A Method of Estimating Settlement by Roller Compaction

Méthode de Calcul du Tassement à Attendre d'un Compactage au Rouleau

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Summary

A method of estimation of settlement in field compaction is presented. It depends upon the performance of confined compression tests in the laboratory which give the compression characteristics of soil. Calculation, by Fröhlich's equation, of the stress distribution in a fill induced by a roller combined with these results gives the wanted estimation of the settlement. The settlement which has already been attained by N passages can be estimated by Sasaki's formula.

Sommaire

Cette communication présente une méthode de calcul des tassements à attendre du compactage sur un chantier. Elle comporte tout d'abord l'exécution en laboratoire de l'essai de compression du sol dans une enceinte rigide; on en déduit les caractéristiques de compression des sols.

En combinant ces résultats, avec le calcul des contraintes produites lors du compactage, que l'on déduit de la formule de Fröhlich, on peut évaluer le tassement.

Le tassement atteint après N passages de rouleau est donné par la formule de Sasaki.

Introduction

Since Proctor published his first report in 1933, work in this field has been developed to the stage where the use of laboratory control tests has become a normal practice when earth structures are constructed with compaction equipment; but quantitative estimation of the state of soils after compaction in the field cannot be made without some judgment based on experience.

A more reasonable quantitative method for controlling soil compaction would be developed if the mechanism of roller compaction, though much more complicated than the laboratory one, were made so clear as to enable a correlation to be obtained between field and laboratory compaction.

To this end, the following tests were made:

(1) laboratory compaction tests (dynamical and statical ones),
(2) laboratory compaction tests with a model roller (a wooden flat-wheel roller, 10 cm in diameter, 20 cm in width),
(3) field compaction tests with various rollers on test fills—the range of soil was from sandy to loam.

Based on the above experiments, a semi-theoretical method of estimating settlement for roller compaction is proposed.

Fundamental Considerations

Compressibility characteristics of soils—Equation 1 expressing the relationship between compressive stress σ and void ratio e of compressed soil was proposed by Terzaghi and others.

$$e = e_0 - C_c \log_{10} \sigma/\sigma_0 \qquad \dots\dots (1)$$

where e_0 is the void ratio at the pressure σ_0 and C_c is the numerical value of the slope on the semi-logarithmic diagram of e *versus* $\log_{10} \sigma$.

When soil is just at the saturated state, the pore water pressure affects the value of C_c if the loading velocity is high enough not to dissipate the pore pressure during its acting period.

Soils for constructing earthworks are not always in the saturated state, and moreover the loading velocity of common-type rollers is not so high, therefore the effect of pore pressure on C_c can be neglected.

The results of the confined compression tests with the apparatus illustrated in Fig. 1 are shown in Figs. 2 and 3.

The relationships of void ratio e_0 and dry density γ_{d0} when $\sigma_0 = 1$ kg/cm^2 to the moulding water content are shown in Fig. 2. The clear relationship between e_0 and C_c could not be deduced for want of sufficient data. However, a linear dependence between e_0 and C_c might be anticipated without serious error and the straight line is expected to be steeper when the grading of soil is better.

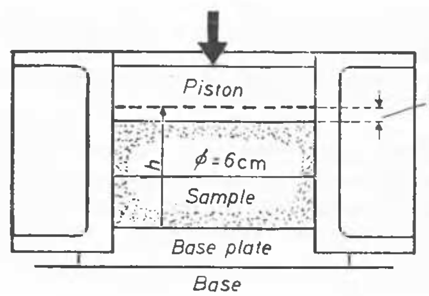

Fig. 1 Sectional view of compression apparatus
Coupe transversale de l'appareil de compression

From equation 1 the compressive strain of the specimen is written

$$\epsilon = \frac{\Delta h}{h} = \frac{1}{1 + e_i}\left\{(e_i - e_0) + C_c \log_{10} \frac{\sigma}{\sigma_0}\right\} \qquad \dots\dots (2)$$

where e_i is the initial void ratio of soil.

