DESIGN AND ANALYSIS FACTORS INFLUENCING POWER SYSTEM GROUNDING

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ABSTRACT:

In this paper a review of major AC substation grounding practices given in international standards is presented with special reference to important considerations, differences and modifications. More especially the major changes in the 2000 version of IEEE Guide for Safety in AC Substation Grounding (Standard 80-2000) with respect to the 1986 version, (Standard 80-1986) that affect the grounding design and analysis are discussed. Comparisons are made for the portions where major changes occur. Examples are presented to show the effects of the changes in the design and analysis of power system grounding.

1. INTRODUCTION

Grounding systems should be designed in order to prevent excessive over-voltages and voltage gradients. Fault currents may damage equipment directly or indirectly as transferred voltages may exceed allowed values in the neighborhood of the fault. Grounding systems are designed to guarantee security of personnel, protection of equipment and continuity of power supply. Hence, engineers must compute the equivalent resistance of the system and the voltage distribution on the earth surface when a fault occurs.

The main differences between the two standards are (a) the difference in mathematical equations for calculation of the reduction factor C_s for derating nominal value of surface layer resistivity, due to the installation of a surface layer of gravel. This affects the calculated max allowable or tolerable step and touch voltage values (b) the difference in the results of calculation of the developed max mesh and step voltages due to alteration on the equivalent number of parallel conductors n, the spacing factors K_m and K_s and the correction factor K_i.

In this paper the major changes in the 2000 version of IEEE Guide for Safety in AC Substation Grounding (Standard 80-2000) with respect to the 1986 version, (Standard 80-1986) that affect the grounding design and analysis are discussed.

Comparisons of the results from the two standards are made for all the portions where major changes occur. Examples are presented to show the effects of the changes on the design and analysis of power system grounding. General conclusions on the standard that leads to more economical design are drawn.

2. THEORETICAL BACKGROUND IN GROUNDING GRID DESIGN

2.1. Basic steps of the design procedure

Grounding systems design according to the IEEE standards methodology, follows particular stages, some of them iteratively:

1. Selection of material of conductors and cross section. Calculations are needed to ensure that thermal damage or errosion / corrosion will be avoided.
2. Calculation of the maximum tolerable touch and step voltages. It is based on the soil resistivity measurements, the thickness and resistivity of the surface layer of gravel and the fault duration.
3. Design of the grounding system configuration in such a way that most or all the area of the site is used. It is desirable to achieve the lowest possible grounding resistance of the grid which should be less than 1ohm.
4. Calculation of the maximum developed touch and step voltages.
5. Check if the safety criteria against harmful touch and step voltages are satisfied. If no, the grid should be reinforced by:
   - reduction of mesh dimensions
   - addition of ground rods

   and maximum developed touch and step voltages must be recalculated.

The design methodology should also take into consideration the minimization of costs of materials and installation.

2.2. Similarities and differences between IEEE Guide for Safety in AC Grounding versions 1986 and 2000.

The two IEEE standards are similar in their structure and contents. Their differences are detected at particular mathematical equations. More analytically, in the calculation methodology and equations for:

A_{min}:minimum conductor cross section area
R_g: substation grounding grid resistance
I_G: maximum grid current
K: reflection factor

there is no difference between the two standards. However differences are observed in mathematical formulas for:

C_s: the surface rating resistivity derating factor. The two analytical equations as well as the two simplified formulas change

n: the equivalent number of parallel conductors is $\max\left(n_x, n_y\right)$ for calculation of K_s, K_i, E_s and $\sqrt{n_x \cdot n_y}$ for calculation of K_m, K_i, E_m according to IEEE 80/1986 standard, and it is $n_a.n_b.n_c.n_d$ according to IEEE 80/2000 standard

Equivalent grid length for calculation of mesh voltages and step voltages if [2] is used, are given below:

$$L_m=L_C+L_R \qquad L_s=L_C+L_R \qquad (1.a)$$

$$L_m = L_C+1.15L_R \qquad L_s = L_C+1.15L_R \qquad (1.a)$$

while in [3] equations (2) are proposed.

$$L_m = L_C+L_R \qquad L_s=0.75L_C+0.85L_R \qquad (1.b)$$

$$L_m = L_C + \left(1.55 + 1.22\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)L_R \qquad L_s = 0.75L_C+0.85L_R \qquad (2.b)$$

Equations (1.a) and (2.a) apply to grids without ground rods or with a few ground rods scattered throughout the grid, but none located in the corners or along the perimeter of the grid. Equations (1.b) and (2.b) apply to grids with ground rods in the corners as well as along the perimeter and throughout the grid.

It can be observed that L_m at grids with rods calculated from (2.b) will always be greater than L_m from (1.b) due to the coefficient 1.55 which is larger than 1.15. This leads to a smaller E_m when the IEEE Std. 80/2000 is used. The same conclusion is not obvious for the L_s calculated according to (1.b) and (2.b) because the latter is always greater due to the coefficients 0.75 and 0.85 with comparison to 1 and 1.15. In both cases and further investigation is needed to conclude if E_s is greater for all grids, when the 80/2000 standard is used.

General formulas of E_m, E_s, $E_{Touch,70}$, and $E_{Step,70}$ are the same, but specific parameters inside the formulas have changed. These are the parameters n, K_i , L_m, L_s

3. DIFFERENCES IN DERATING FACTOR FORMULAS

3.1. Surface rating resistivity derating factor

A layer of high resistivity material, such as gravel, is often spread on the earth's surface above the ground grid to increase the contact resistance between the soil and the feet of persons in the substation. The relatively shallow depth of the surface material, as compared to the equivalent radius of the foot, precludes the assumption of uniform resistivity in the vertical direction when computing the ground resistance of the feet. However for a person in the substation area, the surface material can be assumed to be of infinite extent in the lateral direction. If the underlying soil has a lower resistivity than the surface material, only some grid current will go upward into the thin layer of the surface material, the surface voltage will be very nearly the same as that without the surface material. The current through the body will be lowered considerably with the addition of the surface material because of the greater contact resistance between the earth and the feet. However this resistance may be considerably less than that of a surface layer thick enough to assume uniform resistivity in all directions. The reduction depends on the relative values of the soil and the surface material resistivities and on the thickness of the surface material.

An analytical equation for the ground resistance of the foot on a thin layer of surface material can be obtained with the use of the method of images. The analytical equation presented in the standard 80/2000 involves calculation of infinite terms. For this reason an empirical formula that gives results with an error less than 3% of the analytical results is proposed in [1]:

$$C_s = \frac{1+K}{1-K} - \frac{4 \cdot K}{p\left(1-K\right)}\tan^{-1}\left(2h/b\right) - \\ - 0.21K^2\left(e^{-7h} - e^{-30h}\right) \qquad (3)$$

The empirical formula (4) is proposed in the standard 80/2000 and is much simpler than (3).

$$C_s\left(r\right)_{80/2000} = 1 - \frac{0.09\cdot\left(1-\frac{r}{r_s}\right)}{2\cdot h_s + 0.09} \qquad (4)$$

where

?: soil resistivity

?$_s$: surface layer resistivity

The analytical mathematical equation proposed in standard 80/1986 is as follows:

$$C_s = \left(1 + 2\cdot\sum_n \frac{K^n}{\sqrt{1+\left(\frac{2\cdot n\cdot h_s}{0.08}\right)^2}}\right)\cdot 0.96^{-1} \qquad (5)$$

while the empirical formula proposed in standard 80/1986 is:

$$C_s\left(r\right)_{80/1986} = 1 - \frac{0.106\cdot\left(1-\frac{r}{r_s}\right)}{2\cdot h_s + 0.106} \qquad (6)$$

In the following, the values of coefficient C$_s$ calculated according to (3) to (6) are compared, considering surface layer of gravel of thickness h$_s$ equal to 0.05m, 0.10m, 0.15m 0.20m, 0.25m, 0.30m. Soil resistivity ? varies, being always less than the special resistivity of gravel ?$_s$.

