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A METHOD FOR ESTIMATING THE PROBABLE 1-HOUR RAINFALL BASED ON TIME CONCENTRATION OF HEAVY RAINFALL

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SYNOPSIS

A method for estimating the probable 1-hour rainfall based on time concentration of heavy rainfall is proposed. The method makes use of the Slade type III normal transformation approach and estimates are obtained from the frequency analysis of time concentration of heavy rainfall. By knowing how heavy rainfalls are concentrated, it would be possible to select a suitable type of 1-hour rainfall to be used for the design of hydraulic structures. Although the present work focuses on 1-hour rainfall, the procedure presented herein can easily be used for a wide range of rainfall duration.

INTRODUCTION

In planning and designing hydraulic structures that control storm runoff and floods, such as storm sewers, highway culverts, and dams for a region, a judicious selection of design rainfall is one of the serious problems confronting the design engineers. It should be recognized that design rainfall is of utmost importance because it has a great influence on the safety and economy of a project. Generally, the design rainfall is estimated by two methods. First method is a statistical approach (5), in which, estimates are obtained from the frequency analysis of the rainfall data observed within an area. The second method is a theoretical method similar to that developed by Nagao (10), Etoh and Murota (2) and Hashino (4). The first method is more simple and practical than the second one, and is commonly used to analyze rainfall data for formulating a regional development plan. However, it sometimes yields an overestimate. For example, the exceedance probability of 1 / 50 or 1 / 100 for 1-hour rainfall is estimated to be 200 mm or more. These estimates are clearly excessive and irrational. In earlier studies, one of the authors has investigated time and spatial concentration of heavy rainfalls (8), (9). The aims of the present study are to propose a method based on the previous investigation, which is convenient and practical for estimating the probable 1-hour rainfall, and to evaluate the exceedance probability of time concentration of rainfall which remains uncertain.

LOCALIZED HEAVY RAINFALL "SHUCHU GŌU"

The Japanese localized heavy rainfall called "shuchu gōu" is a phrase usually encountered in a mass communication. This phrase is composed of several concepts and a precise definition is hard to provide. According to Ninomiya (12), a rainfall is classified to be heavy when one-day rainfall is equal to or greater than 10% of the annual rainfall. If it occurs, flooding would be extensive and damages would be serious. In southern and western Japan, one-day rainfall is as much as 200 mm, while in the northern and eastern part it is only 100 mm. Thus, although the definition of a heavy rainfall is ambiguous, at least some definitions exist. The authors agree to the above definition that the rainfall equal to or greater than 10% of the annual rainfall in 24 hours is a heavy rainfall. However, It is necessary to consider the amount and concentration of rainfall for a localized heavy rainfall. The concentration of rainfall involves two concepts, i.e., time and spatial concentrations. The time concentration describes how rainfalls are distributed temporally, while the spatial concentration describes how rainfalls are distributed spatially. Localized heavy rainfall, therefore, is a phrase that encompasses three concepts, i.e., amount of rainfall, time and spatial concentrations of rainfall. Unfortunately, time and spatial concentrations cannot be expressed together. If these two kinds of concentration are defined quantitatively, it will be useful to compare different patterns of rainfall. In this study, we assume 24 hours as the duration of a localized heavy rainfall event and the time concentration of rainfall, C is expressed as follows (8);

$$C = \log_{10}(r_1 / r_{24}) / \log_{10}(24) \quad (1)$$

$$r_1 = R_1 / 1; \quad r_{24} = R_{24} / 24$$

where r_1 and r_{24} are 1-hour and 24-hour average rainfall intensities in mm / hour, respectively. R_{24} = annual maximum rainfall occurring during any 24-hour duration. R_1 = the largest 1-hour rainfall contained in R_{24}.

As shown in Fig. 1, the value of C must be between 0 and 1.0. If the rainfall intensity is distributed uniformly during 24 hours, C is equal to 0. In contrast, when the rainfall is concentrated in one hour, C is equal to 1.0. Fig. 1a is the extreme case in which C is equal to 1.0, and Fig. 1b shows a case that is most common in Japan. Fig. 1c, on the other hand, shows an opposite extreme case in which C is equal to 0. Although it is possible to define and treat the spatial concentration in a similar way as C, it was not considered in this study.