Putting the e_i into equation 1, σ_i, which is called the pre-compression stress in this paper, is obtained as

$$\sigma_i = \sigma_0 \exp\left(\frac{e_0 - e_i}{0{\cdot}4343 C_c}\right) \qquad \dots\dots (3)$$

Earth pressure induced by a roller—The earth pressure induced by a roller is usually estimated by the formula due to Boussinesq, Fröhlich, etc. In these computations the total weight of equipment is distributed uniformly on the contact area between the equipment and the ground surface.

Much larger maximum vertical earth pressures were observed in our laboratory and in the field than those computed by the above said procedure. Therefore, it may be considered that the load distribution on the contact area is not uniform but concentrated at the centre of the loaded strip.

After the actual measurements of earth pressure, a more reasonable way of computation was obtained by considering the infinitely extending line distribution of load, in place of the uniformly distributed area load.

The stress analysis with the line load is much simpler and is accurate enough for practical problems so long as the depth considered in the problem is moderate. Because the problem is considered as a two-dimensional one when the line load distribution is assumed, and since the actual width of a roller is finite, this assumption is reasonable only when the above said restriction is satisfied.

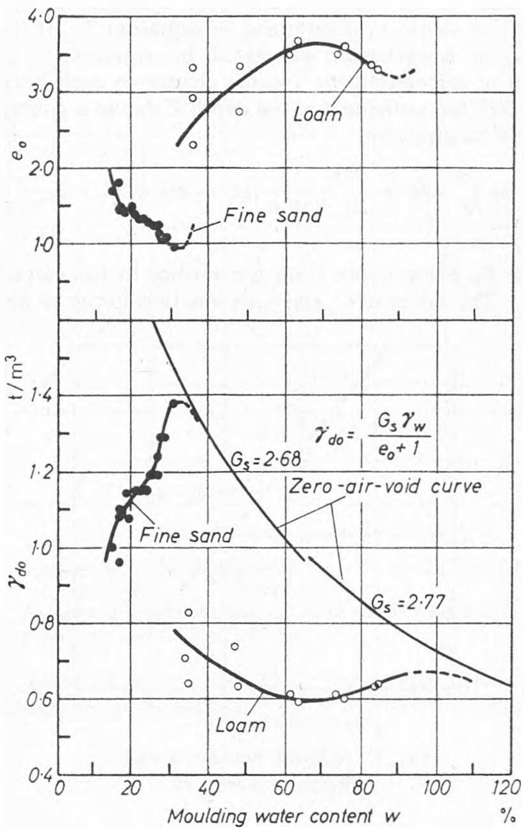

Fig. 2 Results of one-dimensional compression test
Résultats des essais de compression à une dimension

By Fröhlich's formula, the vertical stress σ_Z due to the load p per unit of the length of a straight line of infinite extension is given by

$$\sigma_Z = f\frac{p}{Z}\cos^{\nu+1}\theta \qquad \ldots. (4)$$

in which the value ν is called the concentration index, f is a function only of ν represented by

$$f = \frac{1}{\pi}\cdot\frac{(\nu-1)(\nu-3)(\nu-5)\ldots4{\cdot}2}{(\nu-2)(\nu-4)(\nu-6)\ldots5{\cdot}3} \quad \text{(when } \nu \text{ is odd)}$$

$$= \frac{1}{2}\cdot\frac{(\nu-1)(\nu-3)(\nu-5)\ldots5{\cdot}3}{(\nu-2)(\nu-4)(\nu-6)\ldots4{\cdot}2} \quad \text{(when } \nu \text{ is even)} \qquad \ldots. (5)$$

and the other notations are illustrated in Fig. 4.

The σ_Z is maximum when θ is zero and this maximum is given by

$$\sigma_{Z\max} = f\frac{p}{Z} \qquad \ldots. (6)$$

If we assume that the p is W/B, equation 6 becomes

$$\sigma_{Z\max} = f\frac{W}{ZB} \qquad \ldots. (7)$$

where W is the weight of compaction equipment, and B is the contact width thereof.