To estimate the percentage of difference between the values obtained from standard 80/1986 and standard 80/2000, function (7) is evaluated and plotted in figs 1 and 2.

$$F_{C_s}\left(r\right) = \frac{C_s\left(r\right)_{80/2000} - C_s\left(r\right)_{80/1986}}{C_s\left(r\right)_{80/1986}}\cdot 100\% \qquad (7)$$

The surface layer of gravel is considered to have special resistivity ?$_s$ equal to 1000 Om, 2500 Om and 3000 Om and thickness h$_s$ equal to 0.05m, 0.10m, 0.15m 0.20m, 0.25m, 0.30m. Fig. 1 demonstrates the comparison of the results of (3) and (5) while fig.2 demonstrates the comparison of the results of (4) and (6).

From diagrams of fig.1 where the results of the analytical formula (3) and the empirical formula (5) have been used, the following are deduced:

- Values for Cs as calculated from standard 80/1986 and standard 80/2000 are equal for a particular value of soil resistivity ?$_?$ which depends on the characteristics of the surface layer h$_s$ and ?$_s$
- When soil resistivity is higher than ?$_?$ the value from standard 80/2000 becomes smaller than the value from standard 80/1986.
- For particular thickness of layer of gravel h$_s$, the ?$_o$ takes higher values if the soil resistivity of the surface layer of gravel takes also higher value.

It should be noted however, that in all of the cases where it is practically feasible to install a substation grounding grid, soil resistivity does not exceed 400 Ohms, therefore the value of C$_s$ calculated from the new standard will be always higher than the corresponding C$_s$ calculated using the old standard.

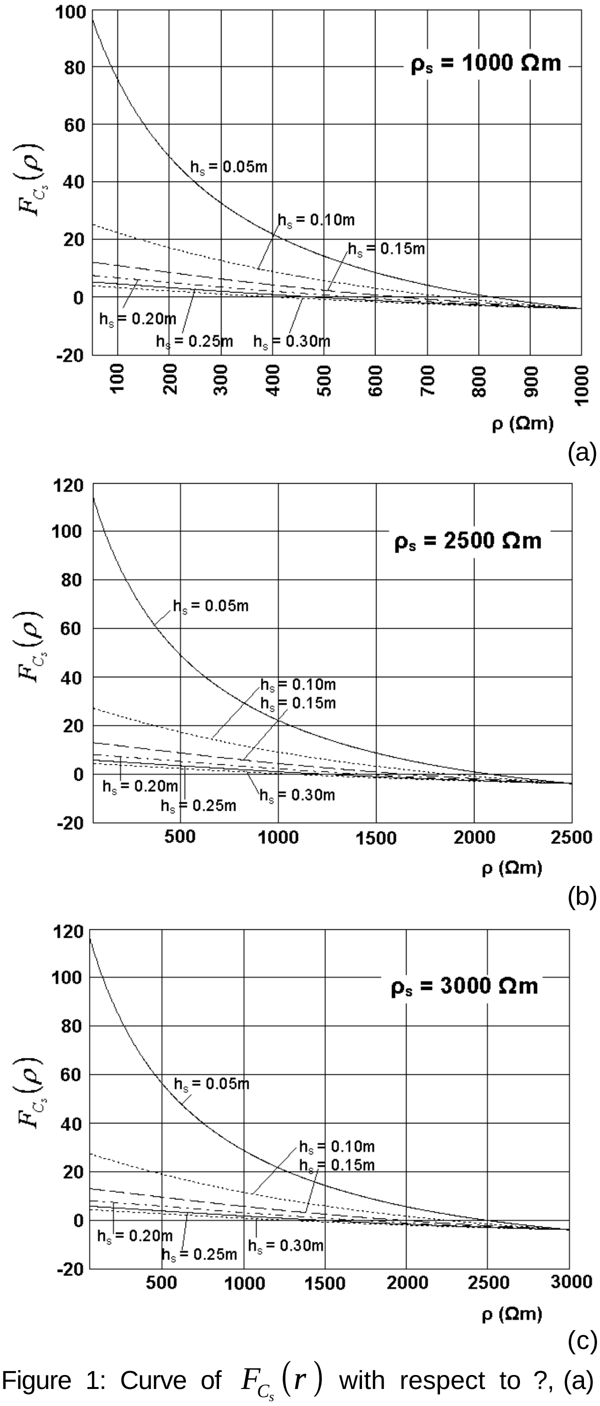

Figure 1: Curve of $F_{C_s}\left(r\right)$ with respect to ?, (a) ?$_s$= 1000 Om, (b) ?$_s$= 2500 Om, (c) ?$_s$= 3000 Om

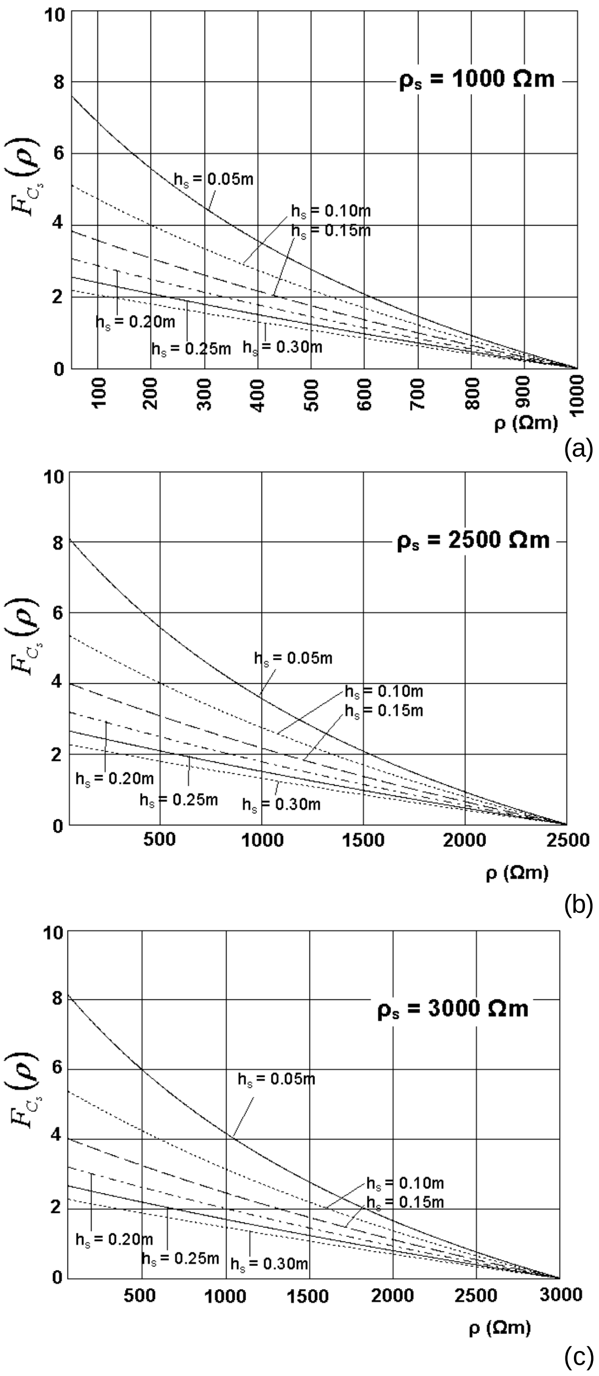

Figure 2: Curve of $F_{C_s}(r)$ with respect to ?, (a) ?$_s$= 1000 Om, (b) ?$_s$= 2500 Om, (c) ?$_s$= 3000 Om

