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By

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CERTAIN PROBLEMS OF THE COMPLEX MODULUS OF A FOUNDATION UNDER DYNAMIC LOADING*

Pan Fu-yee

Abstract: The present paper presents certain research results on determination of the complex elastic moduli of foundations consisting of loess, a sand base layer and fill. The effect of the base layer must be taken into account in determining the complex elastic moduli of a stratified foundation; approximate formulas are also proposed to allow for the area of the foundation and the effect of pressure; when a weak foundation is reinforced with a sand footing, there is a marked increase in its complex modulus. The complex modulus of a fill foundation is lower than that of the same type of earth in its natural state.

In modern design for dynamic machine foundations, the choice of complex modulus is based on the admissible compressive strength of the soil and is generally in compliance with the recommendations of the USSR Technical Specifications for Dynamic Design of Machinery Foundations (SN-18-58). However, since the effects of foundation area, specific pressure and the footing layer on the specific elastic properties of the foundation are touched upon only briefly, several problems are still encountered in practical design work. In view of this state of affairs, the author has made an initial experimental study of the complex modulus for foundations consisting of loess, sand footing and artificial fill, using the approach in which C_0 and D_0 are determined with a heavy-machinery compression model in accordance with the recommendations of the Soviet All-Union Scientific Research Institute for

Waterworks and Sanitary Engineering. Comments pertaining to the contents of this paper will be appreciated.

I. DETERMINATION OF COMPLEX MODULUS OF LOESS FOUNDATION

O.A. Savinov proposed the following working formulas for calculation of the isotropic-compression elastic modulus C_z, the anisotropic-compression modulus C_f and the isotropic sheer modulus C_x):

$$\left.\begin{aligned} C_z &= C_0\left[1+\frac{2(a+b)}{\Delta F}\right]\sqrt{\frac{p}{p_0}}, \\ C_\varphi &= C_0\left[1+\frac{2(a+3b)}{\Delta F}\right]\sqrt{\frac{p}{p_0}}, \\ C_x &= D_0\left[1+\frac{2(a+b)}{\Delta F}\right]\sqrt{\frac{p}{p_0}}. \end{aligned}\right\} \qquad (1)$$

where p is the unit static pressure transmitted from the machine base to the foundation (in tons/m^2), Δ is the specific modulus of the foundation, which is independent of the dimensions of the foundation base (m^{-1}), C_0 and D_0 are the specific moduli of the foundation, independent of the size of the foundation base, at $p = p_0$ (tons/m^3), and a and b are the dimensions of the foundation base; b is the side length of the rotation plane perpendicular to the foundation (m).

In order to use the above formula, we must first determine C_0 and D_0. The author used the heavy-machinery compression model* for experimental field determination of these quantities; the ground of the experimental area was mainly an alluvial deposit of loess classified as large-pored type III settling soil with a low ground-water content; four levels can be distinguished in the ground, and these have the physical properties listed in Table 1.

So that the results obtained would be a faithful reflection of the conditions in a real foundation, the experiment was conducted in a test ditch whose depth was increased progressively, while its width was three times that of the compression-model baseplate to eliminate the influence of the lateral soil on the vibration of the model. The model was mounted in the middle of the ditch and its frequency measured after it had been set into vibration by the impact of a 300-kg wooden weight the bottom of which was encased in steel plate.*

Under vertical impact, the angular frequency of free vibration of the impression model was

$$\lambda_z = 2\pi f_z = \sqrt{\frac{C_z F}{m}}. \qquad (2)$$

where F is the surface area of the base of the compression model (m^2), m is the mass of the model ($ton\text{-}sec^2/m$) and f_z is the vertical free-vibration frequency as measured on the compression model (vibrations/ /sec).