Using the values of $\sigma_{Z\max}$ observed in the field for several

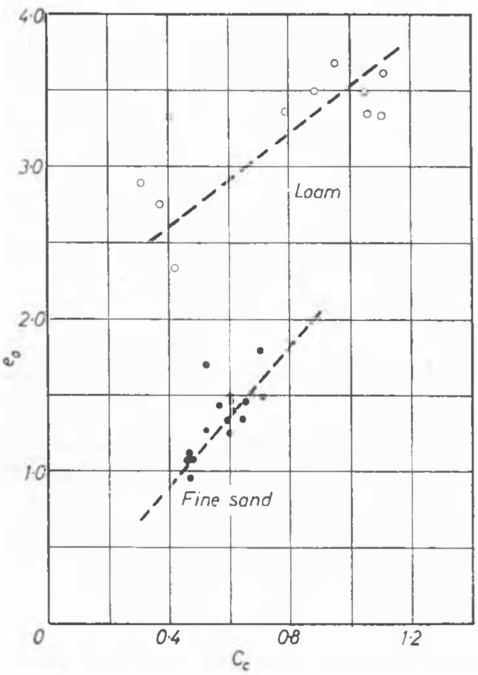

Fig. 3 Relation between e_0 and C_c
Relation entre e_0 et C_c

types of roller, the values of ν were calculated by equations 5 and 6. In general, values of ν of 3 to 5 for loamy soil, and 5 to 6 for sandy soil were obtained.

Settlement of a fill due to the passages of a roller—The settlement Δh of a fill developed by the Nth passage of a roller is

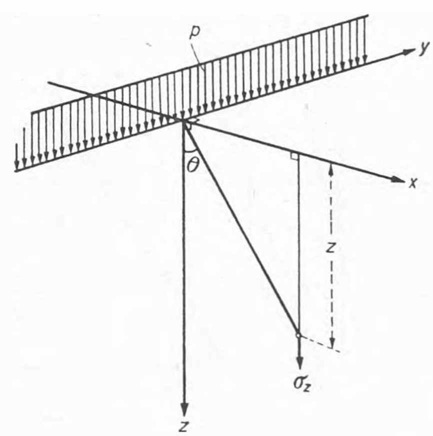

Fig. 4

expressed by the following empirical formula (SASAKI, J. 1952). Mechanism in the compaction of the sand layer (2). *Bulletin Nat. Inst. Agric. Sci., Japan*, Series F, No. 5)

$$\Delta h = \frac{N}{a + bN} \qquad \ldots. (8)$$

in which a and b are coefficients. It will be shown later that these coefficients are connected with each other.

The ultimate value of Δh for an infinite number of passages is given by $1/b$.

Equation 8 is accurate for any type of roller and for any thickness of a layer.

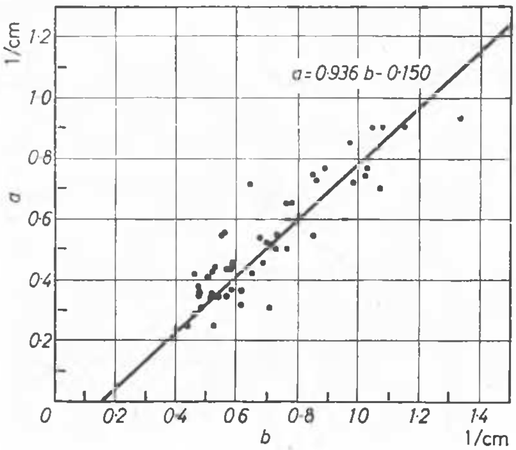

Fig. 5 Relation between a and b (laboratory test)
Relation entre a et b (essai de laboratoire)

Our experiments with a model roller show that a linear relationship exists between a and b (Fig. 5).

This relationship is

$$a = \alpha b - \beta \quad \ldots . \ (9)$$

In this case, the values of α and β are 0·936 and 0·150 1/cm respectively.