From diagrams of fig.2 where the results of the empirical formulae (4) and (6) have been compared, the following are deduced:

- The empirical formula proposed in 80/1986 for calculation of Cs results in higher values in all cases than the empirical formula proposed in 80/2000
- In all cases the values resulting from the new standard 80/2000 are higher.

4. INFLUENCE OF DERATING FACTOR IN TOLERABLE TOUCH VOLTAGES

Maximum tolerable touch voltages are in both the IEEE standards given by the following equation:

$$E_{touch,70} = \left(1000 + 1.5\cdot C_s \cdot r_s\right)\frac{0.157}{\sqrt{t_s}} \qquad (8)$$

Maximum tolerable touch voltage for 50 kg human body $E_{touch,50}$, can be also calculated from (8) where the coefficient 0.116 is used instead of 0.157.

Values of $E_{touch,70}$ calculated from [2] and [3] are compared, considering surface layer of gravel of thickness h_s equal to 0.05m, 0.10m, 0.15m 0.20m, 0.25m, 0.30m. Soil resistivity varies, being always less than the special resistivity of gravel and surface derating factor C_S is calculated from (4) and (6). To estimate the percentage of difference between the values obtained from Std.80/1986 and Std.80/2000, function (9) is evaluated and plotted as shown in fig 3 using empirical formulae for C_S.

$$\begin{aligned} &F_{E_{touch,50}}(r) = F_{E_{touch,70}}(r) = \\ &= \frac{E_{touch,70}(r)_{80/2000} - E_{touch,70}(r)_{80/1986}}{E_{touch,70}(r)_{80/1986}}\cdot 100\% \\ &= \frac{1.5\cdot r_s \cdot \left(C_s(r)_{80/2000} - C_s(r)_{80/1986}\right)}{1000 + 1.5\cdot r_s \cdot C_s(r)_{80/1986}}\cdot 100\% \end{aligned} \qquad (9)$$

In diagrams of fig. 3, the following can be observed:

- Application of the new standard [3] leads always in higher values of tolerable touch voltages than the old standard [2]
- F_{Etouch} varies almost linearly with soil resistivity.
- Larger differences in E_{touch} calculated from the two standards, appear when resistivity of the surface layer of gravel is the highest possible (3000Om).
- Larger differences in E_{touch} from the two standards when the surface layer resistivity remains the same are also observed when the thickness of the surface layer is smaller.
- Percentages of difference between the values obtained from the two standards do not depend on the time duration of the fault or the weight of the human body.

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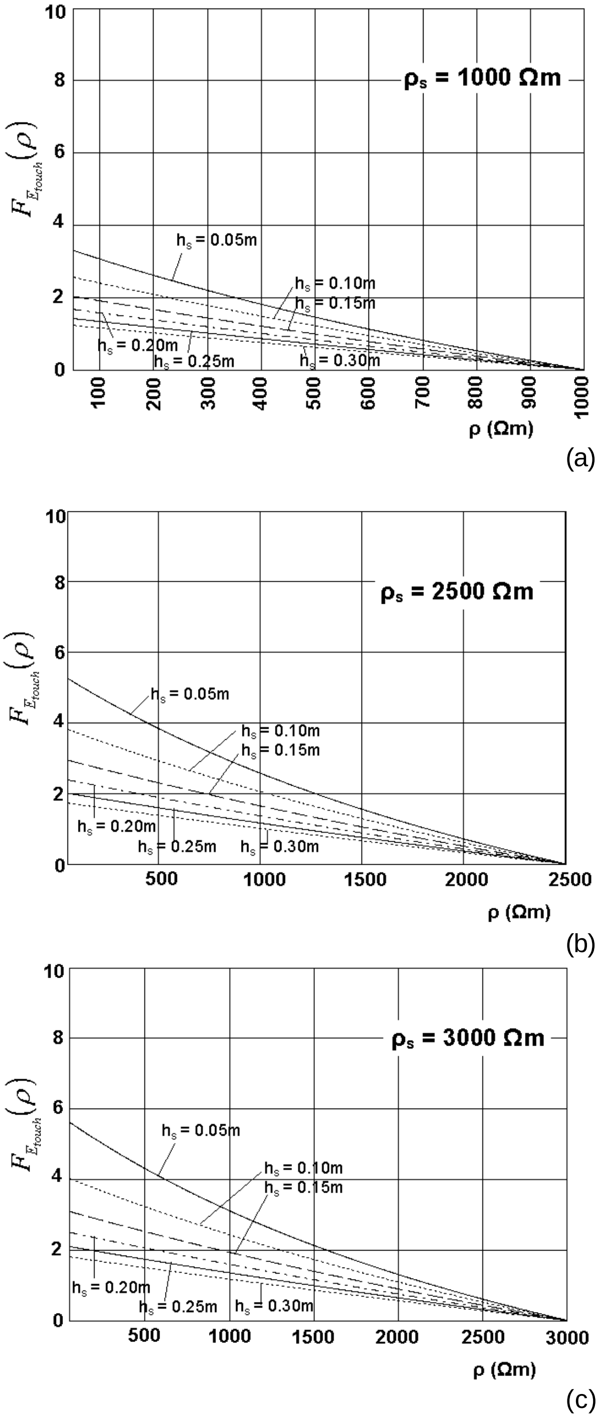


(a)

(b)

(c)

Figure 3: Curve of $F_{E_{touch}}(r)$ with respect to ?, (a) ?s= 1000 Om, (b) ?s= 2500 Om, (c) ?s= 3000 Om

5. INFLUENCE OF DERATING FACTOR IN TOLERABLE STEP VOLTAGES

Maximum tolerable step voltages are in both the IEEE standards [2] and [3] given by equation (10):

$$E_{step,70} = (1000 + 6\cdot C_s \cdot r_s)\frac{0.157}{\sqrt{t_s}} \qquad (10)$$

As previously, the maximum tolerable step voltage for 50 kg human body $E_{step,50}$, can be also calculated from (10) where the coefficient 0.116 instead of 0.157 should be used.