TABLE 1

Physicomechanical Properites of the Various Soil Layers

层次	2 土层描述	3 天然湿度 w%	4 单位容重 γ_w	饱和度 5 G%	孔隙比 6 e	液限 7 w_l	塑限 8 w_p	比重 9 γ_s	10 塑性指数 w_n	11 压缩系数 (1~3公斤)	12 地耐力 (公斤/厘米²)
1	13 人工土、黄褐色、含红砖屑、厚约0.5米	16.0	1.56	45.0	1.03	28.9	15.5	2.7	12.5	0.052	2
2	14 黄土状亚粘土、黄褐色、中密、稍湿、厚约1米	17.1	1.55	44.0	1.05	28.8	18.4	2.7	10.9	0.047	2
3	15 黄土状亚粘土、黄褐—褐色、稍密、稍湿—湿、厚约2米	18.0	1.51	41.5	1.08	28.8	18.0	2.7	10.8	0.087	2
4	16 黄土状亚粘土、浅黄色、稍密—中密、稍湿—很湿、厚约10米	19.5	1.55	47.5	1.03	26.5	18.8	2.7	11.2	0.040	2

1) Sequence of layers; 2) description; 3) natural moisture; 4) bulk density; 5) degree of saturation; 6) porosity ratio; 7) flow stress; 8) plastic limit; 9) specific gravity; 10) plasticity index; 11) compression coefficient (1-3 pages); 12) ground resistance (kilograms/ /cm²); 15) artificial soil, straw-colored, containing flecks of red brick, approximately 0.5 m; 14) loess-like clay, straw-colored, medium packed, slightly wet, about 1 m deep; 15) loess-like clay, straw-to brown-colored, loosely packed, slightly wet to wet, about 2 m deep; 16) loess-like clay, straw-colored, loose to medium packing, slightly wet to very wet, about 10 m deep.

The value of C_z under these conditions may be found by substituting the specific geometrical values and the vertical free vibration frequency thus obtained into Formula (2).

For horizontal impact, the angular frequency of the vertical free vibrations is

$$\lambda=\sqrt{\frac{1}{2\gamma}\left[\lambda_x^2+\lambda_\phi^2-\sqrt{(\lambda_x^2+\lambda_\phi^2)^2-4\gamma\lambda_x^2\lambda_\phi^2}\right]}\,. \qquad (3)$$

where

$$\lambda_x^2=\frac{C_x F}{m}, \qquad \lambda_\phi^2=\frac{C_\phi J}{\theta}, \qquad \gamma=\frac{\theta_0}{\theta}.$$

J is the moment of inertia of the bottom surface of the compression model (m^4), θ is the rotational inertia of the compression model about the horizontal axis passing through the center of gravity of the lower surface of the model (tons-m-sec^2), and θ_0 is the rotational inertia of the concussion model about the axis passing through its center of gravity (tons-m-sec^2).

Substituting the measured free-vibration frequencies of the compression model at the top and bottom of the test ditch in Eq. (3) and solving the simultaneous equations, we obtain the values of C_x and C_f for the operation of the compression model.

When the unit static pressure transmitted from the compression model to the foundation p = 0.2 kg/cm^2, or $p = p_0$, Eq. (1) becomes

$$\left.\begin{aligned} C_z&=C_0\left[1+\frac{2(a+b)}{\Delta F}\right],\\ C_\phi&=C_0\left[1+\frac{2(a+3b)}{\Delta F}\right],\\ C_x&=D_0\left[1+\frac{2(a+b)}{\Delta F}\right].\end{aligned}\right\} \qquad (4)$$

Substituting the geometrical dimensions of the compression model and the values of C_z, C_f and C_x under its influence into Eq. (4), we obtain the values of C_0 and D_0, which represent the elastic characteristics of the foundation. Thus,

$$C_0=\frac{C_z}{6.68}\ \text{或}\ \frac{C_\phi}{12.36}, \qquad (5)$$

$$D_\phi=\frac{C_z}{6.68}, \qquad (6)$$

The free-vibration frequency measured in the experimental ground and the values of C_z, C_0 and C_f calculated from them are listed in Table 2, while the data from several variations of the experiment are compared in Table 3.