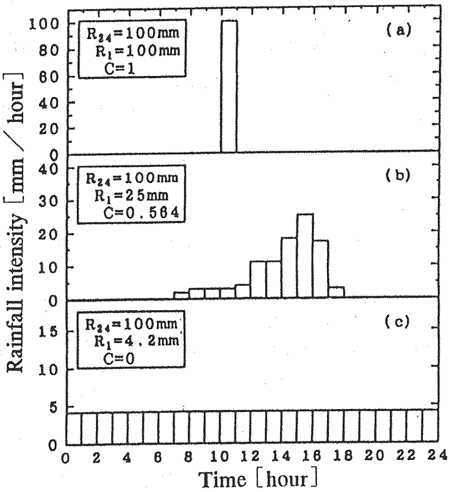

Fig. 1 Samples of special hyetograph representing the time concentration (C).

In Japan, the maximum rainfall in one hour was observed in Nagayo cho, Nagasaki Prefecture in July, 1982 where R_1 = 187 mm with R_{24} = 541 mm (3), (13). This event was not officially observed by the Japan Meteorological Agency. But the rainfall of R_1 = 187 mm cannot be regarded as excessive. This is because in the same prefecture, other unusual rainfall events were also observed in Oseto cho Kobutsu branch school where R_1 = 177 mm with R_{24} = 424 mm, and in Sotomi cho where R_1 = 154 mm followed by 132 mm with R_{24} = 459 mm. The degree of C of these rainfalls are calculated as 0.666 and 0.725 in Nagayo cho and Oseto cho Kobutsu branch school, respectively. It is natural that the degree of C of the former rainfall be considered to be greater than that of the latter because of larger R_1. However, the values of C showed an opposite result. There are many cases that the degree of C is equal to or nearly 1.0 for light rainfalls, but it has practically no significance except for heavy rainfalls.

DATA SOURCES AND DISTRIBUTION CHARACTERISTICS OF C

Annual maximum records of R_{24} were extracted from the hourly observed rainfall data collected from about 206 meteorological observatories selected throughout the country with a total of 8546 station-years. The data sources are the Japan Meteorological Agency-193 stations, 1953-1982, Shikoku-13 stations, 1953-1982 (14), and AMeDAS-137 stations, 1983-1992 (6). Daily maximum rainfalls published by the Japan Meteorological Agency (7) are often different from the maximum R_{24} used in this analysis. The maximum R_1 in a year presented in a tabular form were not always contained in the data of daily maximum rainfalls.

Fig. 2 shows a relationship between C and R_{24} which indicates some characteristics of Eq. 1. This figure also shows that plots of C are scattered apart from the upper limit 1.0 for R_{24} greater than 150 mm. It can be attributed to the fact that the maximum record of 1-hour rainfall in Japan is 187 mm in Nagayo cho, and 150 mm as observed by the National Astronomical Observatory (11). The distribution of C is approximately uniform between 0 and 1.0 for only R_{24} less than 100 mm. These characteristics of C constitute important factors in estimating the probable value of R_1 and emphasize that a prudent consideration is necessary in order to avoid excessive estimates.

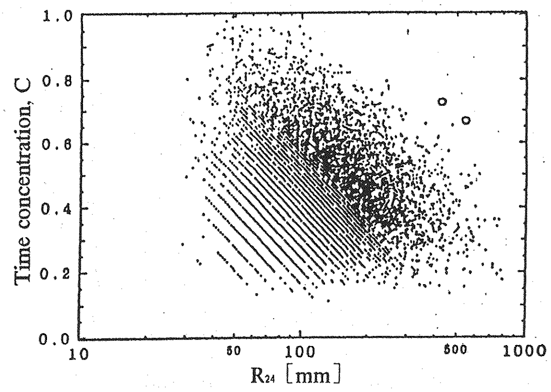

Fig. 2 Distribution of the time concentration (C) against R_{24}.

FREQUENCY DISTRIBUTION AND THE NORMAL TRANSFORMATION OF C

The frequency distribution of C was analyzed according to the value of R_{24} because the distribution of C is not homogeneous against R_{24}.

Fig. 3 shows the relative frequency histogram of C with given R_{24} (100, 200, 300 and 400 mm±5%). The numbers of the data are 706, 394, 132 and 62, respectively. The number of class interval was determined by the Eq. 2 (1)

$$k = 5 \log_{10}(N) \quad (2)$$

where k = number of class intervals; and N = number of data.