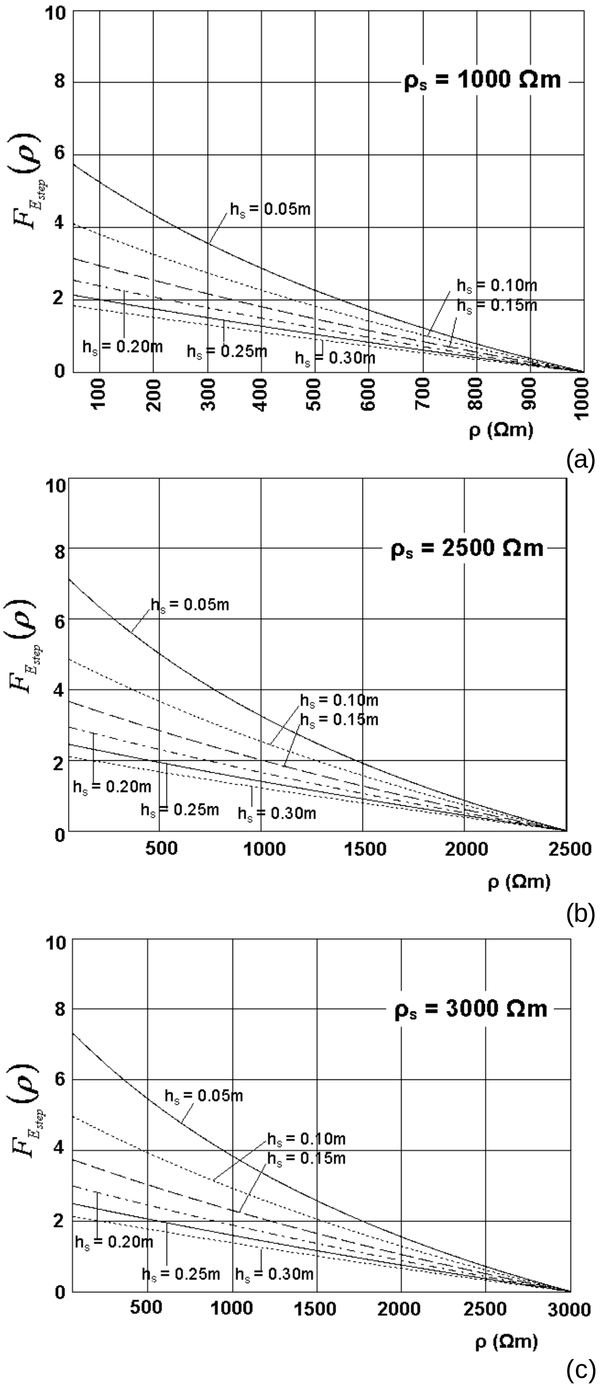
The values of $E_{step,70}$ calculated from the empirical formulae suggested in [2] and [3] are compared, considering surface layer of gravel of thickness h_s equal to 0.05m, 0.10m, 0.15m 0.20m, 0.25m, 0.30m. Soil resistivity varies, being always less than the special resistivity of gravel and surface derating factor C_S is calculated from (4) and (6).

To estimate the percentage of difference between the values obtained from standard 80/1986 and standard 80/2000, function (11) is evaluated and plotted as shown in fig 4.

$$\begin{aligned} &F_{E_{step,50}}(r) = F_{E_{step,70}}(r) = \\ &= \frac{E_{step,70}(r)_{80/2000} - E_{step,70}(r)_{80/1986}}{E_{step,70}(r)_{80/1986}}\cdot 100\% \\ &= \frac{6\cdot r_s \cdot \left(C_s(r)_{80/2000} - C_s(r)_{80/1986}\right)}{1000 + 6\cdot r_s \cdot C_s(r)_{80/1986}}\cdot 100\% \end{aligned} \qquad (11)$$

In diagrams of fig. 4, the following can be observed:

- Application of the new standard [3] always results in higher values of tolerable step voltages than application of the old standard [2]
- F_{Estep} varies almost linearly with soil resistivity.
- Larger differences in E_{step} calculated from the two standards, appear when special resistivity of the surface layer of gravel is the highest possible (3000Om).
- Larger differences in E_{step} calculated from the two standards for the same surface layer resistivity, appear when the thickness of the surface layer is smaller.
- Percentages of difference between the values calculated from the two standards do not depend on the duration of the fault or the human weight.



(a)

(b)

(c)

Figure 4: Curve of $F_{E_{step}}\left(r\right)$ with respect to ?, (a) ?$_S$= 1000 Om, (b) ?$_S$= 2500 Om, (c) ?$_S$= 3000 Om

6. DIFFERENCES IN THE DEVELOPED TOUCH AND STEP VOLTAGES

In this paragraph, values of the maximum developed at the surface of the substation grounding grid, calculated from the two IEEE standards [2] and [3] are compared. Equations for touch and step voltages are given below:

$$E_m = r \cdot K_i \cdot K_m \cdot I_G / L_M \qquad (12)$$

$$E_s = r \cdot K_i \cdot K_s \cdot I_G / L_S$$

It should be noted that maximum developed touch and step voltages vary linearly with respect to soil resistivity and they are calculated from the same mathematical equations in both the standards, thus most of the conclusions drawn for a specific value of soil resistivity, apply for any soil resistivity.

In the following only orthogonal and square grounding grids are considered. For these grid configurations the differences between the calculated developed voltages using the two standards are larger than when the L shape or any shape grids are considered.

For the parameters of the grid, that don't change throughout calculations, typical values are chosen i.e. diameter of the conductors of the grid is 0.01m, grid depth is 0.60m, and current to ground I_G is 15kA. Soil resistivity is 100Om. In general, realistic grounding grids configurations are calculated. Resulting voltages are contrasted to the maximum tolerable values when the duration of fault is taken equal to 0.5s, and the surface layer of gravel is of 0.10m thickness and 2500Om resistivity. Results of calculations are presented in details in App.1.

6.1. Maximum developed touch voltage

6.1.1. Grids with no ground rods or with only a few ground rods scattered throughout the grid, but none in the corners or along the perimeter of the grid. Differences between the values of the standard 80/1986 and the 80/2000 are due to the differences in:

- the equivalent number of parallel conductors n which is calculated from different mathematical equation as it is described in 2.2.
- the correction factor K_i which is also calculated using different mathematical equations, introducing a difference in the results even when n from the two standards is the same as in the square grounding grids.

In fig 5 the ratio of Em calculated according to the 80/2000 standard to the value calculated according to the 80/1986 standard is plotted considering that mesh dimension varies between 2.5m and 10m. In calculation results the following can be observed:

- The ratio of Em calculated according to the 80/2000 standard to the value calculated according to the 80/1986 standard increases linearly and almost with the same slope if mesh dimensions increase, in all the examined cases.

- $Em_{80/2000}$/ $Em_{80/1986}$ ratio when the grid has a few rods in the center, and the exactly the same configuration in the two cases, is equal to the ratio of $Em_{80/2000}$/ $Em_{80/1986}$ calculated for the case when there are no rods at all.
- For the same grid sides ratio, Em value calculated with the 80/2000 standard is a lower percentage of Em calculated with the 80/1986 standard if the area of the grid increases
- Keeping the same grid area and redesigning the grid with a larger sides ratio, results in values of Em from the new standard closer to those of the old standard, and higher $Em_{80/2000}$/ $Em_{80/1986}$.