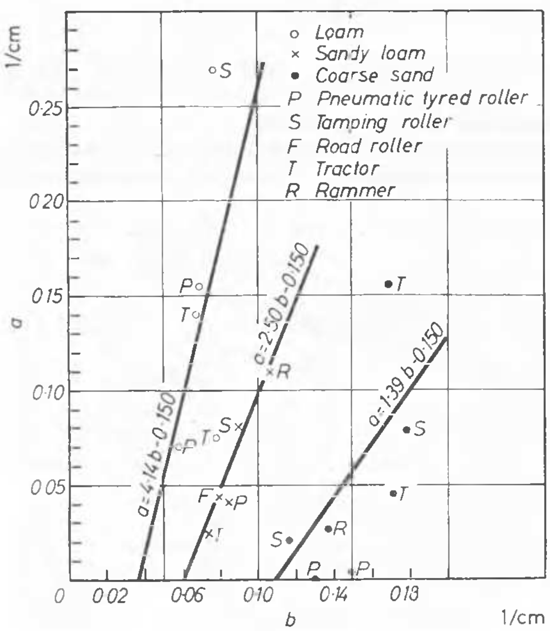

Fig. 6 Relation between a and b (field test)
Relation entre a et b (essai de chantier)

On the other hand, plots in Fig. 6 were obtained from field compaction tests. Fig. 6 shows that a straight line can be fitted through each set of plots for each fill material, and these lines intersect the ordinate at about − 0·150 1/cm. Therefore, assuming β to be 0·150 1/cm, values of α can be obtained from equation 9 and each plot on Fig. 6.

The relationship between the thus obtained α and concentration indices ν which was calculated in the preceding section is shown in Fig. 7.

It can be concluded from Figs. 5, 6 and 7, that the value α depends on the characteristics of the stress concentration of soil, whereas β is independent of soil properties.

Estimation of Compaction with a Roller

Method of estimation—The quantitative estimation of compaction with a roller from laboratory data is made as follows: When an earth fill is compacted with a roller, every part of soil under the tread of the roller is compressed by the compressive stress $\sigma_{Z\max}$ which is given by equation 6 or 7, and the volume is contracted in the region where $\sigma_{Z\max}$ is larger than the pre-compression stress σ_i, determined by equation 3. If the one-dimensional compression expressed by equation 2 can be assumed in calculating the volume change in each horizontal slice of soil, the settlement at the depth Z due to a passage of a roller will be given by

$$\Delta h_Z = \int_Z^{Z_0} \epsilon dZ = \int_Z^{Z_0} \frac{1}{1+e_i}\left\{(e_i - e_0) + C_c \log_{10}\frac{\sigma_Z}{\sigma_0}\right\} dZ \quad \ldots . \ (10)$$

in which Z_0 is the depth from the surface to the place where σ_Z is σ_i. The values of C_c and e_0 in equation 10 can be obtained

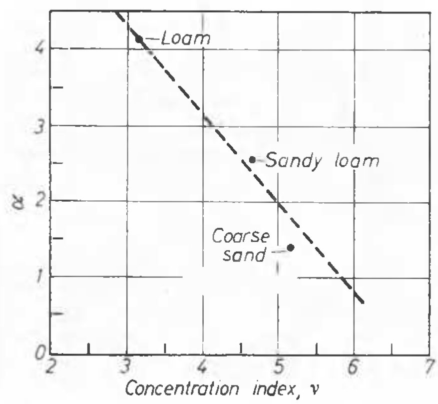

Fig. 7 Relation between α and ν
Relation entre α et ν

by laboratory compression tests, and also e_i is known prior to field compaction work. Therefore the settlement at the depth Z, Δh_Z, can be estimated assuming that e_i is distributed uniformly

$$\Delta h_Z = \frac{1}{1+e_i}\left[Z_0 + MC_c - Z\left\{(e_i - e_0) + C_c\left(\log_{10}\frac{fp}{\sigma_0 Z} + M\right)\right\}\right] \quad \ldots . \ (11)$$