TABLE 2

Experimental Values of Free Vibration Frequencies of Compression Model on Loess

编号 A	B 试坑情况	C f_z (次/秒)	D C_z (吨/米³)	D C_φ (吨/米³)	D C_ϕ (吨/米³)
1	-0.6米处之天然黄土(安装压模后1小时) E	33.00	8,720	1,315	16,260
2	-0.6米处之天然黄土(安装压模后24小时) F	37.50	11,300	1,690	20,900
3	-0.6米处之天然黄土(安装压模后72小时) G	37.50	11,300	1,690	20,900
4	-1.5米处之天然黄土(安装压模后1小时) H	33.45	9,000	1,345	16,650
5	-1.5米处之人工夯实土(安装压模后1小时) I	37.50	11,300	1,690	20,900

Notes: 1. The hand-tamped soil was compacted by hammering three times with a 40-kg stone hammer having a base area of 28 × 28 cm and dropped from 60 cm.
2. f_z is the vertical free vibration frequency measured with with the compression model.

A) No.; B) conditions in test test trench; C) vibrations/sec; D) tons/ /m3; E) natural loess at −0.6 m (1 hour after setting up compression model); F) natural loess at −0.6 m (24 hours after setting up compression model); G) natural loess at −0.6 m (72 hours after setting up compression model); H) natural loess at −1.5 m (1 hour after setting up compression model); I) hand-tamped soil at −1.5 m (1 hour after setting up compression model).

TABLE 3

Comparison of Data from Variations of the Experiment

1 资料来源	2 F (米²)	P_0 (吨/米²) 3	4 C_φ (吨/米³)	4 C_z (吨/米³)	备 5 注
6 作者对黄土质亚粘土进行的实验	0.5	2	1,690	11,300	
7 O.A.萨维诺夫对天然湿度黄土进行的实验	0.5	2	1,500—2,000	10,000—13,400	
8 苏联动力机械基础设計技术規范	0.5			17,800	9 地耐力20(吨/米²)

1) Source of data; 2) m²; 3) ton/m²; 4) ton/m³; 5) remarks; 6) author's experiment on loess; 7) O.A. Savinov's experiment on naturally moist loess; 8) USSR Technical Specifications for Dynamic Design of Machinery Foundations; 9) endurance limit of ground 20 tons/m².

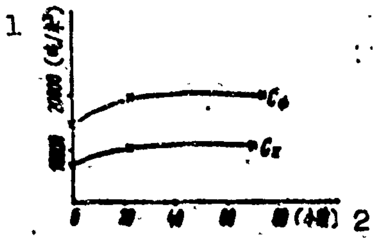

Fig. 1. Time curves of the coefficient C_f and C_z. 1) Tons/ $/m^3$; 2) hours.

It is evident from Table 2 that the complex modulus of the foundation varies with depth in the soil; the deeper the soil layer, the greater the value of this modulus (principally because of increased compactness of the soil due to the pressure of its own weight; further, the complex modulus of foundations consisting of hand-tamped loess is higher than for natural loess. Thus it becomes obvious that the foundation complex modulus is to a certain extent dependent on the elastic modulus of the soil or, in other words, increasing with elastic modulus. Further, the time curves of the coefficients C_f and C_z (see Fig. 1), as plotted from Table 2, indicates that the foundation complex modulus measured with the compression model increases with time to approach a definite limit.

Comparison of the data in Table 3 brings up the following points: the complex modulus found by the author for the loess foundation with the heavy-machinery compression model is basically in agreement with the experimental results of O.A. Savinov for loess of natural moisture content, while the C_z-value determined from the Savinov formula is a more faithful reflection of the base-area effect and the effect of the specific pressure of the foundation on its elastic characteristics. On the other hand, the USSR Technical Specifications for Dynamic Design of Machinery Foundations use the endurance limit of the ground as a basis for determining the foundation complex modulus and constants must be used as coefficients if the size of the base exceeds 10 square meters. In practice, the foundation complex modulus increases with increasing pressure and is a function of the density of soil. Consequently, the data in the Technical Specifications would appear to be somewhat incomplete.