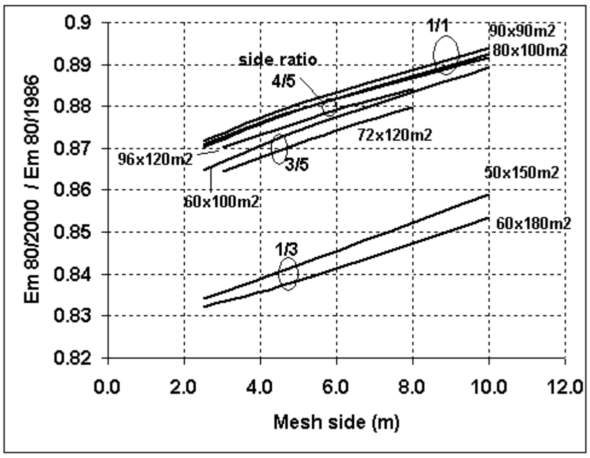


Figure 5: Ratio of $Em_{\mathbf{80/2000}}$ / $Em_{\mathbf{80/1986}}$ versus mesh side dimension for grids without rods

It is also generally observed in the results that in all cases the Em values from the 80/1986 as well as from the 80/2000 standard depend exponentially on the total length of conductors L_M raised in a power 0.70 ± 10^{-2}

6.1.2. Grids with ground rods in the corners as well as in the perimeter and throughout the grid.

Differences between the values of the first and the second standard are due to the differences in:

- The equivalent number of parallel conductors n which is different as explained in 6.1.1.
- Total length Lm of grounding conductors which is different for the same reason as referred in the previous paragraph 6.1.1.
- The correction factor K_i which is calculated using different mathematical equations, introducing a difference in the results even when n from the two standards is the same as in the square grounding grids.

In fig 6 the ratio of Em calculated according to the 80/2000 standard to the value calculated according to the 80/1986 standard is plotted considering that mesh dimension varies between 2.5m and 10m. Additionally 100m rods are installed along the perimeter and throughout the area of the grid. In calculation results the following can be observed:

- As for grids without rods the ratio of Em calculated according to the 80/2000 standard to the value calculated according to the 80/1986 standard increases linearly and almost with the same slope if mesh dimensions increase, in all the examined cases.
- $Em_{80/2000}$ / $Em_{80/1986}$ compared to the values of the same ratio in fig.5 are lower when all the other design parameters are the same.
- If more 100m rods are added to the grid, $Em_{80/2000}$ / $Em_{80/1986}$ ratio remains almost constant versus mesh dimension and for grid sides ratio 1/3, 3/5, 4/5 and 1/1 it is approximately equal to 0.823, 0.850, 0.860, 0.860. Consequently it lower than the ratio plotted in fig. 6.
- The same observations made for the results shown in fig.5 apply in this case.

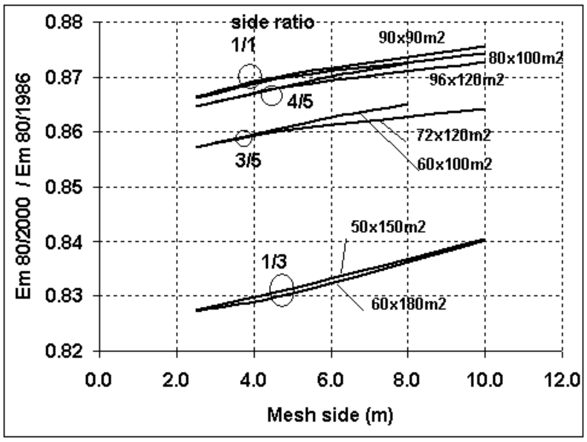


Figure 6: Ratio of $Em_{\mathbf{80/2000}}$ / $Em_{\mathbf{80/1986}}$ versus mesh side dimension for grids with rods

As in the previous case it is also generally observed in the results that in all cases the Em values from both versions of standards depend exponentially on the total length of conductors L_M raised in a power of 0.69 to 0.74

6.2. Maximum developed step voltage

6.2.1. Grids with no ground rods or with only a few ground rods scattered throughout the grid, but none in the corners or along the perimeter of the grid.

Differences between the values of the first and the second standard are due to the differences explained in the previous paragraphs considering:

- the equivalent number of parallel conductors n
- Total length of grounding conductors Ls

- Correction factor K_i.

In the results of table A.1 it is observed that the maximum developed step voltage calculated according to std. 80/2000 is lower than the step voltage calculated according to std 80/1986 only when the ratio of sides is 1/3. However the safety criteria are satisfied in all examined cases

6.2.2. Grids with ground rods in the corners as well as in the perimeter and throughout the grid. Differences between the values of the first and the second standard are due to the differences explained in the previous paragraphs considering:
- the equivalent number of parallel conductors n
- Total length of grounding conductors Ls
- Correction factor K_i.

In the results of table A.2 it is observed that the maximum developed step voltage calculated according to std. 80/2000 is lower than the step voltage calculated according to standard 80/1986 only when the ratio of sides is 1/3. This is the same as if the rods were placed at the center of the grid. The safety criteria are satisfied in all examined cases.

7. CONSIDERATIONS ON SAFETY MARGINS

For the same area of the grid and the same grid and mesh dimensions the calculated mesh voltage E_m with the new standard is equal to a percentage of the old one and the tolerable touch voltage $E_{touch,70}$ from the 80/1986 standard is 99% or smaller than $E_{touch,70}$ from the 80/2000 standard as it can be shown in fig.3. Thus the safety margin given by the new standard for the existing grounding arrangements is greater. If a model for linear dependence of Em on $L_M^{-0.6 \text{ to } -0.8}$ is adopted it will be possible to calculate the saving on conductor length needed to achieve the same safety criteria if the 80/2000 standard is used instead of 80/1986 standard.

7. CONCLUSIONS

In this paper a review of major AC substation grounding practices given in the IEEE international standards is presented with special reference to important considerations, differences and modifications. Comparisons are made for the portions where major changes occur. Examples are presented to show the effects of the changes on the design and analysis of power system grounding.

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Appendix I.

Results from calculations of square and orthogonal grids with sides ratio 1/3 to 4/5 where there are no ground rods or there are a few ground rods scattered throughout the grid, but none located in the corners or along the perimeter of the grid are shown in Table A.1.

Results from calculations of square and orthogonal grids with sides ratio 1/3 to 4/5 where there exist ground rods in the corners as well as along the perimeter and throughout the grid are shown in Table A.2.

For the parameters of the grids, that don't change throughout calculations, and are not shown in Tables A.1 and A.2 typical values are chosen i.e. diameter of the conductors of the grid is 0.01m, grid depth is 0.60m, and current to ground I_G is 15kA. Soil resistivity is 100Om. The duration of fault is taken equal to 0.5s, and the surface layer of gravel is of 0.10m thickness and 2500Om resistivity.