(when $Z_0 \leqq$ initial thickness, h_i, of the fill or layer), or

$$\Delta h_Z = \frac{1}{1+e_i}\left[h_i\left\{(e_i - e_0) + C_c\left(\log_{10}\frac{fp}{\sigma_0 h_i} + M\right)\right\} - Z\left\{(e_i - e_0) + C_c\left(\log_{10}\frac{fp}{\sigma_0 Z} + M\right)\right\}\right] \quad \ldots . \ (12)$$

(when $Z_0 > h_i$) in which M is a constant $\dfrac{\log_{10} x}{\log_e x} = 0{\cdot}4343$, and

$$Z_0 = f\frac{p}{\sigma_0} \times 10^{\frac{e_i - e_0}{C_c}} = f\frac{p}{\sigma_0} \exp\left(\frac{e_i - e_0}{MC_c}\right) \quad \ldots . \ (13)$$

Taking Z to be zero in equation 11 or 12, the total settlement of a fill, that is, the settlement of the surface, can easily be obtained.

The settlement Δh_N of a fill by the Nth passage of a roller is given by equations 8 and 9, if the settlement of a fill due to the first passage of a roller is designated as Δh_1,

$$\Delta h_N = \frac{(1+\alpha)N}{\frac{1}{\Delta h_1}(\alpha + N) + \beta(N-1)} \quad \ldots\ldots (14)$$

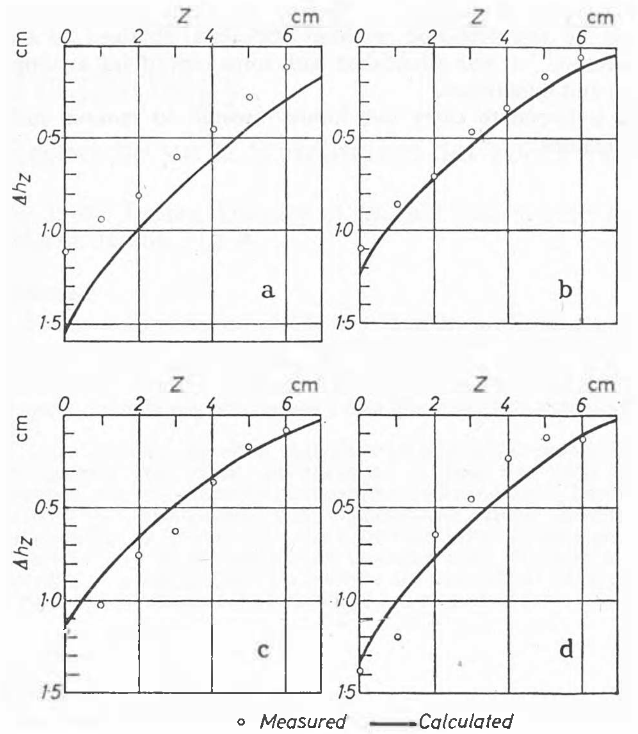

Fig. 8 Settlement at the depth Z within a fill by the first passage of model roller

Tassement à la profondeur Z en le remblayage par le premier passage du modèle rouleau

The degree of compaction which has already been attained by N passages can be estimated from the following equation

$$\frac{\Delta h_N}{\lim_{N\to\infty} \Delta h_N} = \frac{N}{\frac{a}{b} + N} = \frac{N}{\frac{\alpha - \beta\Delta h_1}{1 + \beta\Delta h_1} + N} \quad \ldots\ldots (15)$$