II. DETERMINATION OF ISOTROPIC COMPRESSION COMPLEX MODULUS OF A FOUNDATION CONSISTING OF STRATIFIED SOIL LAYERS

At the present time, foundations are generally treated as homogeneous elastic bodies in designing machinery bases, and the modulus of the supporting layer of the foundation is taken for the entire foundation without special consideration of the footing layer. As results, when there are several layers of soil with sharply different properties in the foundation, the calculated result may not agree with experimental fact. To investigate the effect of footing layers on the complex modulus of a foundation, the author conducted experiments using two kinds of sandy soil with different footing layers. The cross section of the 2 × 2 × 1.5(h)-meter test trench is shown in Fig. 2. The trench was dug to the predetermined depth, tamped 3 times with a stone hammer weighing about 40 kg, and its natural vibration frequency measured by installing the compression model on top of it; then the compression model was dismounted, 0.3 m of of sand was shoveled into one ditch and packed manually, 0.6 m of sawdust was shoveled into the other, and the above sequence of operations was repeated. The observed results are presented in Tables 4 and 5 and plotted in Figs. 3 and 4.

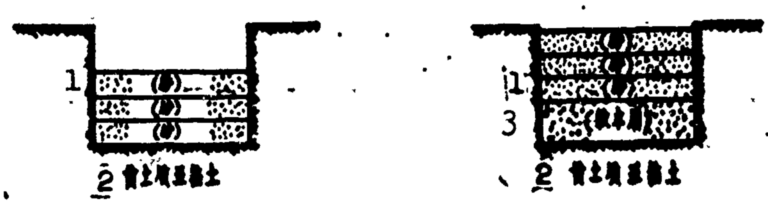

Fig. 2. 1) Sand; 2) loess; 3) soft sawdust.

TABLE 4

First Set of Observed Free Vibration Frequencies of Compression Model on Sand Footing (in loess)

1 编号	2 试坑情况	f_z (次/秒) 3	f_x (次/秒) 3	f_φ (次/秒) 3	C_z (吨/米³) 4	C_φ (吨/米³) 4	C_x 4 (吨/米³)	C_ψ 4 (吨/米³)	D_φ 4 (吨/米³)
1	−1.5米处，人工夯实土 5	37.5	27.3	17.65	11,300	1,690	9,600	20,900	1,430
2	在编号1上虚铺0.3米砂并经人工夯实 6	33.0	25.5	—	8,780	1,315	9,500	16,250	1,420
3	在编号2上再虚铺0.3米砂并经人工夯实 7	30.9	23.8	—	7,700	1,150	8,200	14,200	1,230
4	在编号3上再虚铺0.3米砂并经人工夯实 8	—	25.3	17.75	8,050	1,205	10,600	14,900	1,585

Notes: 1. After three tampings with the stone weight described in the note to Table 2, the 30 cm of shoveled sand had an actual measured thickness of 20 cm.
2. f_x·f_φ are the horizontal free vibration frequencies at the top and bottom points, as measured on the compression model.

1) No.; 2) test trench; 3) vibration/sec; 4) ton/m^3; 5) at −1.5 m, hand-tamped soil; 6) 0.3 m of sand added to No. 1 above and tamped by hand; 7) 0.3 m of sand shoveled onto No. 2 and hand-tamped; 8) 0.3 m of sand shoveled over No. 3 and tamped manually.

TABLE 5

Second Set of Observed Values of Free-Vibration Frequency of Compression Model on Sand Footing (bottom layer soft sawdust, with loess beneath it)

1 编号	2 试坑情况	f_z (次/秒) 3	f_x (次/秒)	C_z (吨/米³) 4	C_φ (吨/米³) 4	C_x (吨/米³) 4	C_ψ (吨/米³) 4	D_φ (吨/米³) 4
1	−1.5米人工夯实土上虚铺0.6米厚软木屑 5	11.62	8.33	1,090	163	865	2,020	129
2	在编号1上虚铺砂0.3米厚并经人工夯实 6	15.00	—	1,810	271	—	3,360	—
3	在编号2上再虚铺砂0.3米厚并经人工夯实 7	19.70	—	3,125	467	—	5,780	—
4	在编号3上再虚铺砂0.3米厚并经人工夯实 8	22.90	—	4,220	632	—	7,830	—

1) No.; 2) test trench; 3) vibration/sec; 4) tons/m^3; 5) 0.6 m soft sawdust shoveled onto 1.5 m of manually tamped soil; 6) 0.3 m of sand shoveled over No. 1 and tamped by hand; 7) 0.3 of sand shoveled over No. 2 and tamped by hand; 8) 0.3 m of sand shoveled over No. 3 and tamped by hand.