Table A.1: Results of calculations for grids without rods

				Em Calculation Parameters (80/2000)						Em Calculation Parameters (80/1986)						Es Calculation Parameters (80/2000)			Es Calculation Parameters (80/1986)					ANSI IEEE Std. 80/1986			ANSI IEEE Std. 80/2000		
Grid dimensions	Mesh	Length of horizontal conductors (m)	Total length of ground rods (m)	n	K_i	K_{ii}	L_M	K_m	E_m (V)	n	K_i	K_{ii}	L_M	K_m	E_m (V)	L_S	K_s	E_s (V)	L_S	K_s	n_s	K_i	E_s (V)	C_s	E Step,70	E Touch,70	C_s	E Step,70	E Touch,70
50x150m^2	10x10m	1700	0	9.134	1.996	0.529	1700	0.977	1719.6	9.798	2.341	0.545	1700	0.988	1999.1	1275	0.327	767.5	1700	0.327	16	3.408	983.7	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3200	0	17.193	3.189	0.663	3200	0.662	989.9	18.466	3.832	0.676	3200	0.652	1170.4	2400	0.386	768.8	3200	0.386	31	5.988	1082.8						
	2.5x2.5m	6200	0	33.312	5.574	0.777	6200	0.309	416.5	35.791	6.812	0.788	6200	0.297	489.9	4660	0.495	890.5	6200	0.495	61	11.148	1336.8						
	10x10m	1700	100	9.134	1.996	0.529	1800	0.977	1624.1	9.798	2.341	0.545	1800	0.988	1888.0	1360	0.327	718.5	1800	0.327	16	3.408	929.0						
	5x5m	3200	100	17.193	3.189	0.663	3300	0.662	959.9	18.466	3.832	0.676	3300	0.652	1135.0	2485	0.386	742.5	3300	0.386	31	5.988	1050.0						
	2.5x2.5m	6200	100	33.312	5.574	0.777	6300	0.309	409.8	35.791	6.812	0.788	6300	0.297	482.2	4736	0.495	874.5	6300	0.495	61	11.148	1314.6						
60x180m^2	10x10m	2400	0	10.746	2.234	0.566	2400	0.966	1334.7	11.533	2.640	0.580	2400	0.946	1561.2	1800	0.327	608.9	2400	0.327	19	3.924	802.5	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	4560	0	20.417	3.666	0.695	4560	0.636	787.2	21.932	4.428	0.708	4560	0.625	910.7	3420	0.386	620.2	4560	0.386	37	7.020	890.8						
	2.5x2.5m	8880	0	39.759	6.528	0.802	8880	0.280	309.2	42.720	8.004	0.812	8880	0.269	363.4	6660	0.495	728.2	8880	0.495	73	13.212	1105.3						
	10x10m	2400	100	10.746	2.234	0.566	2500	0.966	1281.3	11.533	2.640	0.580	2500	0.946	1498.8	1886	0.327	581.5	2500	0.327	19	3.924	770.2						
	5x5m	4560	100	20.417	3.666	0.695	4660	0.636	750.8	21.932	4.428	0.708	4660	0.625	891.2	3505	0.386	605.2	4660	0.386	37	7.020	871.7						
	2.5x2.5m	8880	100	39.759	6.528	0.802	8980	0.280	305.7	42.720	8.004	0.812	8980	0.269	359.4	6745	0.495	719.0	8980	0.495	73	13.212	1093.0						
60x100m^2	10x10m	1360	0	8.638	1.922	0.517	1360	0.983	2095.0	8.775	2.165	0.520	1360	0.981	2343.8	1020	0.327	923.9	1360	0.327	11	2.548	919.1	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	2560	0	16.260	3.051	0.652	2560	0.671	1198.6	16.523	3.498	0.665	2560	0.668	1389.5	1920	0.386	919.3	2560	0.386	21	4.268	964.7						
	2.5x2.5m	4960	0	31.504	5.307	0.769	4960	0.318	508.8	32.016	6.163	0.771	4960	0.316	597.4	3720	0.495	1058.7	4960	0.495	41	7.708	1154.5						
	10x10m	1360	100	8.638	1.922	0.517	1460	0.983	1942.2	8.775	2.165	0.520	1460	0.981	2183.3	1105	0.327	852.8	1460	0.327	11	2.548	856.2						
	5x5m	2560	100	16.260	3.051	0.652	2660	0.671	1153.5	16.523	3.498	0.665	2660	0.668	1318.0	2005	0.386	880.4	2660	0.386	21	4.268	928.4						
	2.5x2.5m	4960	100	31.504	5.307	0.769	5060	0.318	499.8	32.016	6.163	0.771	5060	0.316	575.8	3805	0.495	1036.1	5060	0.495	41	7.708	1131.7						
72x120m^2	8x8m	2352	0	12.449	2.486	0.597	2352	0.864	1369.6	12.649	2.832	0.600	2352	0.861	1555.8	1764	0.342	723.2	2352	0.342	16	3.408	743.5	0.702	2560.0	806.5	0.667	2443.5	777.4
	6x6m	3072	0	16.260	3.051	0.652	3072	0.731	1089.3	16.523	3.498	0.665	3072	0.729	1245.0	2304	0.367	727.8	3072	0.367	21	4.268	763.9						
	3x3m	5952	0	31.504	5.307	0.769	5952	0.389	519.7	32.016	6.163	0.771	5952	0.386	595.5	4464	0.460	818.9	5952	0.460	41	7.708	893.1						
	8x8m	2352	100	12.449	2.486	0.597	2452	0.864	1313.8	12.649	2.832	0.600	2452	0.861	1492.3	1849	0.342	689.9	2452	0.342	16	3.408	713.1						
