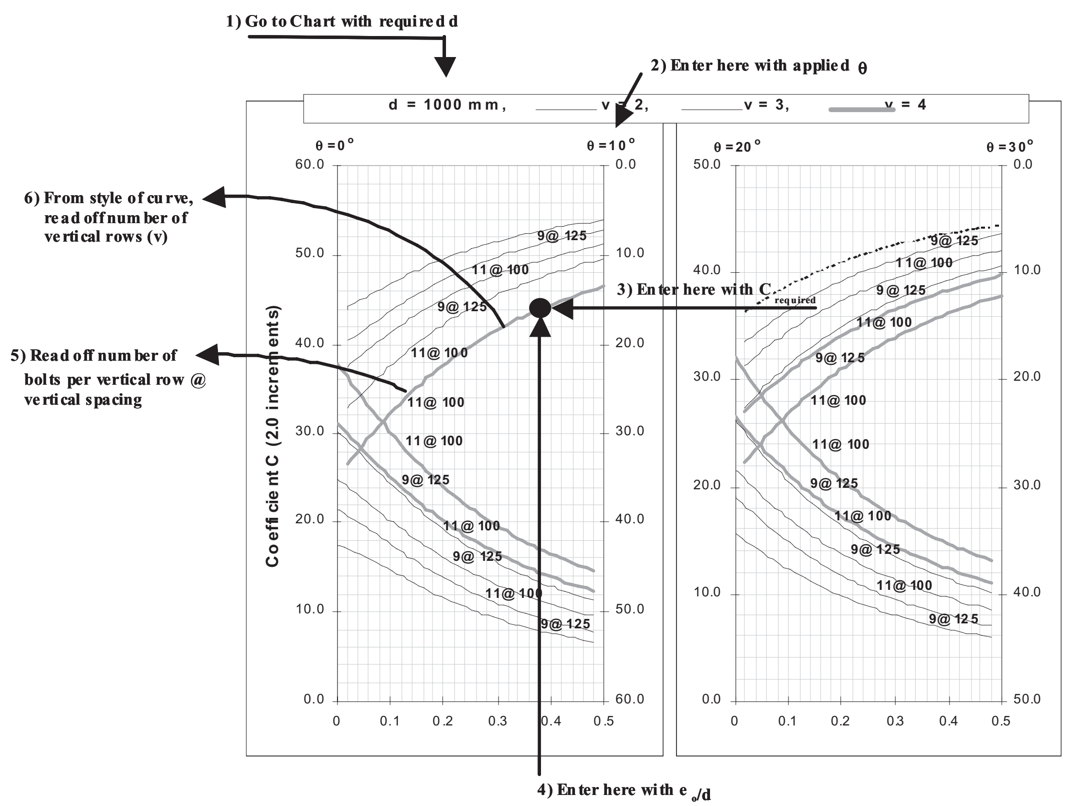

Fig. 4. Use of the design charts by reading off right vertical axis.

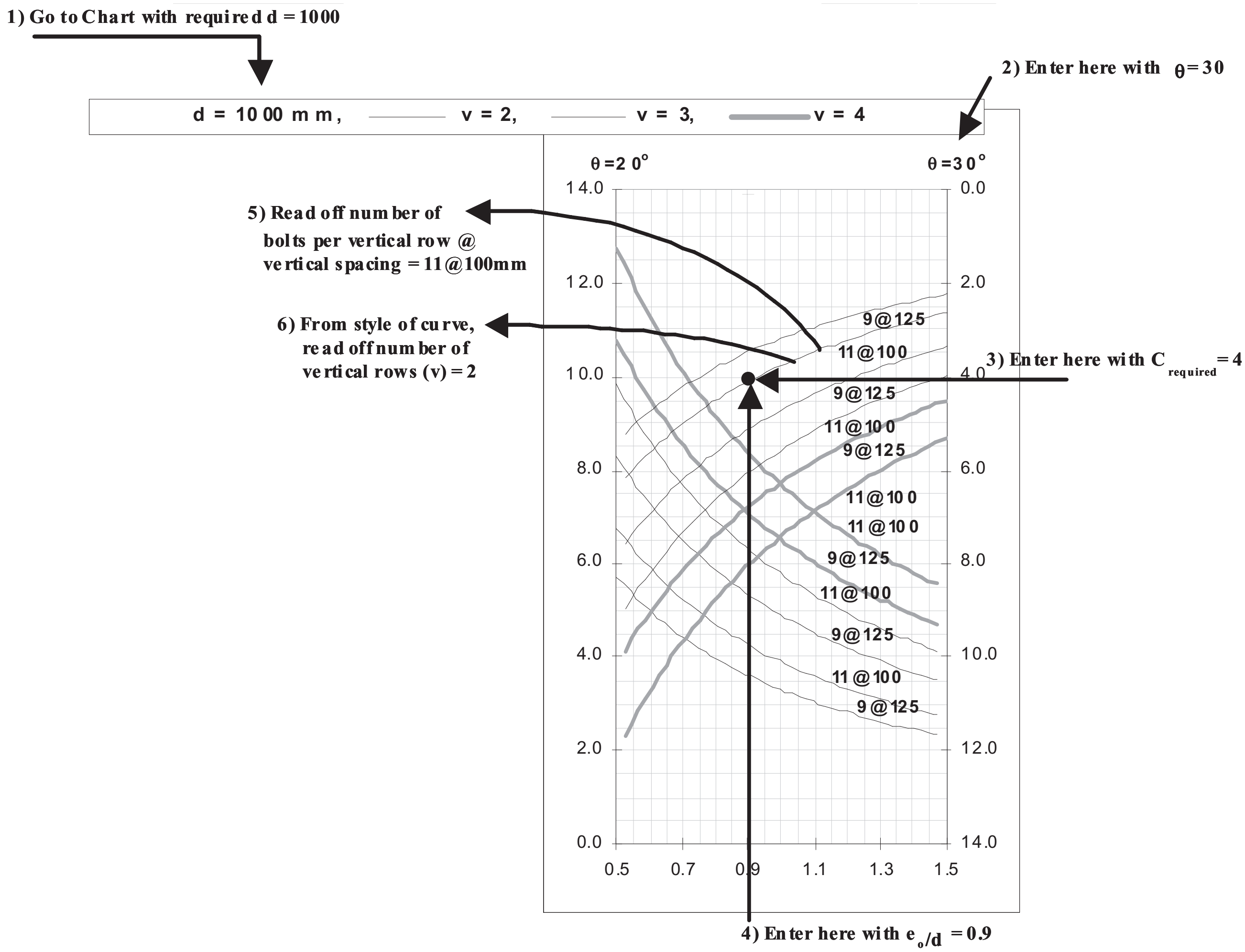

Fig. 5. Use of the design charts for Example 1.

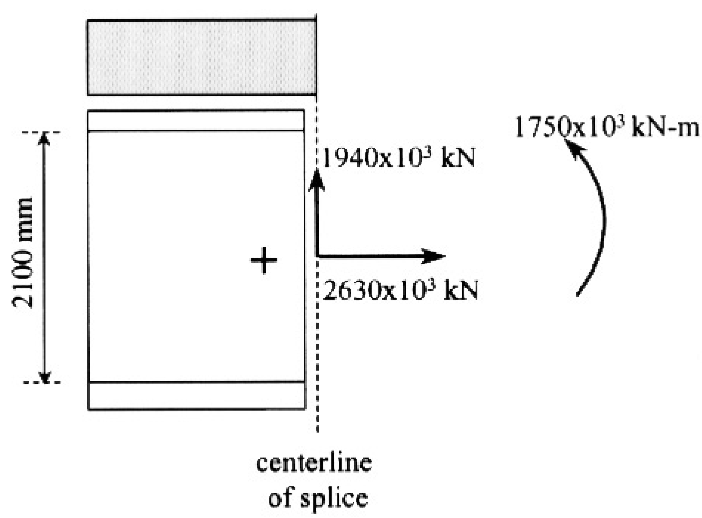

Fig. 6. Web splice design forces for Example 3.

EXAMPLE 2

Given:

Determine the required bolt pattern assuming $d = 2000$ mm, $e_o = 2800$ mm, $\theta = 20°$, and $C_{required} = 9$.

Solution:

Determine the required eccentricity-to-bolted-depth ratio:

$$\frac{e_o}{d} = \frac{2800}{2000} = 1.4$$

Go to the chart containing

$$d = 2000 \text{ mm, } 0.5 < \frac{e_o}{d} \leq 1.5, \text{ and } \theta = 20°.$$

Enter the chart with

$$C_{required} = 9 \text{ and } \frac{e_o}{d} = 1.4.$$

Use three vertical rows of twenty-six bolts at 80 mm vertical spacing and 75 mm horizontal spacing.

To verify the validity of the charts, the resistance of the bolts will be checked. From Equation 6, with $s = 80$ mm, $g = 75$ mm, $n = 26$, and $v = 3$:

$$\sum d_i^2 = \frac{3 \times 26}{12}\left[80^2\left(26^2 - 1\right) + 75^2\left(3^2 - 1\right)\right] = 28.37 \times 10^6 \text{ mm}^2$$

From Equation 5, with

$$x_{max} = 75 \text{ mm, } y_{max} = 1000 \text{ mm, } d_{max} = \sqrt{75^2 + 1000^2} = 1003 \text{ mm}$$

$$e = 2800 + 75 = 2875 \text{ mm, } \Sigma d_i^2 = 28.37 \times 10^6 \text{ mm}^2, \theta = 20°$$

$$n = 26, \text{ and } v = 3:$$

$$C_{provided} = \frac{1}{\sqrt{\frac{1}{\left(78\cos 20\right)^2} + \frac{2 \times 2875\left(75 + 1000\tan 20\right)}{78 \times 28.37 \times 10^6} + \left(\frac{2875 \times 1003}{28.37 \times 10^6}\right)^2}} = 9.3$$

$$C_{required} = 9.0 < C_{provided} = 9.3 \quad \text{o.k.}$$

EXAMPLE 3

Given:

Determine the required bolt pattern for the composite girder and strength-limit-state design forces shown in Figure 6. Use 22 mm diameter A325M bolts with the threads included in both shear planes. Assume that bolt shear resistance controls the selection of the bolts at the strength limit state, and that the slip resistance of the bolts is adequate at the service limit state.

Solution:

Assuming a 10 mm gap clearance between the connected girder segments and a 40 mm edge distance for the bolts, the eccentricity of the inclined force shifted line of action with respect to the first row of bolts adjacent to the force can be determined as:

$$e_o = \frac{10}{2} + 40 + \frac{1750 \times 10^6}{1940 \times 10^3} = 947 \text{ mm}$$

From Equation 3, determine the angle of the inclined force line of action with respect to the vertical axis:

$$\theta = \tan^{-1}\left(\frac{2630 \times 10^3}{1940 \times 10^3}\right) = 53.6°$$

Determine the required bolted depth assuming a 150 mm assembly clearance on each side of the top and bottom bolts:

$$d = 2100 - (2 \times 150) = 1800 \text{ mm}$$

Determine the required eccentricity-to-bolted-depth ratio:

$$\frac{e_o}{d} = \frac{947}{1800} = 0.53$$

Determine the factored shear resistance of one 22 mm diameter A325M bolt with the threads included in the shear planes (AASHTO, 1998):

$$R_r = \phi_s\left(0.38 A_b F_{ub} N_s\right) = \frac{0.8}{1000}\left(0.38 \times \frac{\pi \times 22^2}{4} \times 830 \times 2\right)$$
$$= 191.8 \text{ kN}$$

in which ϕ_s is the resistance factor for bolts in shear, A_b is the area of one bolt, F_{ub} is the specified minimum tensile strength of the bolt, and N_s is the number of shear planes.

Determine the required C coefficient:

$$C_{required} = \frac{1940 \times 10^3}{191.8 \times 10^3} = 10.1$$

Go to the chart containing

$$d = 1800 \text{ mm}, \; 0.5 < \frac{e_o}{d} \leq 1.5, \text{ and } \theta \approx 50^\circ.$$

Enter the chart with

$$C_{required} = 10.1 \text{ and } \frac{e_o}{d} = 0.53.$$

Use two vertical rows of twenty-five bolts at 75 mm vertical spacing and 75 mm horizontal spacing.

The value of θ used in the selection of the bolts was less than the actual value. Consequently, the resistance of the bolts should be checked. From Equation 6, with $s = g = 75$ mm, $n = 25$, and $v = 2$:

$$\sum d_i^2 = \frac{2 \times 25}{12}\left[75^2\left(25^2 - 1\right) + 75^2\left(2^2 - 1\right)\right] = 14.7 \times 10^6 \text{ mm}^2$$

From Equation 5, with

$$x_{max} = 37.5 \text{ mm}, \; y_{max} = 900 \text{ mm}, \; d_{max} = \sqrt{37\ 5^2 + 900^2}$$
$$= 900.8 \text{ mm}, \; e = 947 + 37\ 5 = 984\ 5 \text{ mm}, \; \Sigma d_i^2 = 14.7 \times 10^6 \text{ mm}^2$$
$$\theta = 53.6^\circ, n = 25, \text{ and } v = 2:$$

$$C_{provided} = \frac{1}{\sqrt{\left(\frac{1}{(50\cos 53.6)^2} + \frac{2 \times 984.5\,(37.5 + 900 \tan 53.6)}{50 \times 14.7 \times 10^6}\right)^2 + \left(\frac{984.5 \times 900.8}{14.7 \times 10^6}\right)^2}}$$

$$C_{required} = 10.1 < C_{provided} = 11.1 \quad \text{o.k.}$$

SUMMARY

In this paper, elastic design charts for the rapid selection of web bolts subjected to an eccentric, inclined force were presented along with three design examples. The charts are developed to be used for composite bridge girder splices at either the strength limit state or the service limit state, but can be used for any other eccentric shear connection. The charts can be used for connections with bolted depths ranging from 900 mm to 2000 mm, eccentricity-to-bolted-depth ratios up to 1.5, forces applied at 0° to 80° from the vertical axis, a uniform vertical bolt spacing, and a horizontal bolt spacing of 75 mm. The required bolt pattern can be determined directly from the charts for a known bolted depth, eccentricity, applied force, angle of the force line of action, and factored resistance of one bolt.