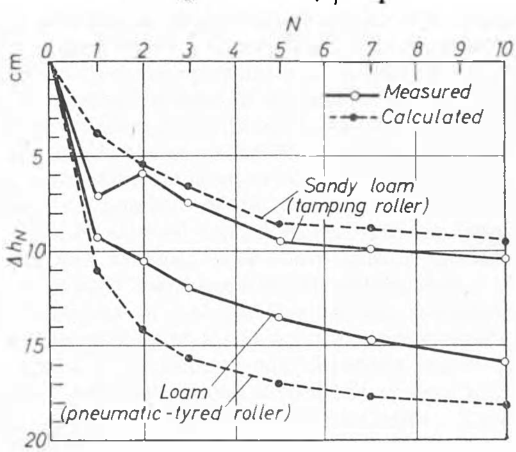

Fig. 9 Settlement of the surface of a fill developed by the Nth passage of roller

Tassement de la surface du remblayage développé par N passages du rouleau

The estimation of the obtained density can be made from the settlement data (equation 11 or 12) of every slice of soil, if wanted.

The compaction control by measuring settlement is more practical than that with measurement of density, because the determination of field density cannot be made without considerable error. In this case, however, the excess settlement due to lateral displacement under the tread of a roller should be carefully separated.

Examples of estimation of settlement

(a) Case of a model roller—A wooden flat-wheel roller (10 cm in diameter, 20 cm in width) was used for the model compaction test. Some of the measured settlements for sandy soils are shown in Fig. 8. The test conditions are shown in Table 1.

Table 1

	W in kg	*w*%	e_i	h_i *in* cm
a	2·70	20·8	2·86	6·89
b	3·20	27·8	2·23	6·91
c	3·70	28·2	2·10	6·86
d	4·20	18·1	2·80	6·90

W: weight of the roller $\quad$ e_i: initial void ratio

w: water content of soil $\quad$ h_i: initial thickness of soil layer

Results of one-dimensional compression tests for the same soils and calculated values of Z_0 are shown in Table 2. The concentration index ν for loose sandy soil was taken to be 6.

Table 2

	e_0	C_c	Z_0 *in* cm
a	1·35	0·600	25·6
b	1·11	0·495	36·4
c	1·08	0·480	30·9
d	1·44	0·635	36·6

In Fig. 8, the measured settlements due to the first passage of a roller are plotted by circular marks and results of calculation with equation 12 are shown by real lines.

(b) Case of field compaction with four kinds of equipment—Two examples obtained from field compaction tests are shown in Table 3. Contact pressures in the third column of Table 4 were calculated from the second column.

Table 3

	Loam				*Sandy loam*			
Initial thickness of a layer	about 50 cm				about 50 cm			
Natural water content	123·3%				33·0%			
Liquid limit	150·2%				47·4%			
Plasticity index	21·7				17·5			
e_0	4·53				1·45			
C_c	2·11				1·105			
ν	3				3			
	e_i	Z_0 (cm)	Δh_1 (cm) *calculated*	Δh_1 (cm) *measured*	e_i	Z_0 (cm)	Δh_1 (cm) *calculated*	Δh_1 (cm) *measured*
Pneumatic-tyred roller	4·43	28·5	11·1	9·3	—	—	—	—
Tamping roller	4·70	14·8	5·5	2·7	1·69	21·1	3·8	7·1
Tandem road roller	4·70	23·0	8·5	8·7	1·55	24·5	4·6	6·4
Tractor	4·72	22·4	8·2	8·6	1·69	31·2	5·1	10·3

Table 4

	Weight of equipment in tons	*Contact pressure p in* kg/cm
Pneumatic-tyred roller	6	50·0
Tamping roller	2·31	19·3
Tandem road roller	6	30·0*
Tractor	16	28·5†

* Contact pressure at the rear wheel
† The weight of a tractor was assumed to be uniformly distributed for five guiding wheels

Calculated settlements are plotted against the repetitions of roller passage in Fig. 9. The values α and β in equation 14 are obtained; that is, $\alpha = 2{\cdot}56$, $\beta = 0{\cdot}150\text{cm}^{-1}$, from Fig. 7, assuming ν to be 3.

Conclusion

Estimation of settlement in the field compaction works can be made by the proposed method with data obtained in the laboratory. It was established with some simplifying assumptions and hypotheses.

It is hoped to carry out future research to remove such ambiguities.