	6x6m	3072	100	16.260	3.051	0.652	3172	0.731	1055.0	16.523	3.498	0.665	3172	0.729	1205.8	2389	0.367	702.0	3172	0.367	21	4.268	739.8						
	3x3m	5952	100	31.504	5.307	0.769	6052	0.389	511.1	32.016	6.163	0.771	6052	0.386	585.6	4549	0.460	804.5	6052	0.460	41	7.708	878.4						
80x100m^2	10x10m	1780	0	9.920	2.112	0.548	1780	0.966	1719.6	9.960	2.367	0.548	1780	0.966	1926.6	1336	0.327	776.0	1780	0.327	11	2.548	702.3	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3380	0	18.836	3.432	0.680	3380	0.649	987.7	18.894	3.906	0.681	3380	0.648	1123.4	2535	0.386	783.3	3380	0.386	21	4.268	730.7						
	2.5x2.5m	6580	0	36.669	6.071	0.791	6580	0.293	406.0	36.783	6.983	0.792	6580	0.293	466.2	4936	0.495	913.9	6580	0.495	41	7.708	870.2						
	10x10m	1780	100	9.920	2.112	0.548	1880	0.966	1628.1	9.960	2.367	0.548	1880	0.966	1824.2	1420	0.327	728.5	1880	0.327	11	2.548	664.9						
	5x5m	3380	100	18.836	3.432	0.680	3480	0.649	959.4	18.894	3.906	0.681	3480	0.648	1091.1	2620	0.386	757.9	3480	0.386	21	4.268	709.7						
	2.5x2.5m	6580	100	36.669	6.071	0.791	6680	0.293	400.0	36.783	6.983	0.792	6680	0.293	459.2	5020	0.495	898.4	6680	0.495	41	7.708	857.2						
96x120m2	8x8m	3096	0	14.378	2.772	0.627	3096	0.843	1132.7	14.422	3.137	0.627	3096	0.843	1281.1	2322	0.342	612.5	3096	0.342	16	3.408	564.8	0.702	2560.0	806.5	0.667	2443.5	777.4
	6x6m	4056	0	18.836	3.432	0.680	4056	0.709	900.2	18.894	3.906	0.681	4056	0.709	1023.8	3042	0.367	620.3	4056	0.367	21	4.268	576.5						
	3x3m	7896	0	36.669	6.071	0.791	7896	0.364	420.1	36.783	6.983	0.792	7896	0.364	482.5	5922	0.460	707.0	7896	0.460	41	7.708	673.3						
	8x8m	3096	100	14.378	2.772	0.627	3196	0.843	1097.3	14.422	3.137	0.627	3196	0.843	1241.0	2407	0.342	590.8	3196	0.342	16	3.408	547.1						
	6x6m	4056	100	18.836	3.432	0.680	4156	0.709	878.5	18.894	3.906	0.681	4156	0.709	999.3	3127	0.367	603.4	4156	0.367	21	4.268	564.8						
	3x3m	7896	100	36.669	6.071	0.791	7996	0.364	414.6	36.783	6.983	0.792	7996	0.364	476.5	6007	0.460	697.0	7996	0.460	41	7.708	664.5						
90x90m^2	10x10m	1800	0	10.000	2.124	0.549	1800	0.965	1708.2	10.000	2.376	0.549	1800	0.965	1910.9	1350	0.327	771.7	1800	0.327	10	2.376	647.4	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3420	0	19.000	3.466	0.682	3420	0.647	981.1	19.000	3.924	0.682	3420	0.647	1114.0	2565	0.386	779.6	3420	0.386	19	3.924	663.9						
	2.5x2.5m	6660	0	37.000	6.120	0.792	6660	0.292	402.4	37.000	7.020	0.792	6660	0.292	461.6	4995	0.495	910.2	6660	0.495	37	7.020	783.1						
	10x10m	1800	100	10.000	2.124	0.549	1900	0.965	1618.3	10.000	2.376	0.549	1900	0.965	1810.3	1435	0.327	726.0	1900	0.327	10	2.376	613.4						
	5x5m	3420	100	19.000	3.466	0.682	3520	0.647	953.2	19.000	3.924	0.682	3520	0.647	1082.3	2650	0.386	754.8	3520	0.386	19	3.924	645.1						
	2.5x2.5m	6660	100	37.000	6.120	0.792	6760	0.292	396.5	37.000	7.020	0.792	6760	0.292	454.8	5080	0.495	895.0	6760	0.495	37	7.020	771.5						
100x100m^2	10x10m	2200	0	11.000	2.272	0.570	2200	0.953	1475.8	11.000	2.548	0.570	2200	0.953	1655.0	1650	0.327	675.5	2200	0.327	11	2.548	558.2	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	4200	0	21.000	3.752	0.700	4200	0.632	846.8	21.000	4.268	0.700	4200	0.632	963.2	3150	0.386	689.2	4200	0.386	21	4.268	588.0						
	2.5x2.5m	8200	0	41.000	6.712	0.807	8200	0.276	338.2	41.000	7.708	0.807	8200	0.276	388.3	6150	0.495	810.8	8200	0.495	41	7.708	698.3						
	10x10m	2200	100	11.000	2.272	0.570	2300	0.953	1411.8	11.000	2.548	0.570	2300	0.953	1583.1	1735	0.327	642.4	2300	0.327	11	2.548	543.5						
	5x5m	4200	100	21.000	3.752	0.700	4300	0.632	827.1	21.000	4.268	0.700	4300	0.632	940.8	3235	0.386	671.1	4300	0.386	21	4.268	574.3						
	2.5x2.5m	8200	100	41.000	6.712	0.807	8300	0.276	334.1	41.000	7.708	0.807	8300	0.276	383.7	6235	0.495	798.7	8300	0.495	41	7.708	689.9						