NOMENCLATURE

d	the bolted depth between the centerline of the outermost top and bottom web bolts
d_i	the radial distance from the bolt under consideration to the center of gravity of the bolts
d_{max}	the radial distance from the critical bolt to the center of gravity of the bolts
e	the horizontal distance from the inclined force shifted line of action to the centroid of the web bolts on the side of the splice under consideration
e_g	the horizontal distance from the centerline of the splice to the centroid of the web bolts on the side of the splice under consideration
e_o	the horizontal distance from the inclined force shifted line of action to the first row of bolts adjacent to the force, on the side of the splice under consideration
g	the horizontal spacing of the bolts
n	the number of bolts in a vertical row
s	the vertical spacing of the bolts
v	the number of vertical rows of bolts
x_{max}	the horizontal distance from the critical bolt to the center of gravity of the bolts
y_{max}	the vertical distance from the critical bolt to the center of gravity of the bolts
A_b	the area of one bolt
C	the vertical design shear for the web normalized with respect to the factored resistance of one bolt
F_{ub}	the specified minimum tensile strength of a bolt
H_{uw}	the horizontal design force resultant at the mid-depth of the web at a point of splice
M_{uw}	the design moment at the mid-depth of the web at a point of splice
N_s	the number of shear planes
P_{rw}	the inclined factored resistance of the web bolts
P_{uw}	the inclined design force for the web bolts
R_r	the factored resistance of one bolt
V_{uw}	the vertical design shear for the web at a point of splice
ϕ_s	the resistance factor for bolts in shear
θ	the angle between the inclined force line of action and the vertical axis

ACKNOWLEDGMENTS

The financial support of the American Iron and Steel Institute is greatly appreciated. Special thanks are due to Camille G. Rubeiz, PE, Director, Transportation and Infrastructure Program, AISI. The help of Dawn Jindra and Jay Wiley, former research assistants at Clarkson University, in preparing the design charts is appreciated.

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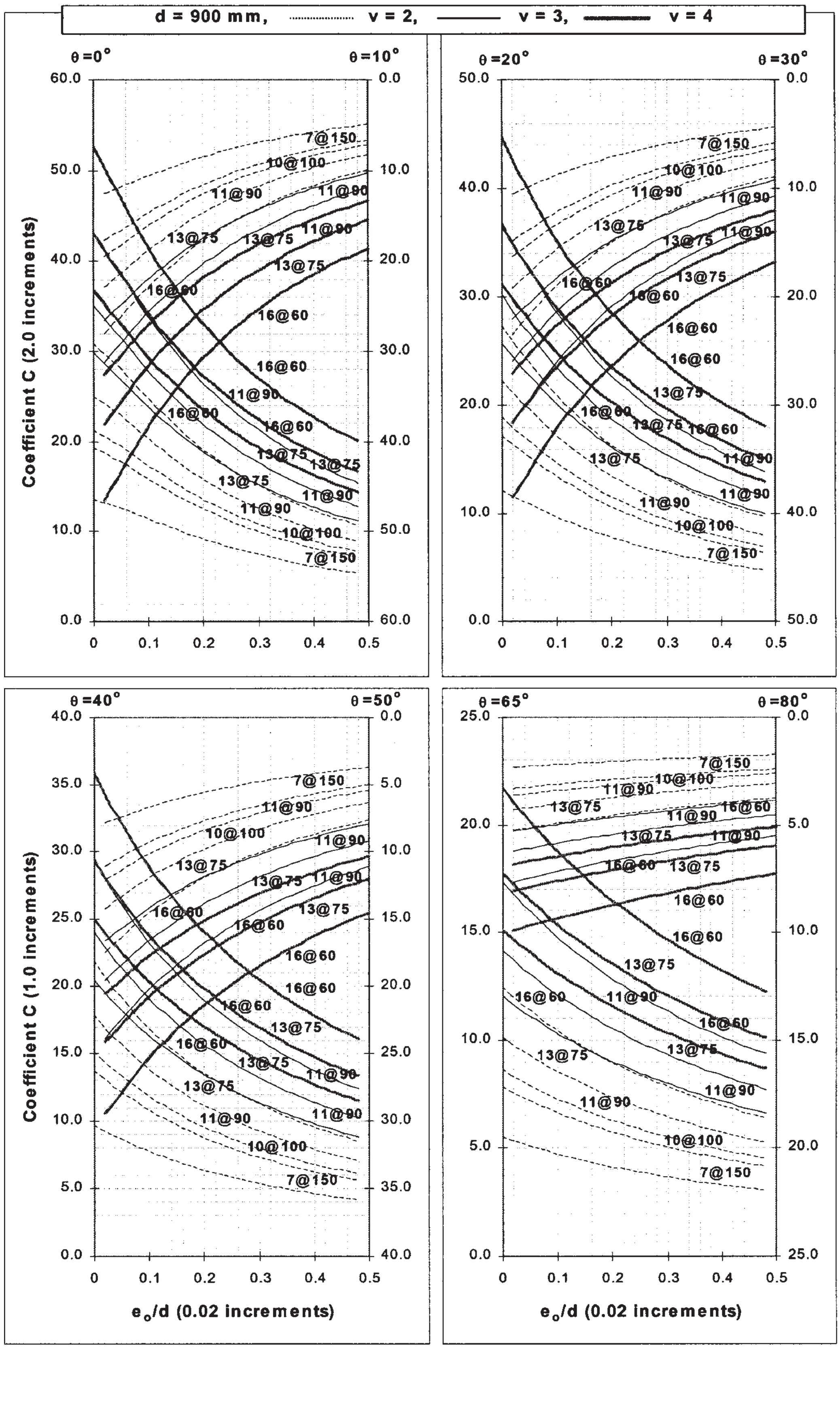
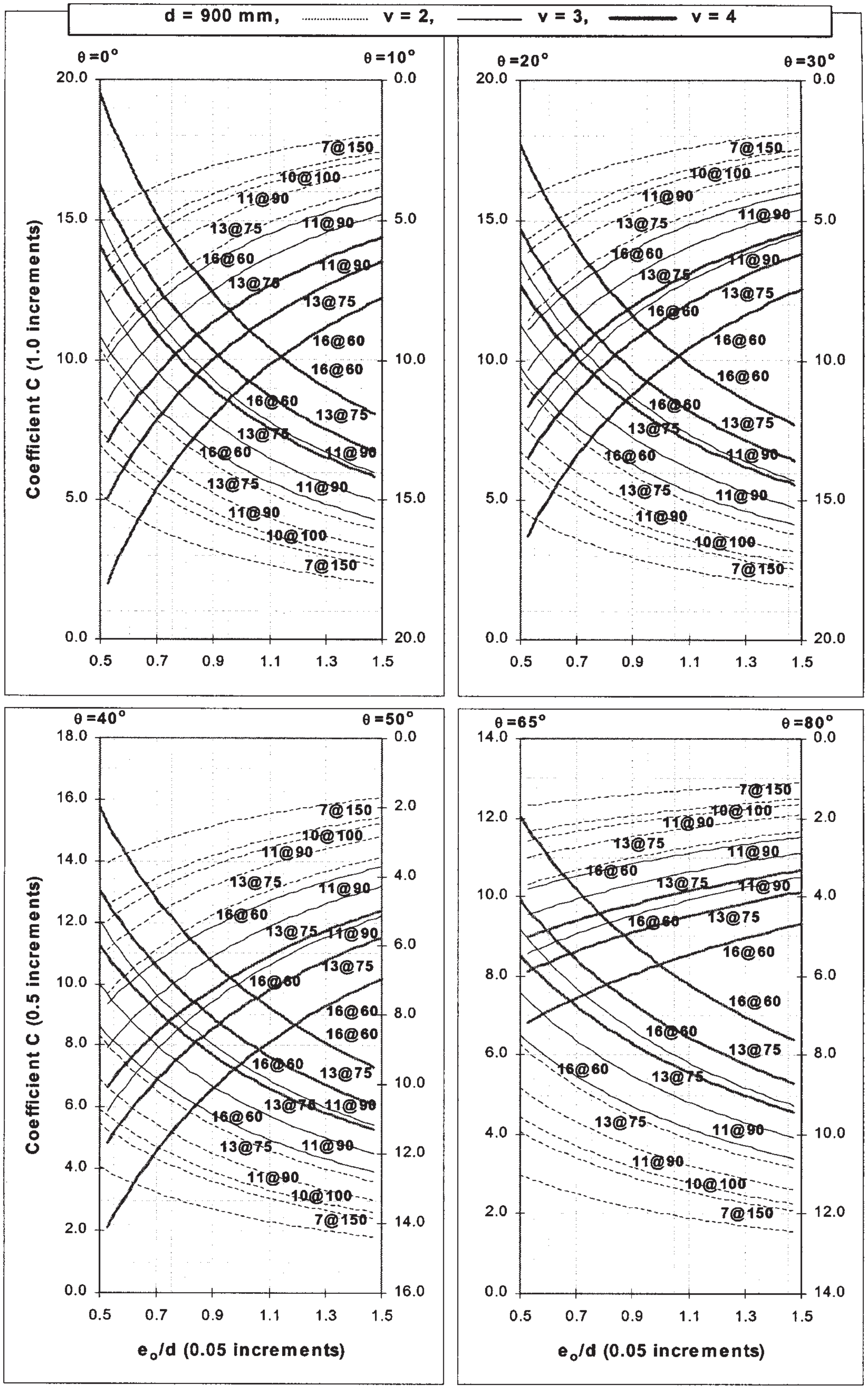
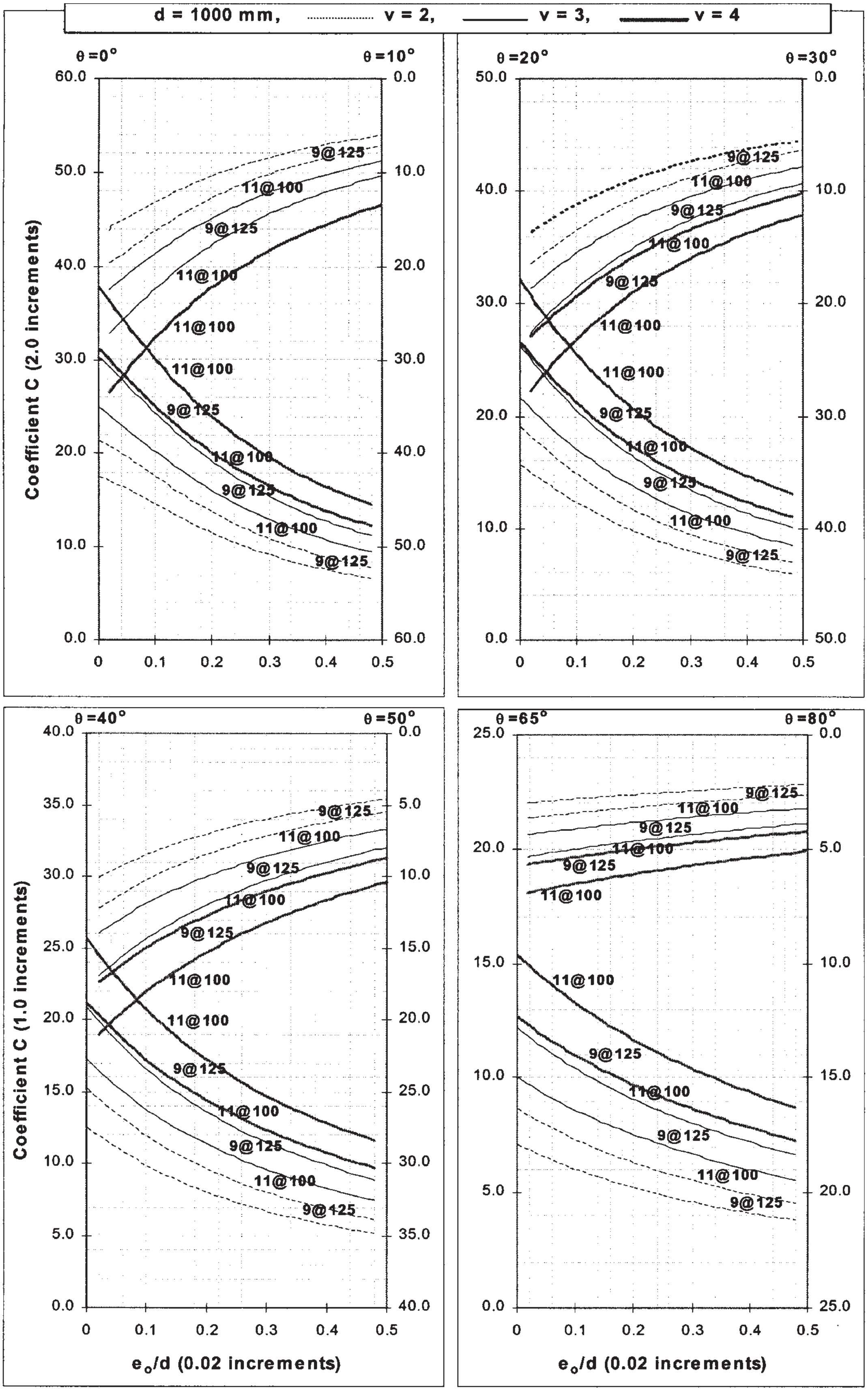
APPENDIX I—DESIGN CHARTS