As illustrated in Fig. 2, the values of C range from 0 to 1.0 for $R_{24} \leqq 100$ mm. But its range becomes narrower and the average of C decreases with the increase in R_{24}. Therefore in this analysis, C was transformed into normal variable using the Slade type Ⅲ (5) normal transformation as shown below;

$$\xi = \alpha \log_{10}\left(\frac{C}{C_0}\right)\left(\frac{1-C_0}{1-C}\right) \quad (3)$$

where ξ = normal variable; α = fitting parameter to simulate a normal distribution and C_0 = numerical constant obtained when the average of ξ is equal to 0.

The value of α was determined by the least squares method such that the cumulative frequency plots of ξ follow a normal distribution on the normal paper. Assuming an average value of ξ to be 0, Eqs. 4 and 5 were derived to compute C_0.

$$\log_{10}(C_0') = -\left(\sum_{i=1}^{N} \log_{10}\left(\frac{C_i}{1-C_i}\right)\right) / N \quad (4)$$

$$C_0 = 1 / (C_0'+1) \quad (5)$$

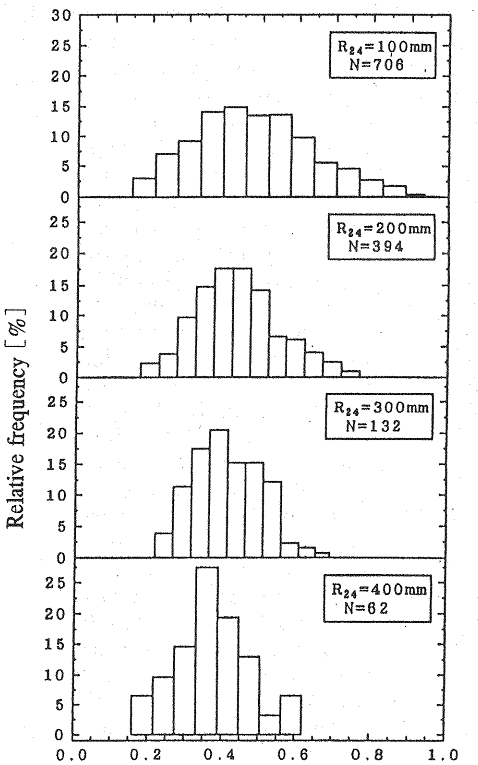

Fig. 3 Relative frequency histogram of C for R_{24} = 100 ~ 400 mm.

Fig. 4 presents a cumulative distribution of C transformed into a normal variable ξ which fits closely to a normal distribution when R_{24} is 200, 300 and 400 mm. For R_{24} greater than 400 mm, the transformed values also agree with a normal distribution even if the number of data is scarce. When $R_{24} \leqq 100$ mm, the fitting shows a concave shape distribution which has a greater deviation at the upper and lower ends of the scale. Thus, the probable values of the transformed variables are underestimated. To improve the fitness, the Slade type Ⅲ transformation was applied to C^2 as given in Eq. 6. Thus, the fitting was improved significantly as shown in Fig. 5.

$$\zeta = \beta \log_{10}\left(\frac{C^2}{C_0^2} \cdot \frac{C_M^2 - C_0^2}{C_M^2 - C^2}\right) \quad (6)$$

where C_M^2 = upper limit of C^2 and varies according to the value of R_{24} but $C_M^2 \leqq 1.0$; ζ and β = the same definition as ξ and α in Eq. 3, respectively.

The authors made C_M hold the nature of C. In Fig. 2, the abscissa in C = 0 represents R_{24}. On the other hand, the abscissa in C = 1.0 represents R_{24} = R_1. Accordingly, the abscissa in C = 1.0 represents R_1. C = 1.0 is the upper limit value of the distribution of C but when R_{24} is greater than 100 mm, the distribution of C departs from 1.0. The upper limit value of C must be less than 1.0 to successfully transform C to normal variables. The intersection of the abscissa in C = 1.0 and the line representing the upper limit of C is defined as the hypothetical R_1. Of course, the result when setting the upper limit to 1.0 and the result without restricting to one are a little different.

The values of fitting parameter, β were obtained by the least squares method, applying Eq. 6 to the data of R_{24} = 40 to 640 mm (± 5%included).