Table A.2: Results of calculations for grids with rods

				Em Calculation Parameters (80/2000)						Em Calculation Parameters (80/1986)						Es Calculation Parameters (80/2000)			Es Calculation Parameters (80/1986)					ANSI IEEE Std. 80/2000			ANSI IEEE Std. 80/1986		
Grid dimensions	Mesh	Length of horizontal conductors (m)	Total length of ground rods (m)	n	K_i	K_{ii}	L_M	K_m	E_m (V)	n	K_i	K_{ii}	L_M	K_m	E_m (V)	L_S	K_s	E_s (V)	L_S	K_s	n	K_i	E_s (V)	C_s	E Step,70	E Touch,70	C_s	E Step,70	E Touch,70
50x150m^2	10x10m	1700	100	9.134	1.996	1	1857.3	0.885	1427.1	9.798	2.341	1	1815	0.854	1652.1	1360	0.327	719.8	1815	0.327	16	3.408	921.3	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3200	100	17.193	3.189	1	3357.3	0.606	861.3	18.466	3.832	1	3315	0.644	943.0	2485	0.386	742.6	3315	0.386	31	5.988	1045.2						
	2.5x2.5m	6200	100	33.312	5.574	1	6357.3	0.361	461.9	35.791	6.812	1	6315	0.309	337.4	4735	0.495	874.6	6315	0.495	61	11.148	1311.4						
	10x10m	1700	200	9.134	1.996	1	2014.6	0.885	1315.7	9.798	2.341	1	1930	0.854	1553.7	1445	0.327	677.2	1930	0.327	16	3.408	888.4						
	5x5m	3200	200	17.193	3.189	1	3514.6	0.606	822.8	18.466	3.832	1	3430	0.644	911.4	2570	0.386	717.8	3430	0.386	31	5.988	1010.2						
	2.5x2.5m	6200	200	33.312	5.574	1	6514.6	0.361	450.7	35.791	6.812	1	6430	0.309	331.4	4820	0.495	659.1	6430	0.495	61	11.148	1288.0						
60x180m^2	10x10m	2400	100	10.746	2.234	1	2556.9	0.864	1132.3	11.533	2.640	1	2515	0.832	1310.3	1886	0.327	551.6	2515	0.327	19	3.924	765.6	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	4560	100	20.417	3.666	1	4716.9	0.582	676.9	21.932	4.428	1	4675	0.622	741.1	3505	0.386	605.2	4675	0.386	37	7.020	868.9						
	2.5x2.5m	8880	100	39.759	6.528	1	9036.9	0.329	356.1	42.720	8.004	1	8995	0.186	248.2	6745	0.495	719.0	8995	0.495	73	13.212	1091.2						
	10x10m	2400	200	10.746	2.234	1	2713.9	0.864	1068.8	11.533	2.640	1	2630	0.832	1253.0	1970	0.327	556.4	2630	0.327	19	3.924	732.1						
	5x5m	4560	200	20.417	3.666	1	4873.9	0.582	667.0	21.932	4.428	1	4790	0.622	723.3	3590	0.386	590.8	4790	0.386	37	7.020	848.0						
	2.5x2.5m	8880	200	39.759	6.528	1	9193.9	0.329	350.0	42.720	8.004	1	9110	0.186	245.1	6830	0.495	710.1	9110	0.495	73	13.212	1077.4						
60x100m^2	10x10m	1360	100	8.638	1.922	1	1518.1	0.893	1686.9	8.775	2.165	1	1475	0.868	1912.4	1106	0.327	652.8	1475	0.327	11	2.548	847.5	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	2560	100	16.260	3.051	1	2718.1	0.612	1030.0	16.523	3.498	1	2675	0.655	1094.9	2005	0.386	660.4	2675	0.386	21	4.268	923.2						
	2.5x2.5m	4960	100	31.504	5.307	1	5118.1	0.358	557.3	32.016	6.163	1	5075	0.223	406.8	3806	0.495	1036.1	5075	0.495	41	7.708	1128.3						
	10x10m	1360	200	8.638	1.922	1	1676.3	0.893	1535.9	8.775	2.165	1	1590	0.868	1774.1	1190	0.327	791.9	1590	0.327	11	2.548	786.2						
	5x5m	2560	200	16.260	3.051	1	2876.3	0.612	973.4	16.523	3.498	1	2790	0.655	1049.8	2090	0.386	844.6	2790	0.386	21	4.268	885.2						
	2.5x2.5m	4960	200	31.504	5.307	1	5276.3	0.358	540.6	32.016	6.163	1	5190	0.223	306.8	3890	0.495	1013.4	5190	0.495	41	7.708	1103.3						
72x120m^2	8x8m	2352	100	12.449	2.486	1	2509.6	0.779	1157.8	12.649	2.832	1	2467	0.748	1287.8	1849	0.342	689.9	2467	0.342	16	3.408	708.8	0.702	2560.0	806.5	0.667	2443.5	777.4
	6x6m	3072	100	16.260	3.051	1	3229.6	0.662	937.9	16.523	3.498	1	3187	0.619	1019.0	2389	0.367	702.0	3187	0.367	21	4.268	736.3						
	3x3m	5952	100	31.504	5.307	1	6109.6	0.398	518.7	32.016	6.163	1	6067	0.294	447.4	4549	0.460	804.5	6067	0.460	41	7.708	876.2						
	8x8m	2352	200	12.449	2.486	1	2667.2	0.779	1088.2	12.649	2.832	1	2582	0.748	1230.4	1934	0.342	659.6	2582	0.342	16	3.408	677.2						
	6x6m	3072	200	16.260	3.051	1	3387.2	0.662	894.3	16.523	3.498	1	3302	0.619	983.5	2474	0.367	677.9	3302	0.367	21	4.268	710.7						
	3x3m	5952	200	31.504	5.307	1	6267.2	0.398	505.7	32.016	6.163	1	6182	0.294	439.0	4634	0.460	789.8	6182	0.460	41	7.708	858.9						
80x100m^2	10x10m	1780	100	9.920	2.112	1	1937.9	0.874	1429.6	9.960	2.367	1	1895	0.852	1596.2	1420	0.327	729.6	1895	0.327	11	2.548	668.5	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3380	100	18.836	3.432	1	3537.9	0.593	862.5	18.894	3.906	1	3495	0.541	906.6	2620	0.386	757.9	3495	0.386	21	4.268	706.6						
	2.5x2.5m	6580	100	36.669	6.071	1	6737.9	0.339	458.1	36.783	6.983	1	6695	0.205	320.8	5020	0.495	898.4	6695	0.495	41	7.708	855.3						
	10x10m	1780	200	9.920	2.112	1	2095.7	0.874	1321.9	9.960	2.367	1	2010	0.852	1504.9	1505	0.327	688.3	2010	0.327	11	2.548	621.9						
	5x5m	3380	200	18.836	3.432	1	3695.7	0.593	825.7	18.894	3.906	1	3610	0.541	877.8	2705	0.386	734.1	3610	0.386	21	4.268	684.1						
	2.5x2.5m	6580	200	36.669	6.071	1	6895.7	0.339	447.6	36.783	6.983	1	6810	0.205	315.4	5105	0.495	883.6	6810	0.495	41	7.708	840.9						
96x120m2	8x8m	3096	100	14.378	2.772	1	3253.4	0.760	971.4	14.422	3.137	1	3211	0.731	1070.8	2407	0.342	590.9	3211	0.342	16	3.408	544.6	0.702	2560.0	806.5	0.667	2443.5	777.4
	6x6m	4056	100	18.836	3.432	1	4213.4	0.643	785.5	18.894	3.906	1	4171	0.602	845.0	3127	0.367	603.4	4171	0.367	21	4.268	562.6						
	3x3m	7896	100	36.669	6.071	1	8053.4	0.379	428.3	36.783	6.983	1	8011	0.276	360.7	6007	0.460	697.0	8011	0.460	41	7.708	683.6						
	8x8m	3096	200	14.378	2.772	1	3410.8	0.760	926.6	14.422	3.137	1	3326	0.731	1033.8	2492	0.342	570.7	3326	0.342	16	3.408	525.7						
	6x6m	4056	200	18.836	3.432	1	4370.8	0.643	757.2	18.894	3.906	1	4286	0.602	822.3	3212	0.367	587.4	4286	0.367	21	4.268	547.5						
	3x3m	7896	200	36.669	6.071	1	8210.8	0.379	420.1	36.783	6.983	1	8126	0.276	355.6	6092	0.460	687.3	8126	0.460	41	7.708	664.2						
90x90m^2	10x10m	1800	100	10.000	2.124	1	1957.9	0.873	1421.2	10.000	2.376	1	1915	0.851	1584.0	1436	0.327	726.0	1915	0.327	10	2.376	608.6	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	3420	100	19.000	3.466	1	3577.9	0.592	867.3	19.000	3.924	1	3535	0.540	899.4	2650	0.386	754.6	3535	0.386	19	3.924	642.3						
	2.5x2.5m	6660	100	37.000	6.120	1	6817.9	0.338	454.8	37.000	7.020	1	6775	0.204	317.5	5080	0.495	895.0	6775	0.495	37	7.020	769.8						
	10x10m	1800	200	10.000	2.124	1	2115.8	0.873	1315.1	10.000	2.376	1	2030	0.851	1494.3	1520	0.327	685.4	2030	0.327	10	2.376	574.1						
	5x5m	3420	200	19.000	3.466	1	3735.8	0.592	821.1	19.000	3.924	1	3650	0.540	871.0	2735	0.386	731.2	3650	0.386	19	3.924	622.1						
	2.5x2.5m	6660	200	37.000	6.120	1	6975.8	0.338	444.5	37.000	7.020	1	6890	0.204	312.2	5165	0.495	880.3	6890	0.495	37	7.020	756.9						
100x100m^2	10x10m	2200	100	11.000	2.272	1	2357.6	0.861	1244.3	11.000	2.548	1	2315	0.839	1384.4	1736	0.327	642.4	2315	0.327	11	2.548	540.0	0.702	2560.0	806.5	0.667	2443.5	777.4
	5x5m	4200	100	21.000	3.752	1	4357.6	0.579	747.5	21.000	4.268	1	4315	0.527	792.2	3236	0.386	671.1	4315	0.386	21	4.268	572.3						
	2.5x2.5m	8200	100	41.000	6.712	1	8357.6	0.326	391.2	41.000	7.708	1	8315	0.191	265.9	6236	0.495	720.7	8315	0.495	41	7.708	688.7						
	10x10m	2200	200	11.000	2.272	1	2515.2	0.861	1166.3	11.000	2.548	1	2430	0.839	1318.9	1820	0.327	612.4	2430	0.327	11	2.548	514.4						
	5x5m	4200	200	21.000	3.752	1	4515.2	0.579	721.4	21.000	4.268	1	4430	0.527	761.9	3320	0.386	653.9	4430	0.386	21	4.268	557.5						
	2.5x2.5m	8200	200	41.000	6.712	1	8515.2	0.326	383.9	41.000	7.708	1	8430	0.191	262.3	6320	0.495	709.0	8430	0.495	41	7.708	679.3						