Note that the horizontal bolt spacing, *g*, is assumed equal to 75 mm.




d = 900 mm, v = 2, v = 3, v = 4
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (1.0 increments)
Coefficient C (0.5 increments)
e_o/d (0.05 increments)
e_o/d (0.05 increments)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θ =10°
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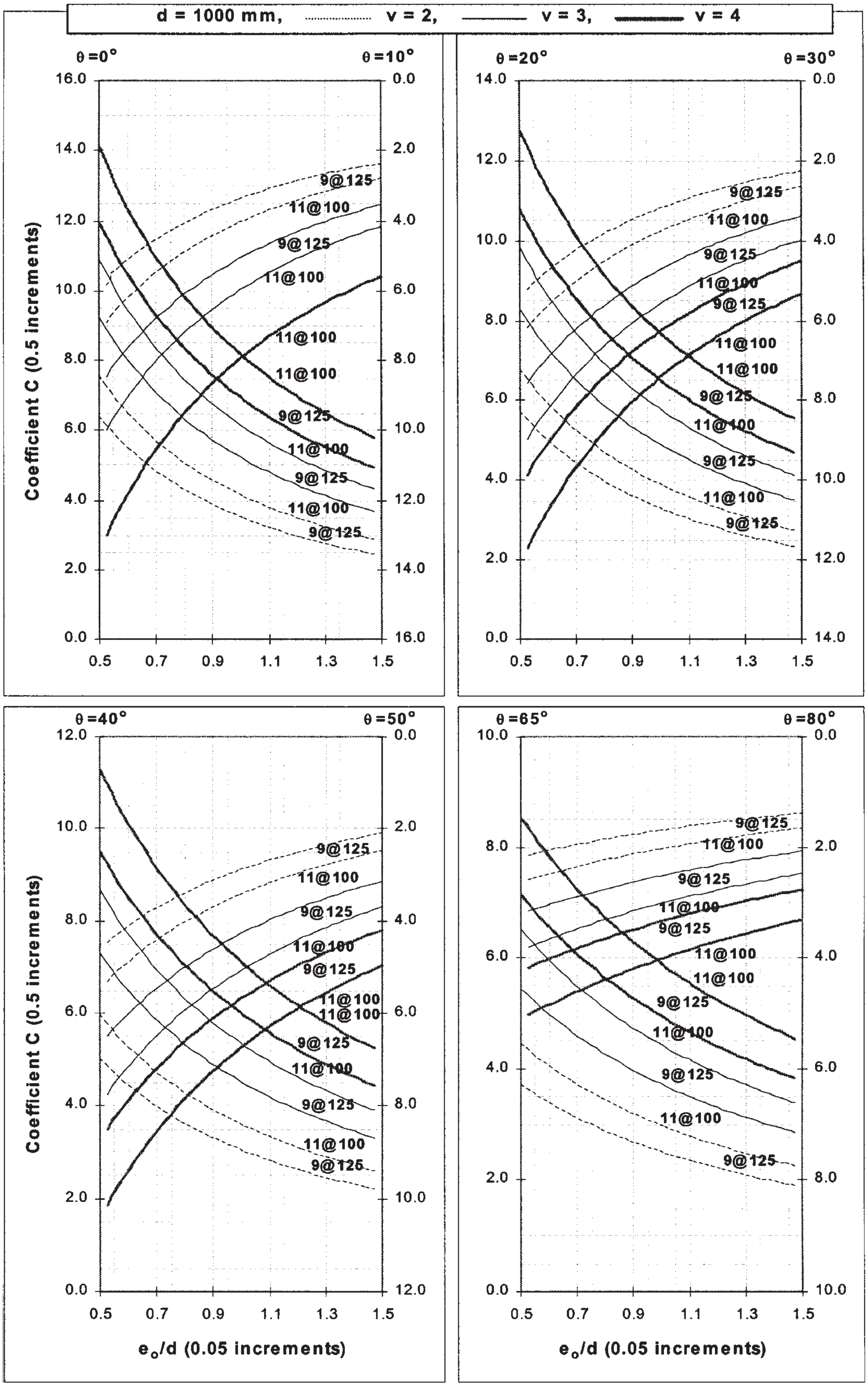
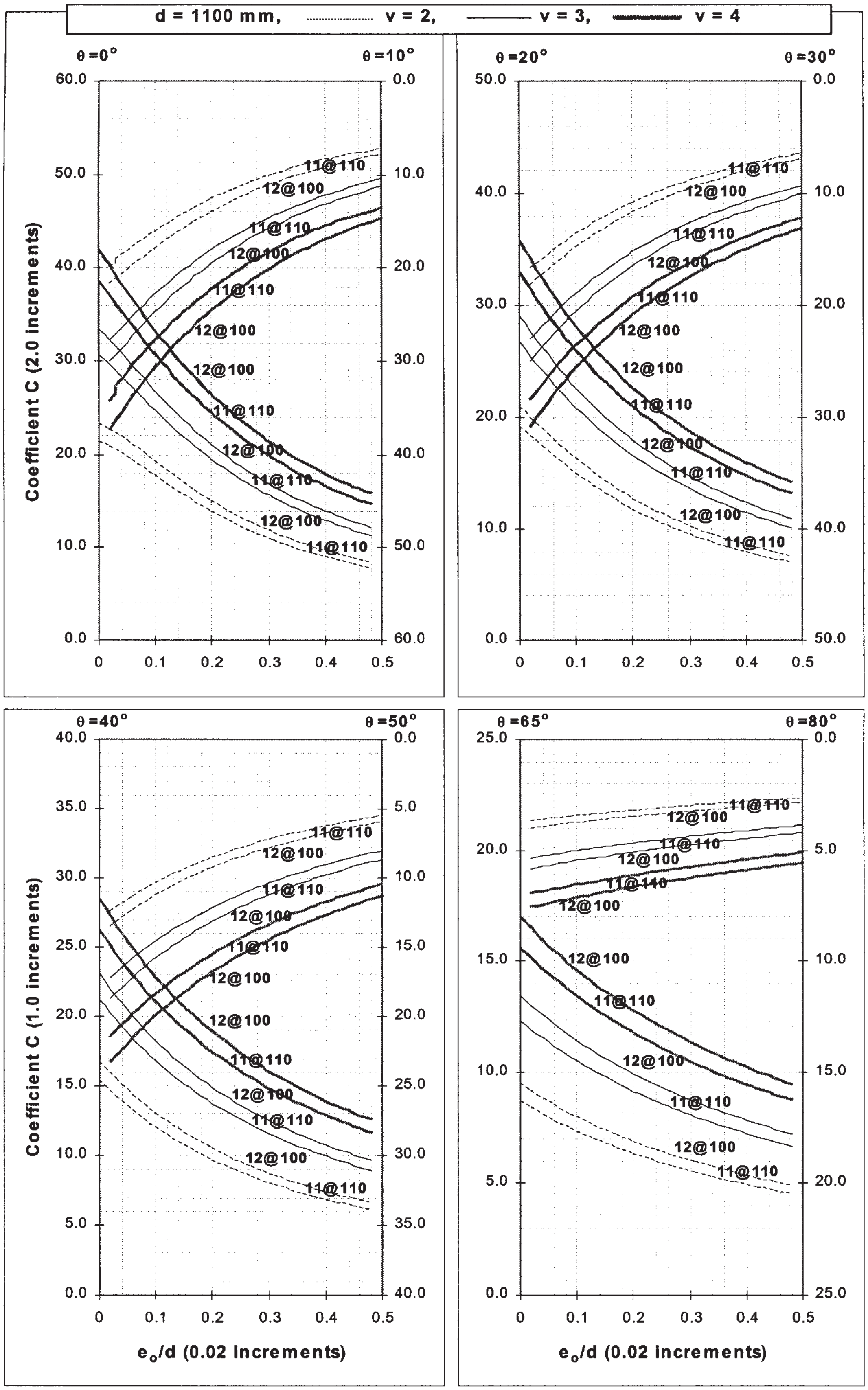
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (2.0 increments)
Coefficient C (1.0 increments)
e_o/d (0.02 increments)
e_o/d (0.02 increments)
9@125
11@100

APPENDIX I CONTINUED

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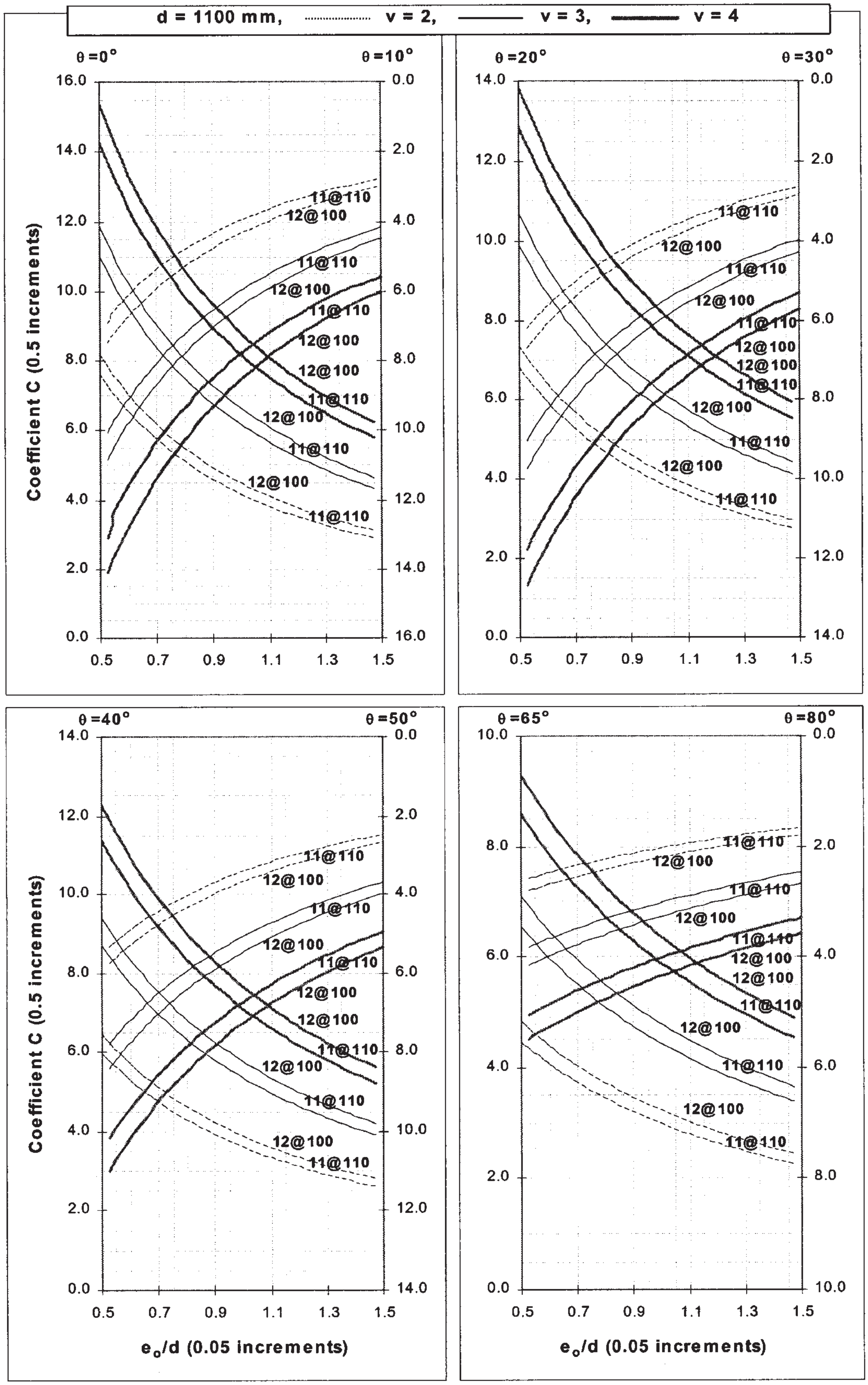
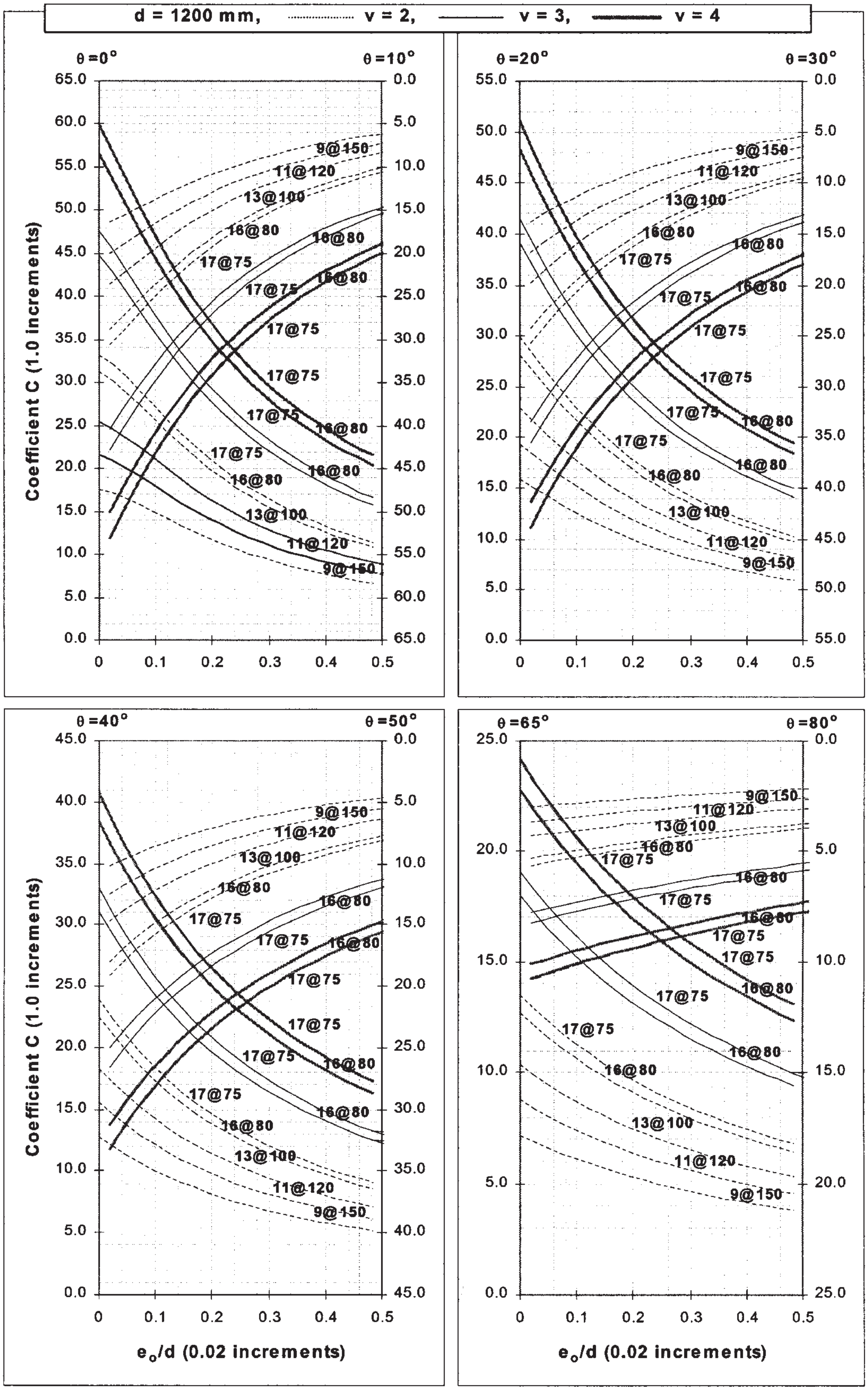
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (2.0 increments)
Coefficient C (1.0 increments)
e_o/d (0.02 increments)
11@110
12@100