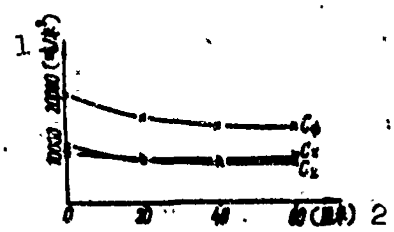

Fig. 3. Coefficients C_x, C_f and C_z as functions of sand footing thickness (loess bottom layer). 1) ton/m3; 2) cm.

Fig. 4. C_f and C_z as functions of sand footing layer thickness (soft sawdust bottom layer, resting on layer of loess). 1) ton/m3; 2) cm.

The above results indicate that the foundation complex moduli are clearly different for sand footings having the same thickness and packed in the same way but with different bottom layers; as the thickness of the sand footing increases, the two moduli move closer together. Thus the bottom layer can influence the foundation complex modulus only to a certain depth. The Polish expert Dr. I. Keshell suggests that $\sqrt{2}b$ should be used for the depth of the compression layer to calculate the uniform-compression complex modulus of a stratified soil foundation, while b should be used to calculate the isotropic sheer modulus C_x; here b is the length of the short side of the base.

In view of the numerous factors that affect the elastic characteristics of a foundation, our initial hypothesis will embody the assumptions that the total elastic displacement of the foundation within a given compression-layer depth is equal to the sum of the elastic strains of the several layers and that the Poisson's ratio μ is a constant; then the isotropic compression complex modulus of the stratified foundation may be obtained from the equation

$$\frac{\bar{p}_0 h_0}{C_0} = \sum_{i=1}^{n} \frac{\bar{p}_i h_i}{C_i}. \qquad (7)$$

where $\overline{p}_0$ is the average value of the longitudinal stresses produced within the compression layer by the vibration of the base (kg/cm^2), h_0 is the thickness of the compression layer (cm), C_0 is the complex modulus of elasticity of the foundation within the limits of the compression layer (kg/cm^2), which depends only on the properties of the ground, $\underline{n}$ is the number of foundation layers within the compression layer, $\overline{p}_i$ is the average value of the longitudinal stresses produced in the ith layer by the vibration of the base (kg/cm^2), h_i is the thickness of the ith layer (cm), and C_i is the modulus of elasticity of the ith layer of the foundation (kg/cm^3), which depends only on the properties of that layer of soil and is independent of the thickness of that layer and other factors, such as the dimensions of the base.

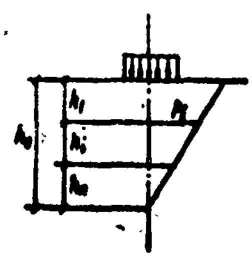

Fig. 5

Let the stress distribution in the compression layer be triangular; then

$$\overline{p}_0 = \frac{p_1}{2}, \qquad \overline{p}_i = \frac{p_i + p_{i+1}}{2},$$

where p_i is the longitudinal stress at the upper surface of the ith layer.

Substituting the above into Eq. (7), we obtain

$$\frac{p_1 h_0}{2C_0} = \sum_{i=1}^{n} \frac{(p_i + p_{i+1}) h_i}{2C_i}. \qquad (8)$$

From the similar triangles in Fig. 5, we have

$$p_i = \frac{p_1}{h_0} \sum_{i=1}^{n} h_i, \qquad (9)$$

On substitution of Eq. (9) into (8),

$$\frac{1}{C_0} = \sum_{i=1}^{n} \frac{1}{C_i} \cdot \frac{\left(h_i + 2 \sum_{j=i+1}^{n} h_j\right) h_i}{h_0^2}. \qquad (10)$$

TABLE 6

Comparison of Theoretical Calculation with Observed Results

1 土层情况	2 計算之 C_z 值 3 (噸/米³)	4 实测之 C_z 值 3 (噸/米³)	5 差数 (%)
6 图 6 a	8,900	8,780	11.6
图 6 b	7,650	7,700	0.7
图 6 c	6,950	8,050	13.7

Notes: 1. Data used in calculations: thickness of compression layer $h_0=\sqrt{2}\times 0.707+1$ meter; C_z = 11,300 tons/m3 for loess; C_z = 6480 tons/m3 for sand.
2. See Table 4 for observed value.