Fig. 6 shows the relationship between the gradient of the line representing β and R_1 corresponding to R_1 = 160 to 400 mm and R_{24} = 160 to 640mm. As it is apparent from Fig. 6 that the gradient of β varies with the value of R_1, i.e., the gradient is negative when R_1 < 300 mm and it becomes positive as R_1 > 300 mm. When R_1 = 300 mm, the gradient is almost 0. Also, it was found that the transformation of C fits closely to normal variable when R_1 = 300 mm. Thus, it was assumed that the maximum hypothetical R_1 = 300 mm. Consequently, the upper limit C_M of the transformation equation becomes as follows:

$$C_M^2 = \log_{10}(300 \cdot 24 / R_{24}) / \log_{10}(24)$$

$$\text{for } R_{24} \geqq 300 \text{ mm} \quad (7.1)$$

$$C_M = 1.0$$

$$\text{for } R_{24} \leqq 300 \text{ mm} \quad (7.2)$$

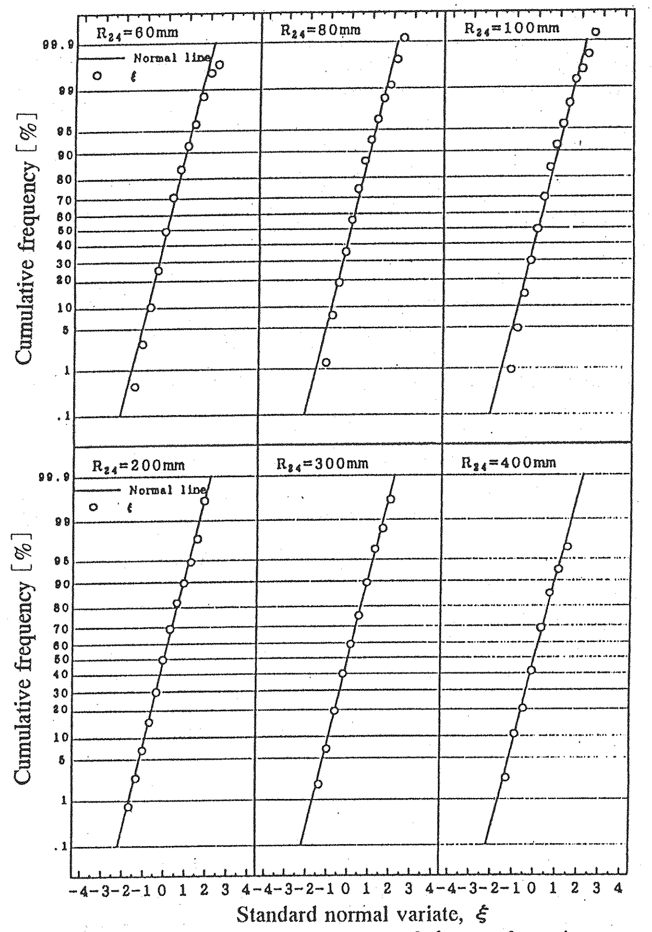

Fig. 4 Cumulative frequency of ξ, transformed by the Slade type Ⅲ equation.

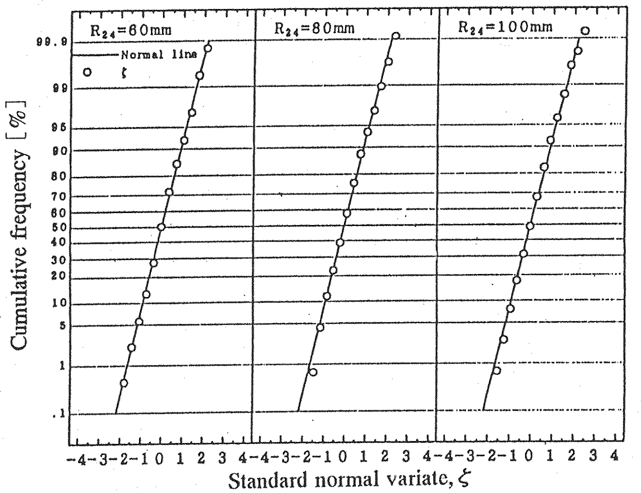

Fig. 5 Cumulative frequency of ζ, transformed by the Slade type Ⅲ equation.