APPENDIX I CONTINUED

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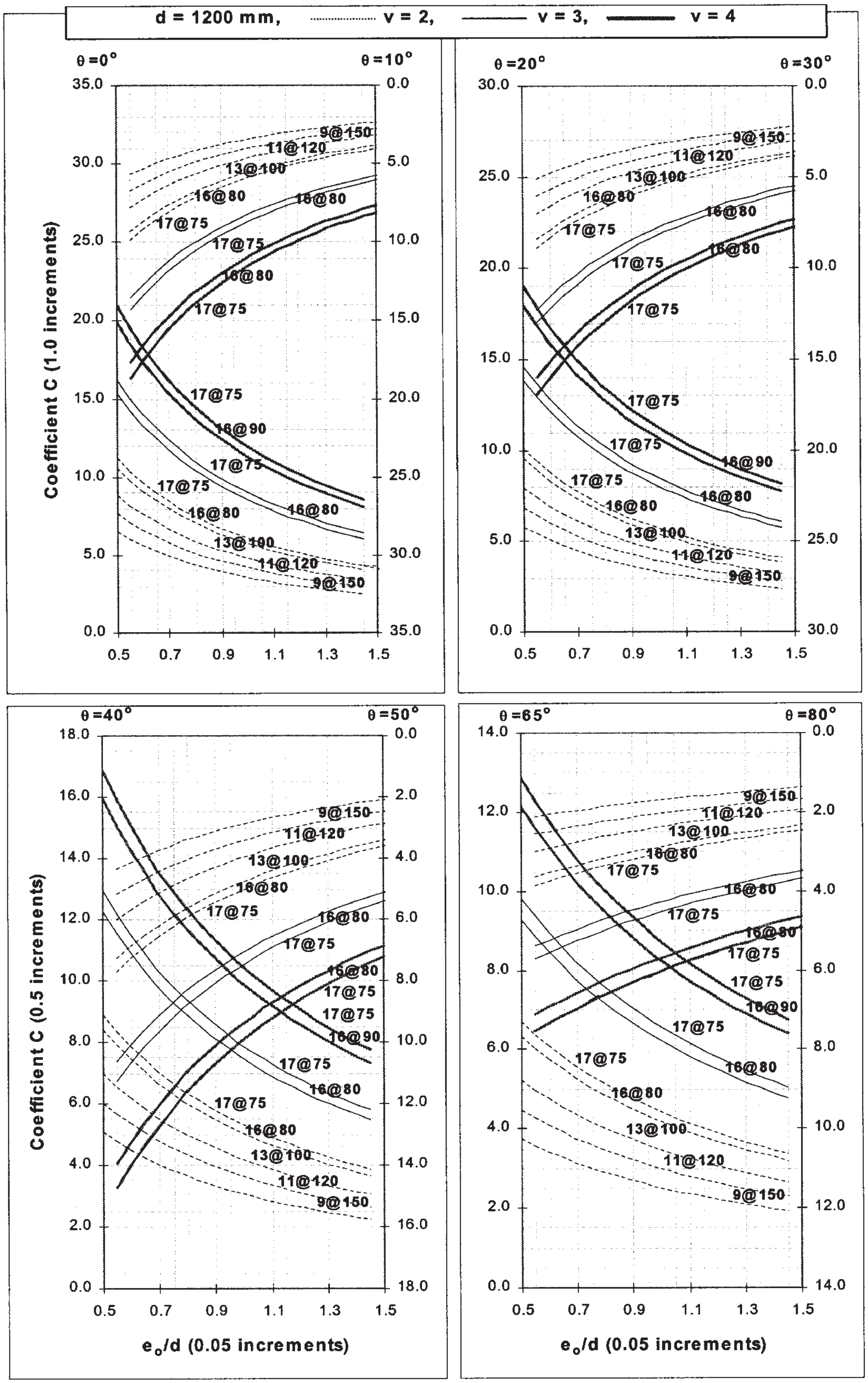
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (1.0 increments)
e$_o$/d (0.02 increments)
9@150
11@120
13@100
16@80
17@75

APPENDIX I CONTINUED



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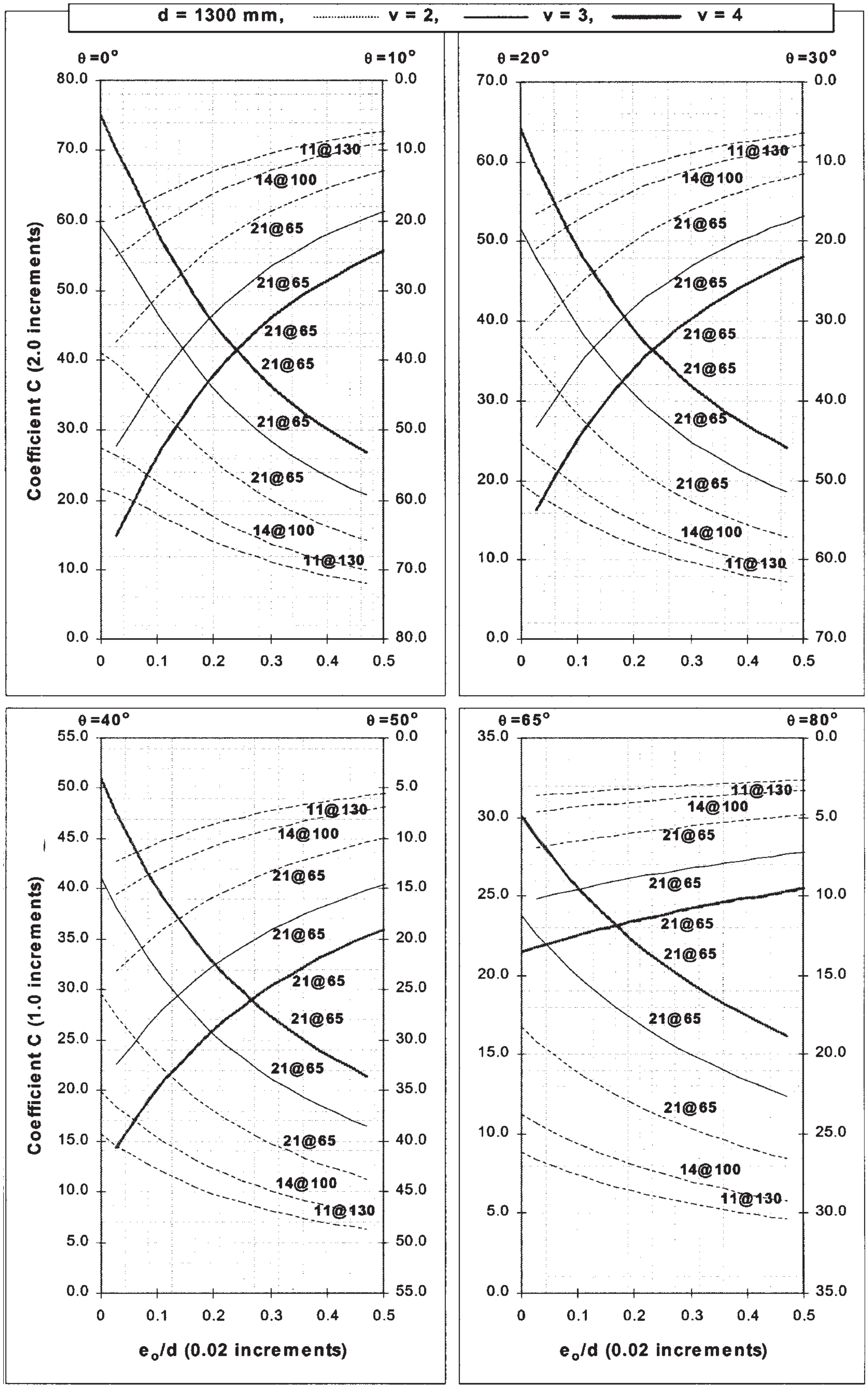

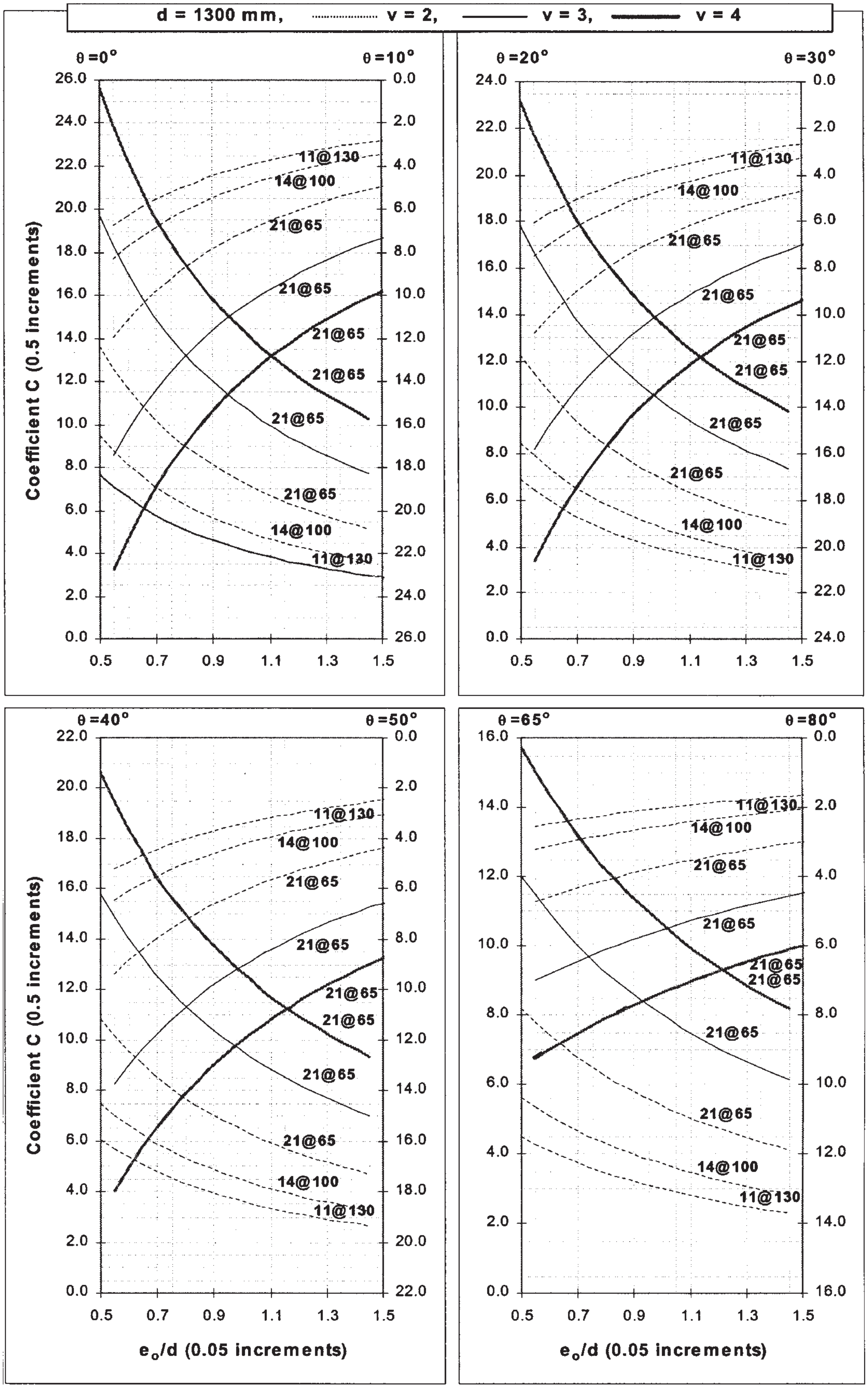
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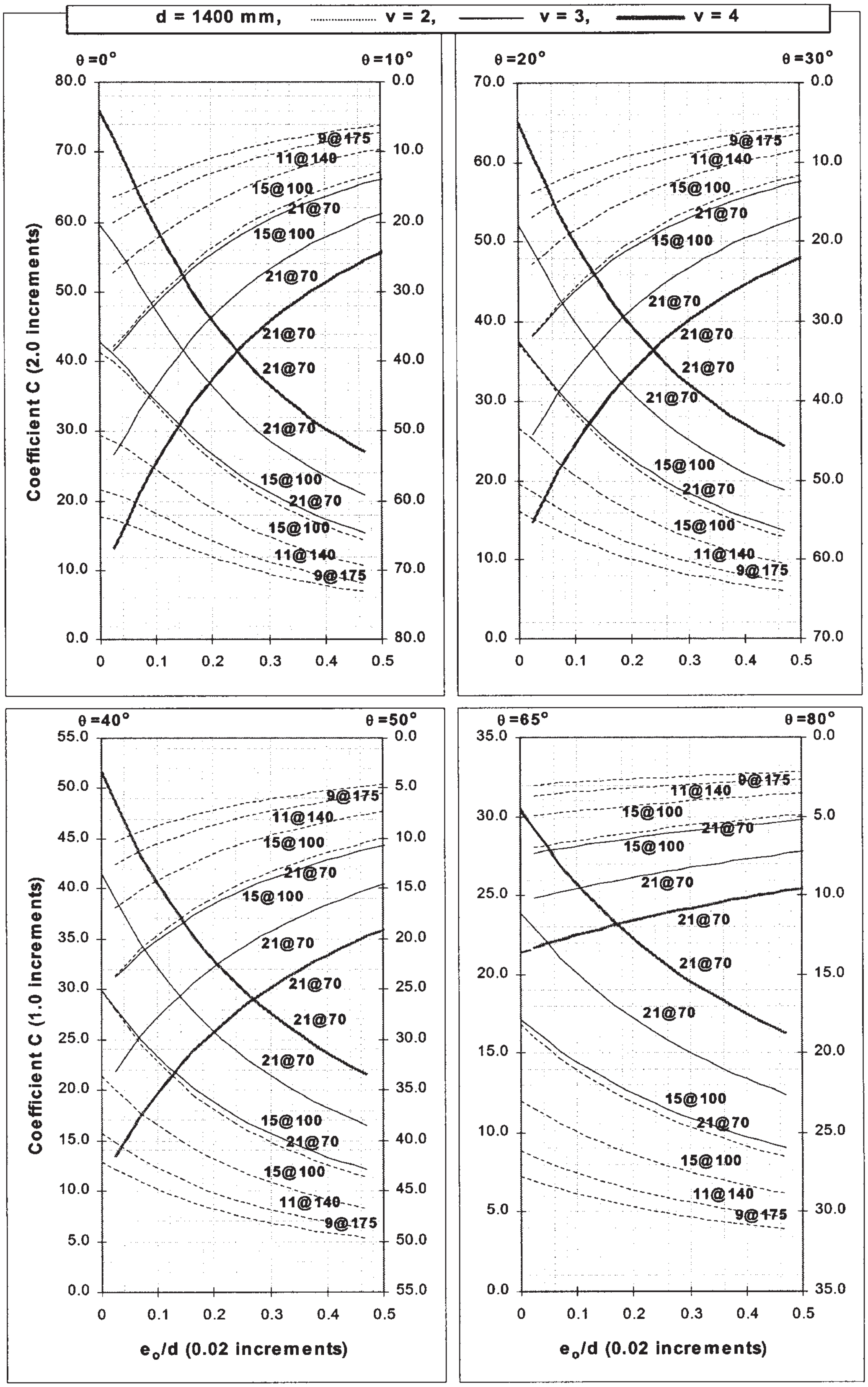
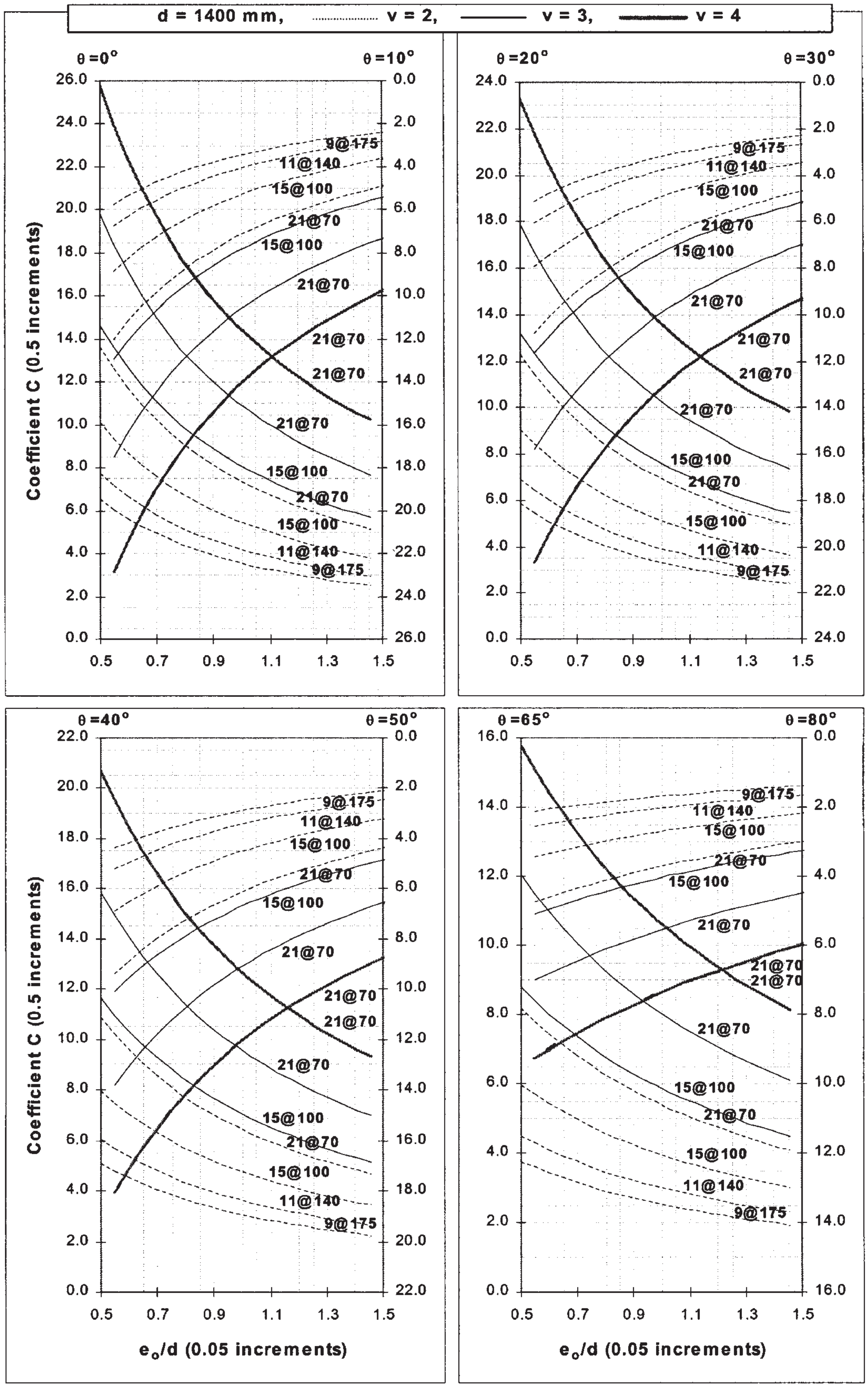
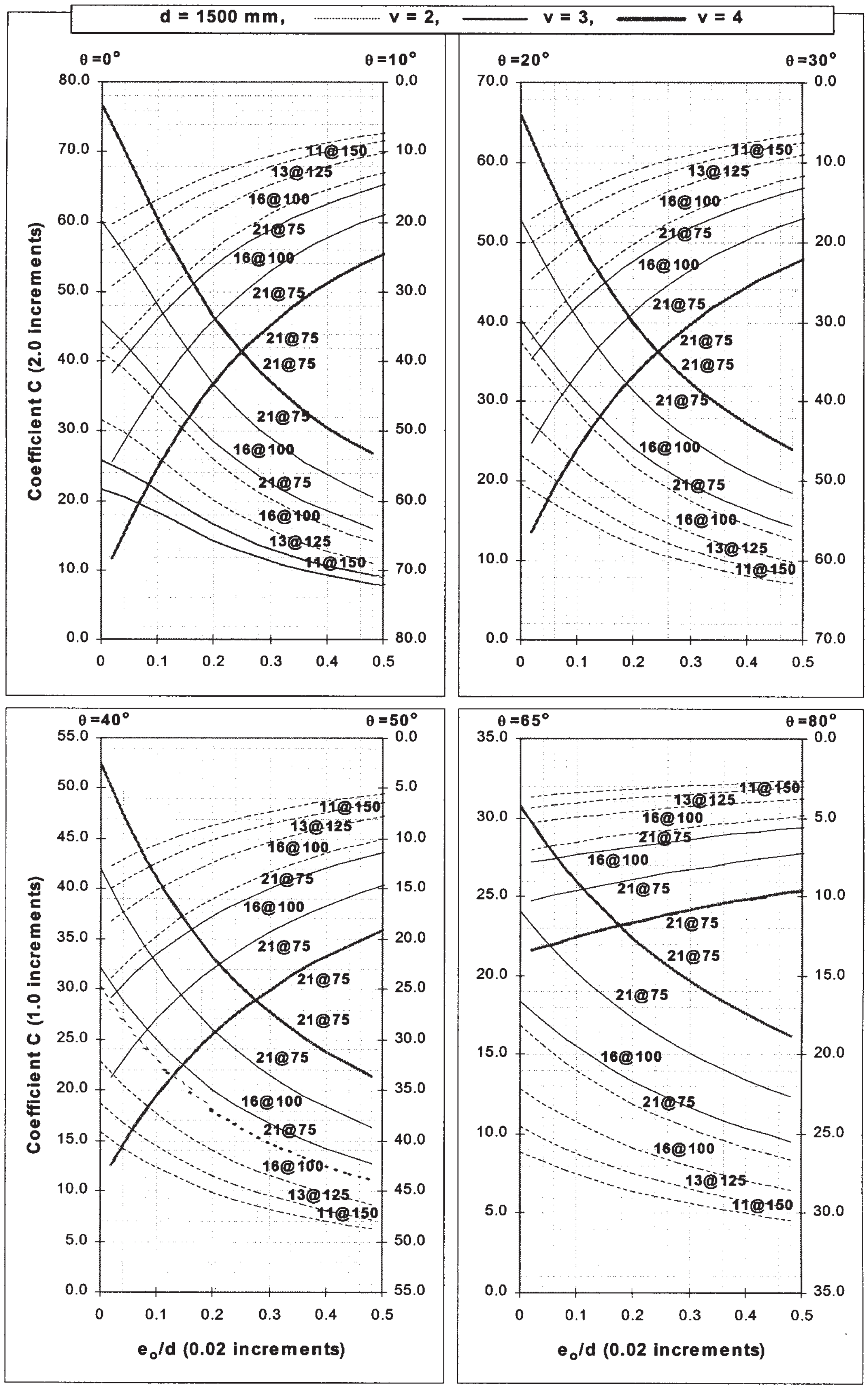
θ =0° θ =10°
θ =20° θ =30°
θ =40° θ =50°
θ =65° θ =80°
Coefficient C (0.5 increments)
e$_o$/d (0.05 increments)
11@130
14@100
21@65