Fig. 7 shows the relationships between β, C_0^2 and R_{24} which were derived by using Eq. 6 as a transformation equation. When $R_{24} < 300$ mm, the distribution of β was approximated by a straight line with positive gradient. The values of β are apparently scattered when R_{24} is greater than 300 mm. However, it is found that the value of β increases when $R_{24} \leqq 300$ mm, and becomes constant when $R_{24} \geqq 300$ mm on the semi-logarithmic paper. C_0^2 was assumed to be explained by a straight line on the same paper. The relationships obtained are expressed by the following equations:

$$\beta = 1.2 \log_{10}(R_{24}) - 0.643 \pm \Delta\beta \quad \text{for } R_{24} \leqq 300 \text{ mm} \tag{8.1}$$

$$\beta = 2.35 \pm \Delta\beta \quad \text{for } R_{24} \geqq 300 \text{ mm} \tag{8.2}$$

$$C_0^2 = -0.142 \log_{10}(R_{24}) + 0.506 \pm \Delta C_0^2 \tag{9}$$

where $\Delta\beta$ and ΔC_0^2 = estimation errors.

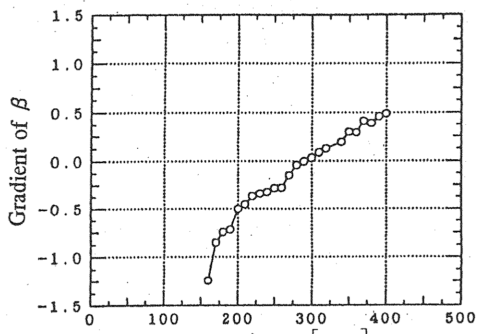

Fig. 6 Relationshp between the gradient of β and the hypothetical R_1

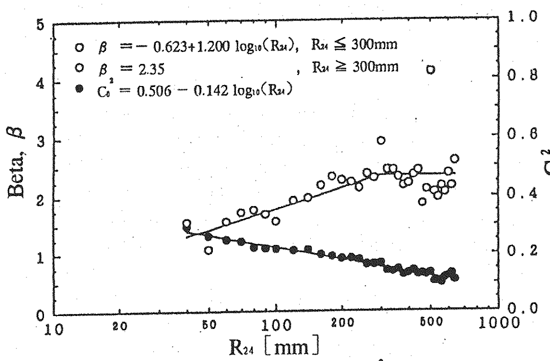

Fig. 7 Relationships between β, C_0^2 and R_{24} (the hypothetical R_1 = 300 mm).

PROBABILITY DISTRIBUTION OF C

It was found out that C^2 was successfully transformed to normal variable ζ by Eq. 6. And the three parameters in Eq. 6 were obtained as Eqs. 7, 8 and 9 which are expressed as function of R_{24}. Using these relationships, we can estimate the probability of C for any R_{24}.

Fig. 8 depicts the lines of the maximum and selected exceedance probabilities (1 / 2, 1 / 1, 1 / 25, 1 / 100, 1 / 1000) within the range of R_{24} = 40 ~ 640 mm. The lines for each exceedance probability change their gradients significantly at R_{24} = 300 mm, i.e., the point where the upper limit of the transformation is changed from Eq. 7.1 for $R_{24} \geqq 300$ mm to Eq. 7.2 for $R_{24} \leqq 300$ mm. It suggests that the probability estimation of C varies with the value of C_M.

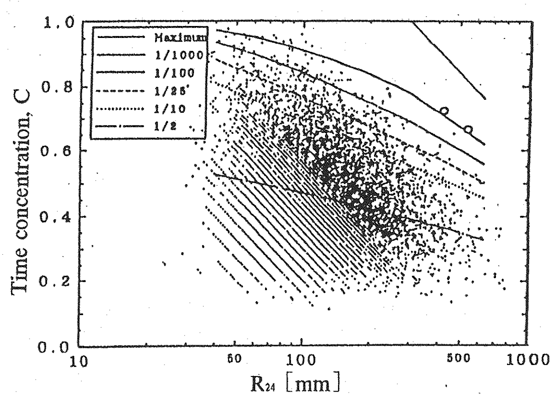

Fig. 8 Distribution of the probability estimation of the time concentration (C) against R_1.