APPENDIX I CONTINUED



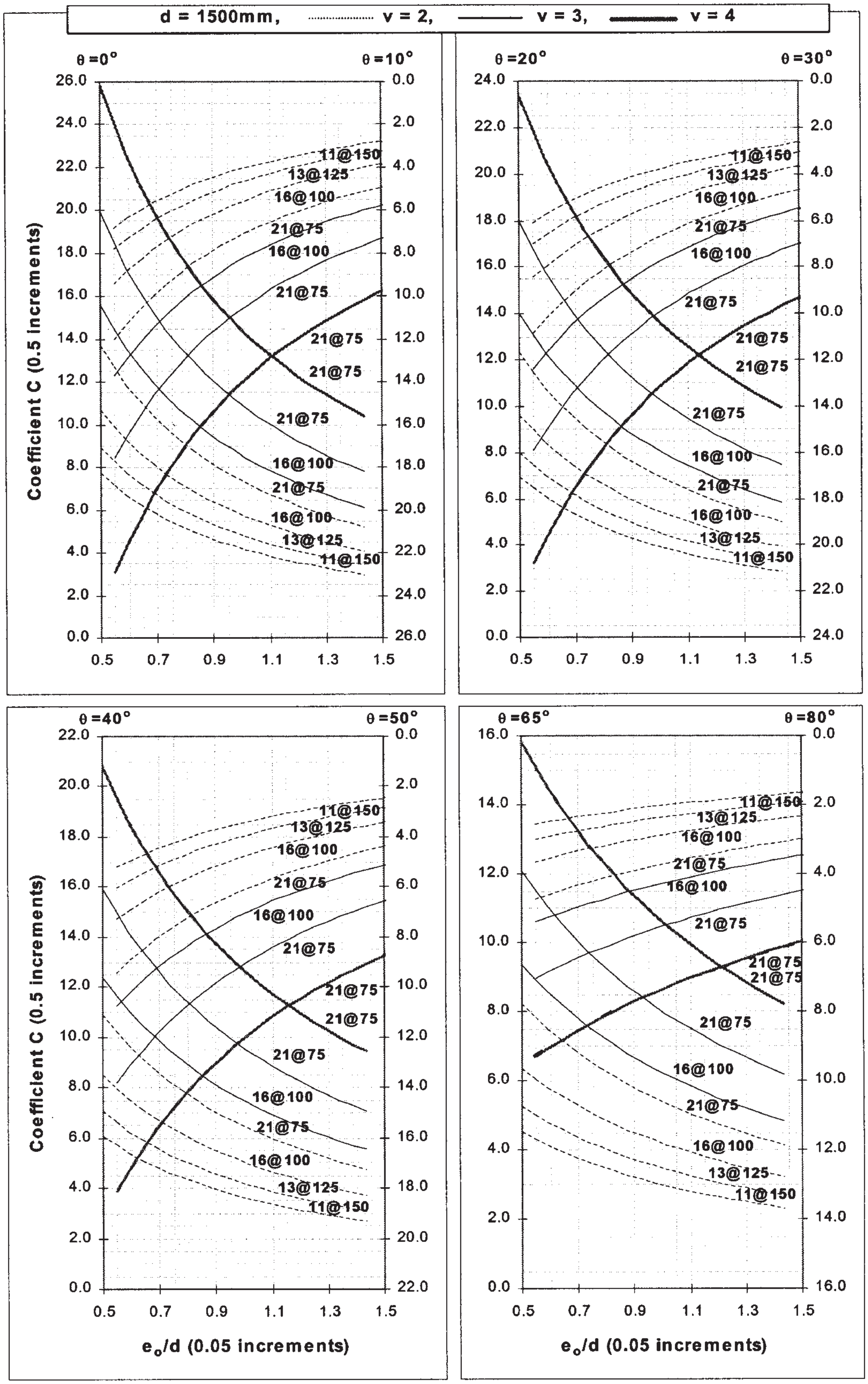
APPENDIX I CONTINUED



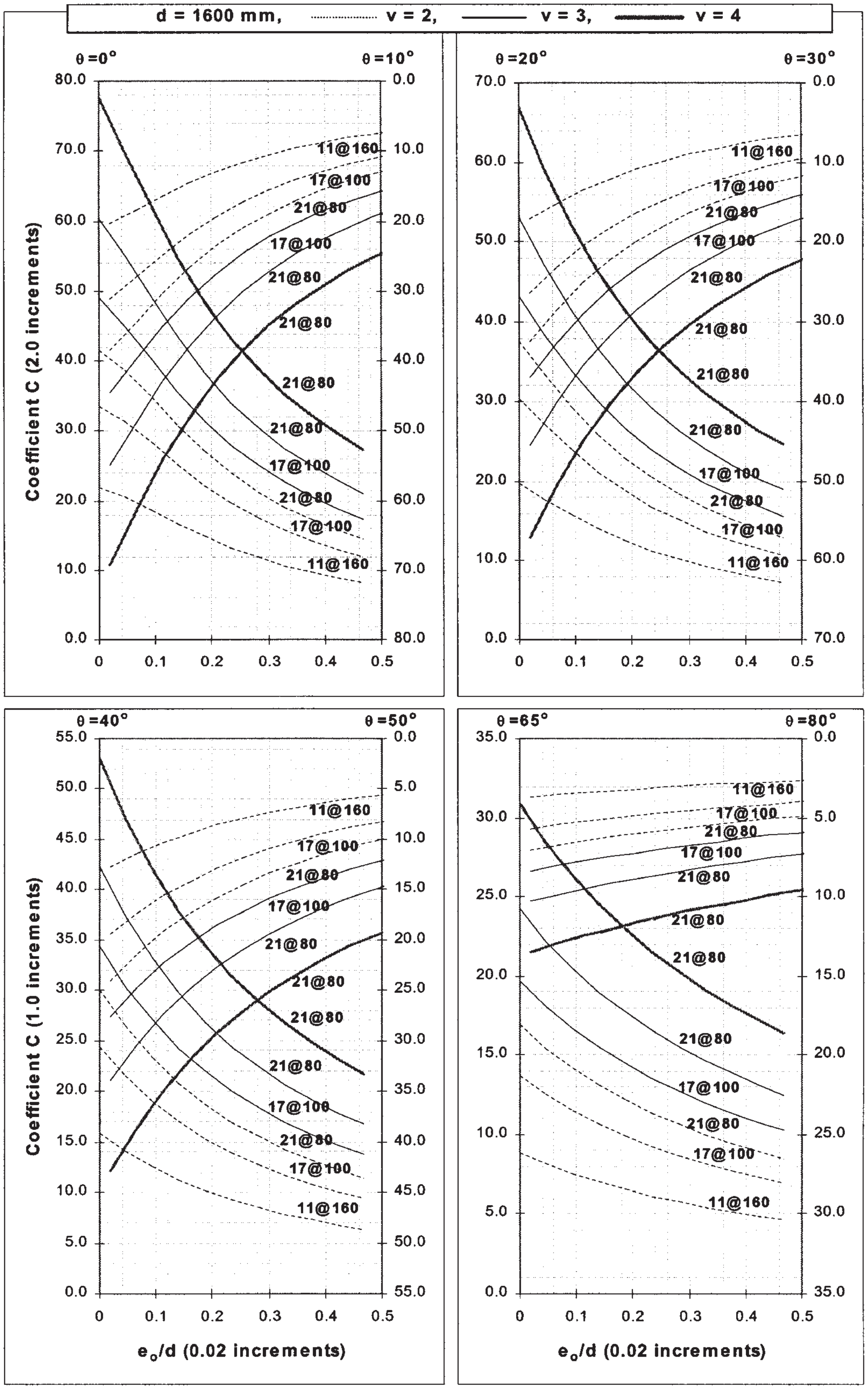


d = 1500 mm, v = 2, v = 3, v = 4
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (2.0 increments)
Coefficient C (1.0 increments)
11@150
13@125
16@100
21@75
e_o/d (0.02 increments)

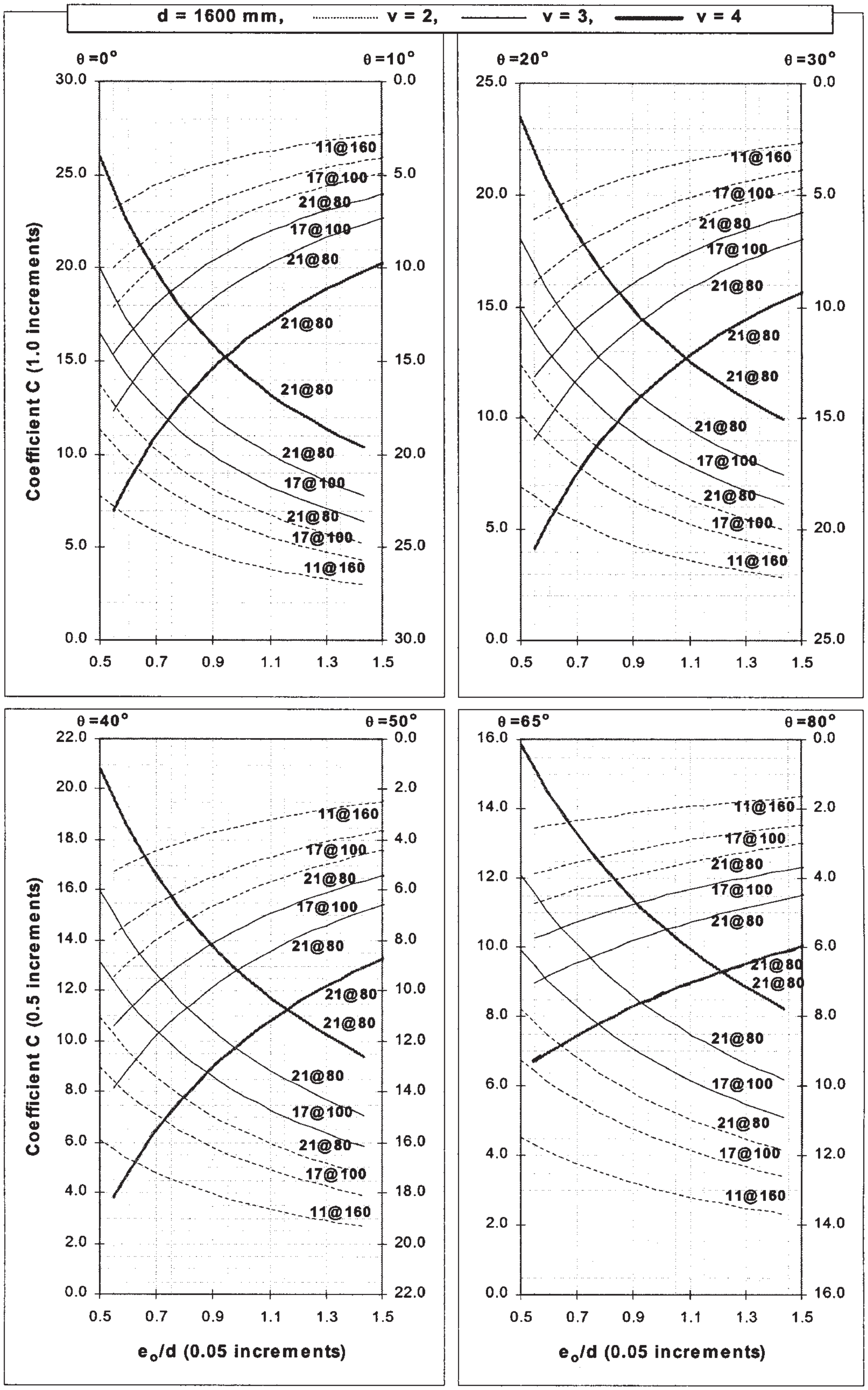
APPENDIX I CONTINUED

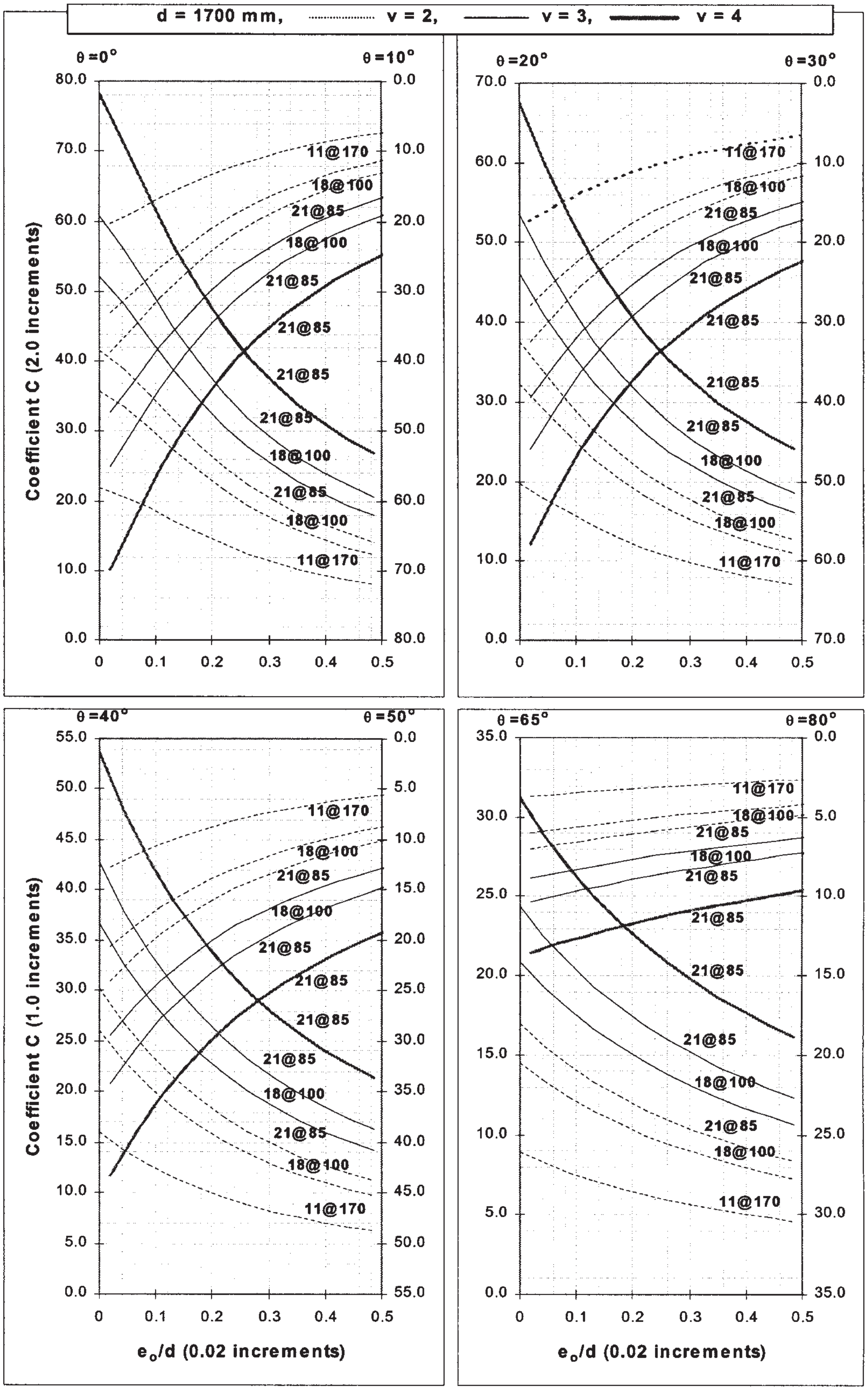


APPENDIX I CONTINUED

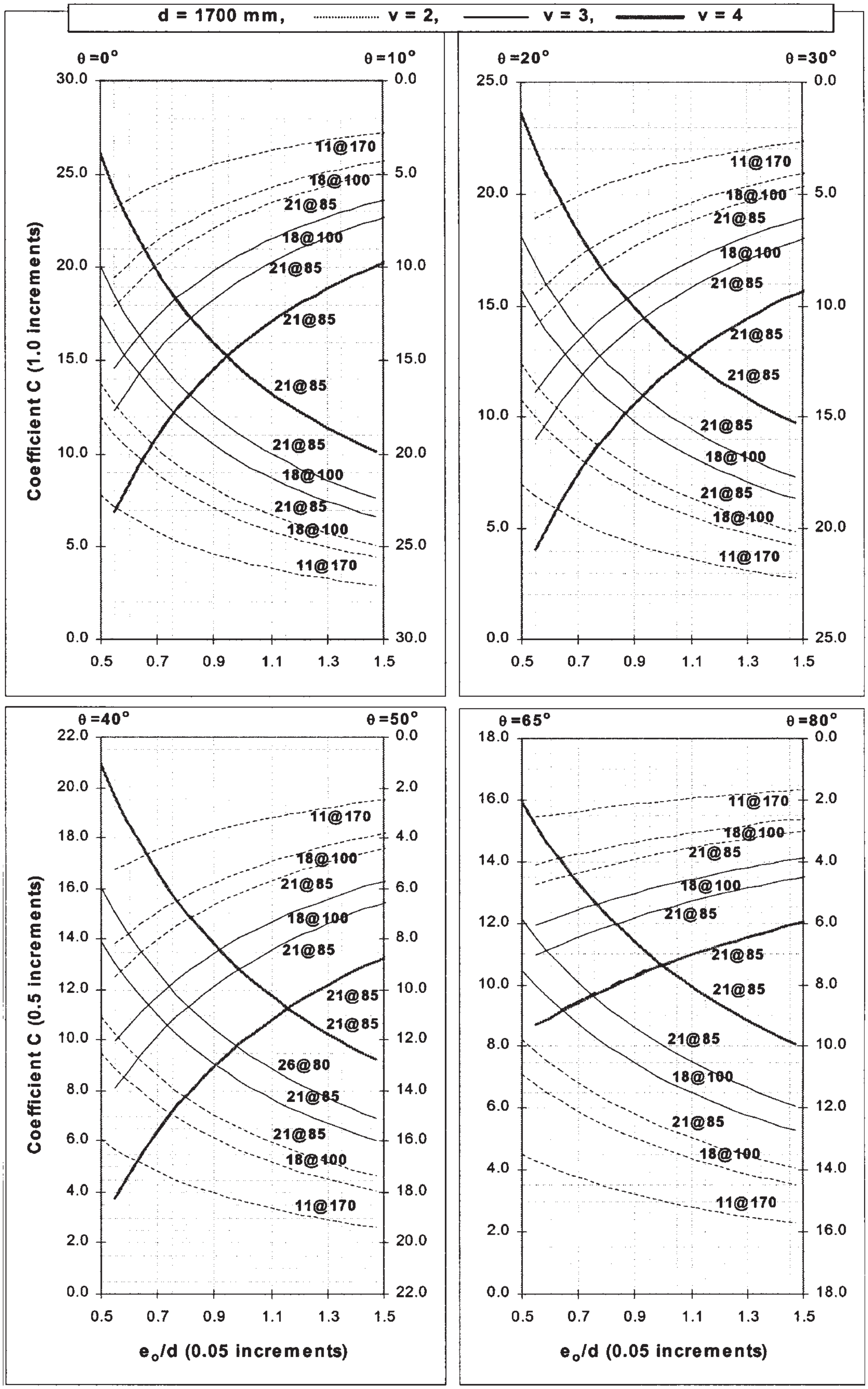


APPENDIX I CONTINUED

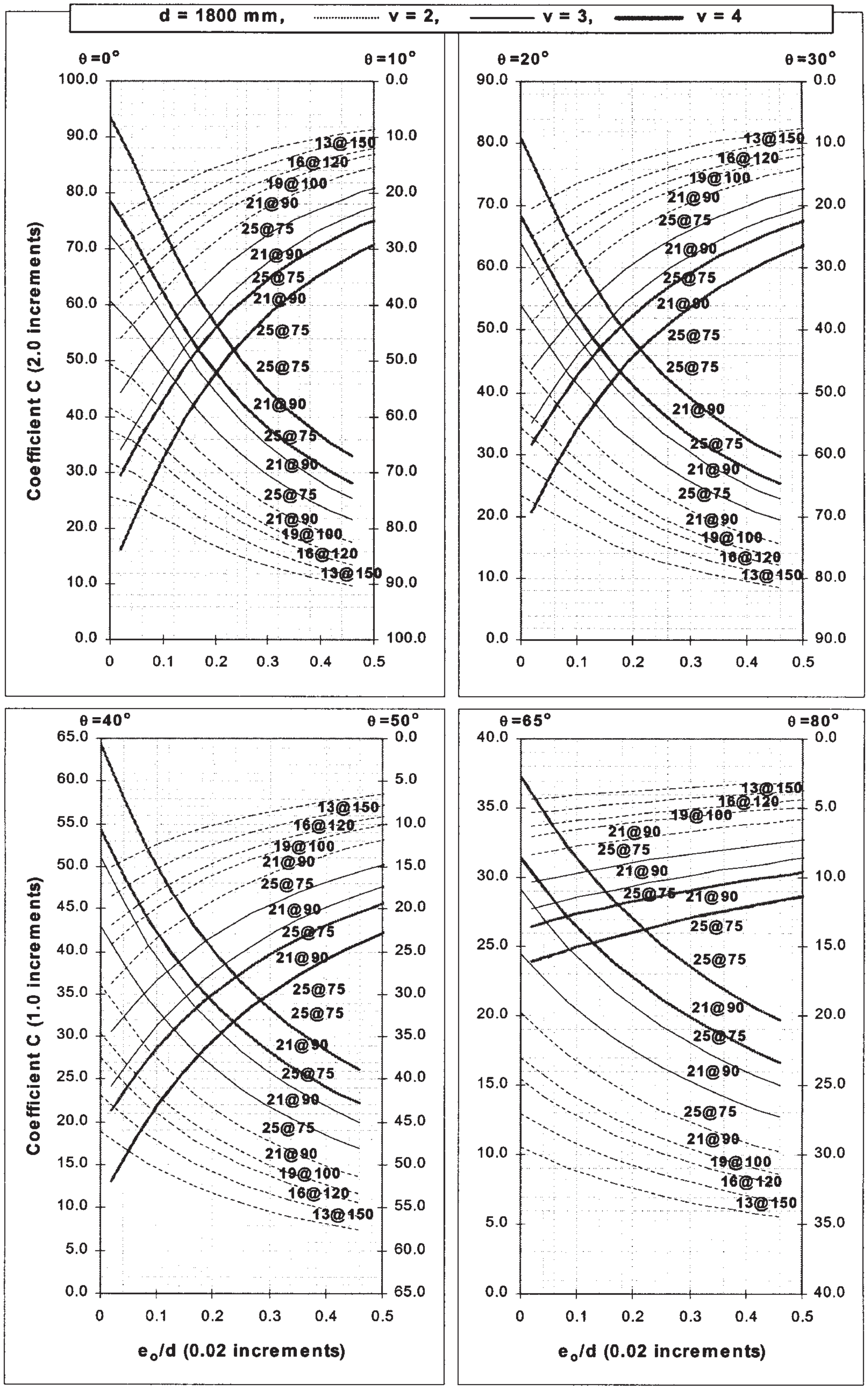


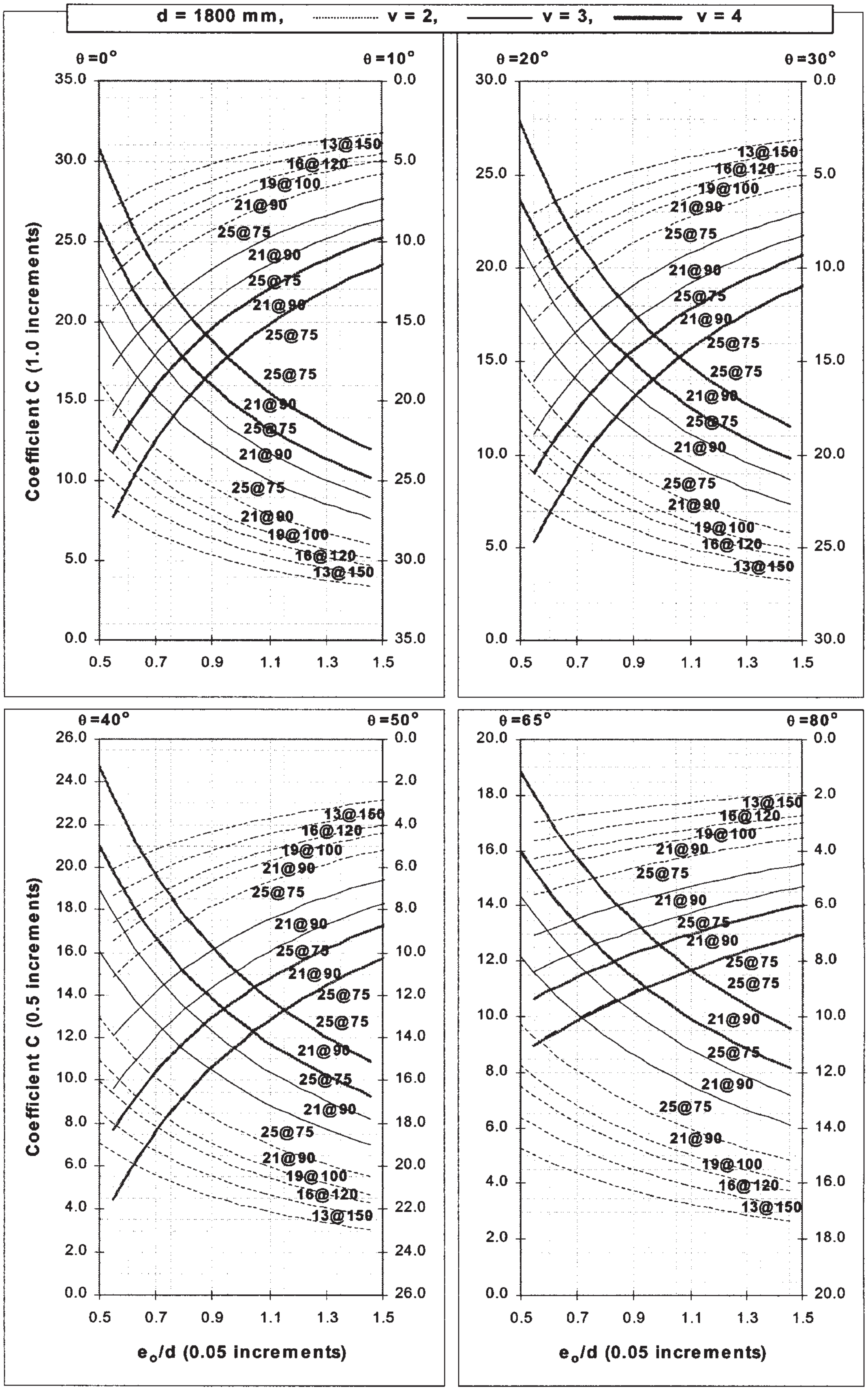

d = 1700 mm, v = 2, v = 3, v = 4
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (2.0 increments)
Coefficient C (1.0 increments)
e_o/d (0.02 increments)
11@170
18@100
21@85