Although it is possible to extrapolate the exceedance probability lines, they are limited because it is extremely risky to extrapolate especially for larger R_{24} due to the scarcity of data. In Fig. 8, some values of C are distributed over the lines of 1 / 100 and 1 / 1000 exceedance probability. This is because C_M hold the physical limit of C. In other word, because C_M must be set to 1.0 when $R_{24} \leqq 300$ mm, the estimated values of exceedance probability seem to be underestimated. The result in such a range is not so important but must be improved in the future.

From Fig. 8, it is possible to estimate the exceedance probability of C for the record breaking rainfalls. The exceedance probability of C = 0.666 for Nagayo cho, Nagasaki Prefecture is estimated to be 1 ／ 1564 and that for Oseto cho Kobutsu branch school having C = 0.725 is almost 1 ／ 1961.

EXCEEDANCE PROBABILITY OF 1-HOUR RAINFALL

There are four fundamental steps for estimating the probable 1-hour rainfall. Firstly, the exceedance probability and amount of R_{24} must be given. Secondly, the values of C_M^2, β and C_0^2 are computed using Eqs. 7, 8 and 9, respectively. Thirdly, the values of ξ are substituted into Eq. 6 to determine C. Finally, the probable 1-hour rainfall is estimated by substituting the value of C into Eq. 1. The lines in Fig. 9 show the result of estimated exceedance probability of 1-hour rainfall corresponding to R_{24}. The two open circles in Fig. 9 indicate the two extraordinary rainfall events observed in Nagasaki prefecture. Because R_1 depends on R_{24}, it seems better to treat R_1 and R_{24} together. In this study, R_1 is paired with R_{24} in accordance with the definition mentioned earlier. Accordingly, the exceedance probability of R_1 varies with the value of R_{24}.

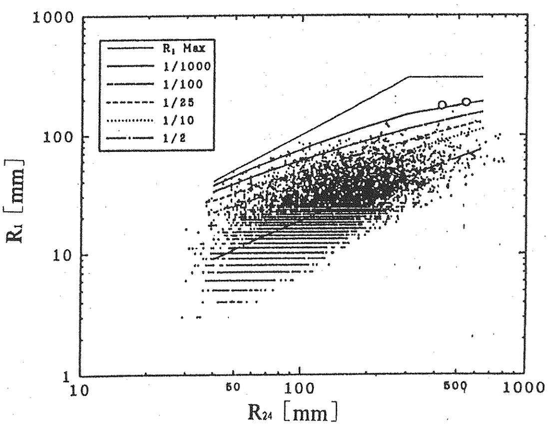

Fig. 9 Distribution of the probability estimation of R_1 against R_{24}.

The data used in this analysis are mostly obtained from the Japan Meteorological Agency except for some data of Shikoku Island. If more heavy rainfall data are added such as the Typhoon 7505 or the unusual heavy rainfall event that occurred in July, 1982 (not officially observed by the Japan Meteorological Agency), it is expected that larger R_{24} values will be extracted.

CONCLUSION

In this study, we focused the method for estimating the probable 1-hour rainfall based on C. It was found that the proposed method is relatively convenient and practical. Using this method, it was demonstrated that it is possible to evaluate some level of exceedance probability of C. Based on the present result, it can be concluded that probable 1-hour rainfall greater than 200 mm is an excessive estimate for exceedance probability of 1 ／ 50 or 1 ／ 100. Since R_1 depends on R_{24}, it seems better to treat R_1 and R_{24} together.

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APPENDIX – NOTATION

The following symbols are used in this paper:

C = time concentration of rainfall;
R_{24} = annual maximum 24-hour rainfall;
R_1 = largest 1-hour rainfall in R_{24};
r_{24} = 24-hour average rainfall intensity;
r_1 = 1-hour rainfall intensity;
k = number of class intervals;
N = number of data;
ξ = normal variable;
α = fitting parameter;
C_0 = numerical constant obtained when the average of ξ is equal to 0;
C_0' = numerical constant;
C_i = ith data of C;
ζ = normal variable;
β = fitting parameter;
C^2 = square of C;
C_M = upper limit of C;
C_M^2 = square of C_M;
C_0^2 = square of C_0;
$\Delta\beta$ = estimation error of β ; and
ΔC_0^2 = estimation error of C_0^2.

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