APPENDIX I CONTINUED

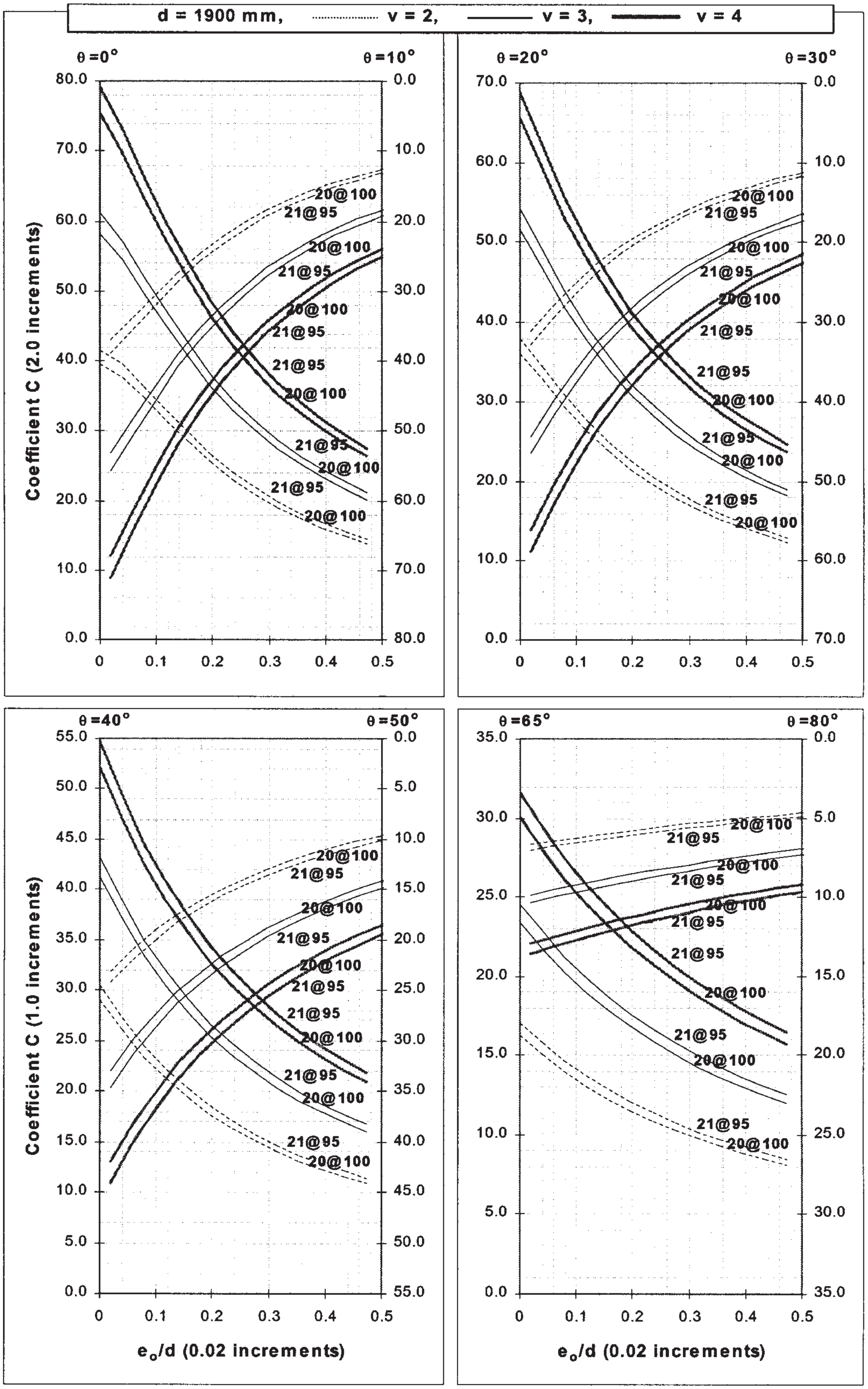


APPENDIX I CONTINUED

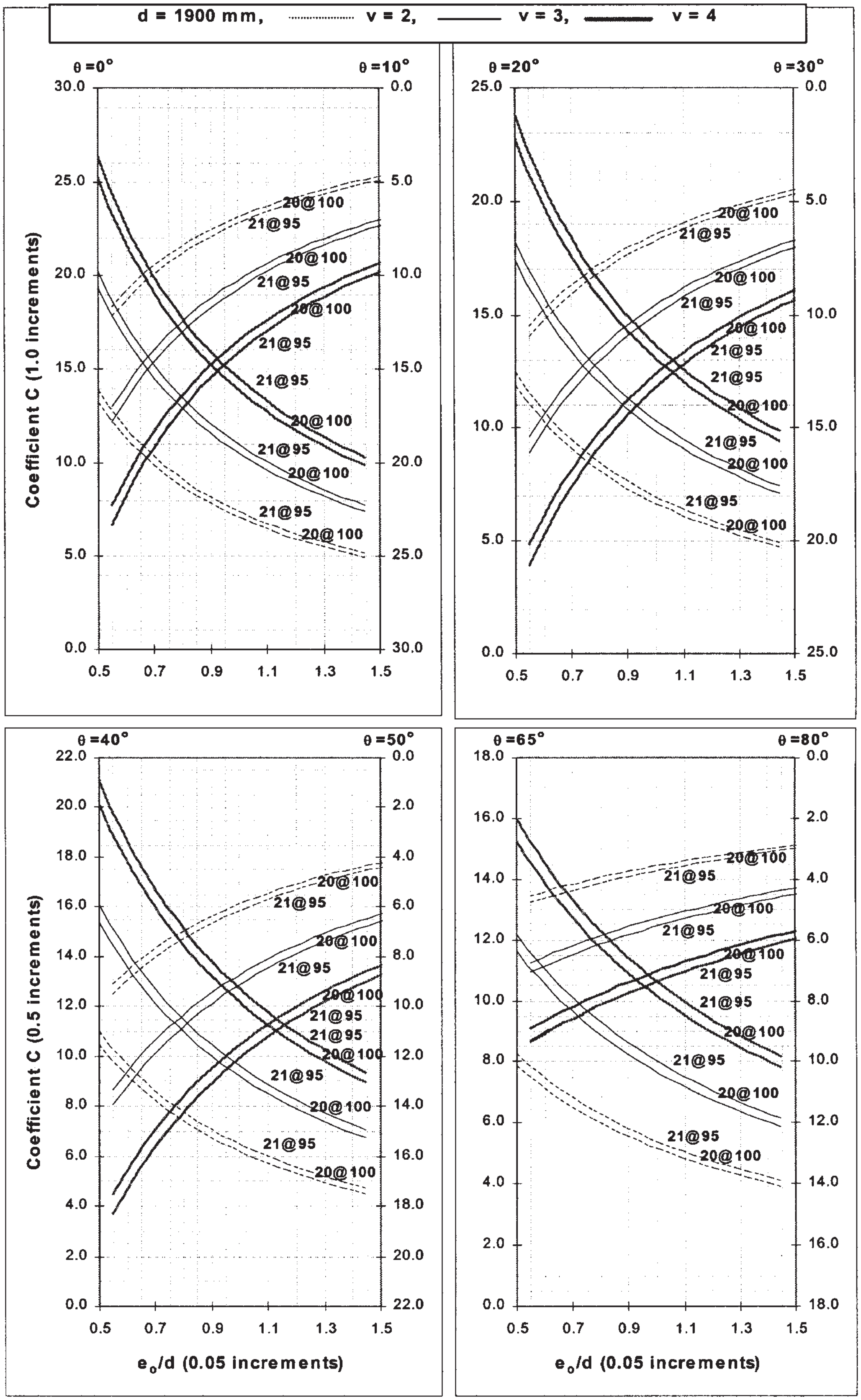



d = 1800 mm, v = 2, v = 3, v = 4
θ =0°
θ =10°
θ =20°
θ =30°
θ =40°
θ =50°
θ =65°
θ =80°
Coefficient C (1.0 increments)
Coefficient C (0.5 increments)
13@150
16@120
19@100
21@90
25@75
e_o/d (0.05 increments)

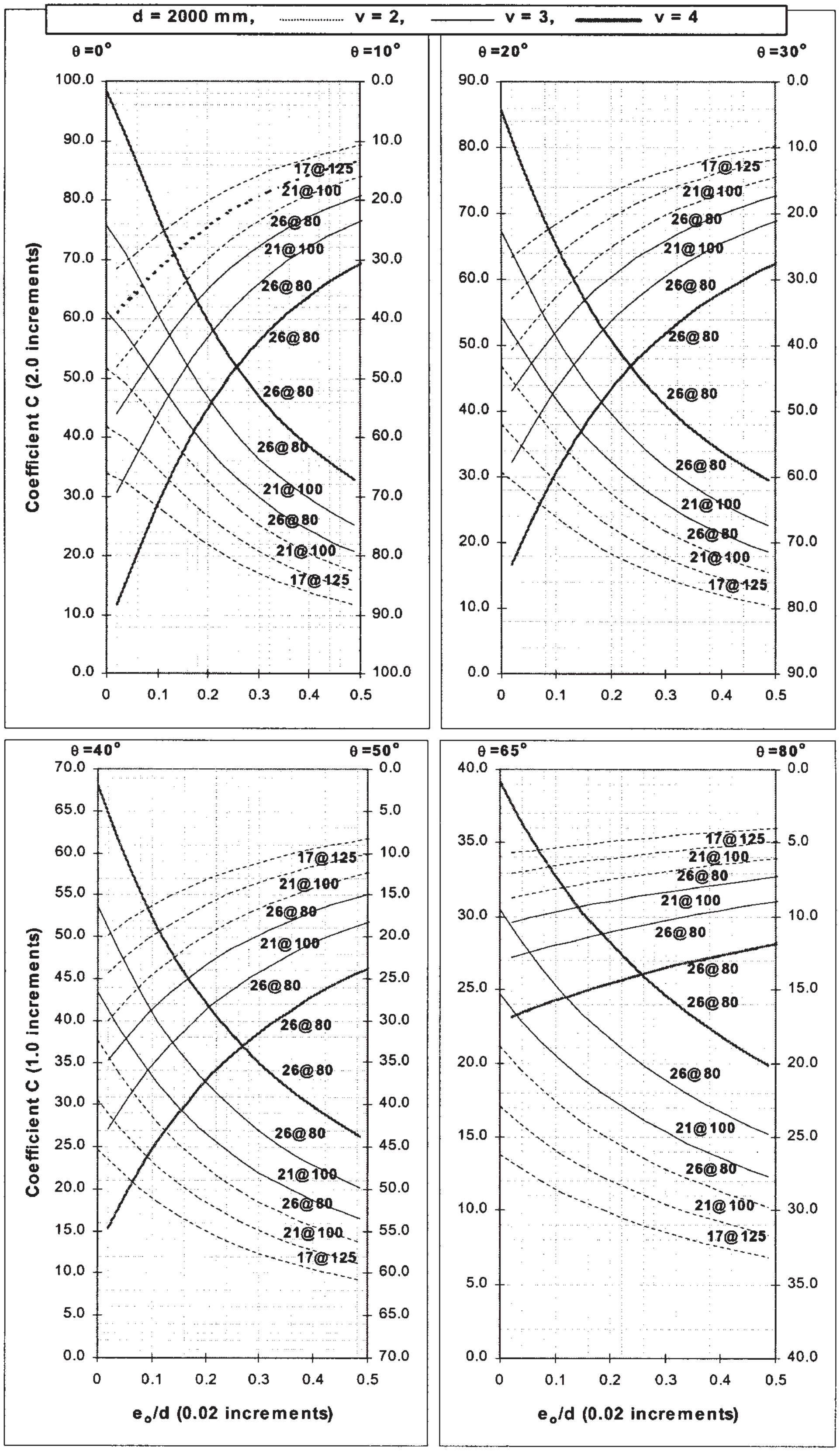
APPENDIX I CONTINUED



APPENDIX I CONTINUED



APPENDIX I CONTINUED



APPENDIX I CONTINUED