1) Condition of soil layers; 2) calculated C_z; 3) tons/m^3; 4) observed value of C_z; 5) difference; 6) Fig.

To check the validity of Formula (10), we make a comparison in Table 6 and Fig. 7 between the experimental results and the calculated figures obtained by the formula for sand footing layers of different thicknesses laid over loess (Fig. 6).

The comparison shows that the isotropic compression complex modulus of the foundation as calculated from Eq. (10) comes quite close to the experimental result in the case of a layered foundation. Formula (10) especially reflects the effects of bottom layers with different moduli and is even more suitable for practical situations than the design procedure presently in use. However, the test area had only loess, so the factors considered here may not be all-embracing, and the general validity of the formula would require further investigation.

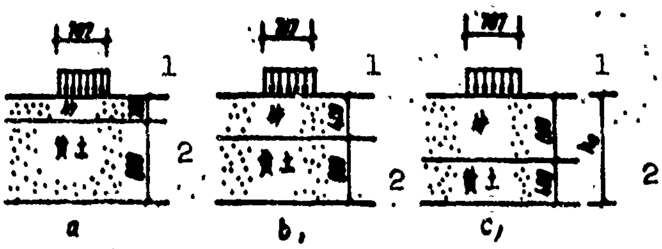

Fig. 6. Working diagram of sand footings having different thicknesses. 1) Sand; 2) loess.

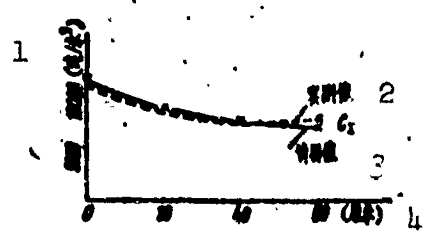

Fig. 7. Coefficient C_z as a function of sand-footing thickness (loess bottom layer). 1) tons/m^3; 2) observed value; 4) cm.

III. THE PROBLEM OF REINFORCING WEAK FOUNDATIONS BY USE OF SAND FOOTINGS

It is a well-known fact that soft or highly nonuniform soils are not suitable for use as natural machine foundations. Consequently when the soil below the machine base does not possess sufficient strength and it is not economical to deepen the foundation, the foundation must be reinforced artificially.

One of the methods of strengthening a foundation artificially is to use a sand footing layer. It is seen from Fig. 4 that a sand footing layer less than one-third of the thickness of the compression model baseplate increases the isotropic compressive modulus C_z of the foundation by 66%. On the other hand, since the water content of the sand has only slight influence on its elasticity properties, reinforcement of weak soils with sand footings will produce good results for weak machine foundations (especially when the depth of weak material replaced is not large). The effect becomes the more conspicuous the weaker the soil layer replaced.

In the case of drop-hammer foundations, the vibrational acceleration is too large (usually in excess of 1g) to permit the use of sand footings.

IV. CONSTRUCTION OF DYNAMIC MACHINE FOUNDATIONS WITH MANUAL REFILL

Construction of dynamic machine foundations with manual refill is a rather complicated problem, not only because of the soil water content, but also because of its porosity. Experiments were conducted with manual refill (refilling with the original soil) in order to gain some basic understanding of the problem. The experimental trench was dug in deeper loess (see Fig. 8); the soil-layer structure and physical properties are indicated in Table 1, and the ditch dimensions and tamping procedures were the same as before. The results of the experiments are shown in Table 7.

TABLE 7

Observed Natural Vibration Frequencies of Compression Model on Refill

编号 A	试坑情况 B	f_z (次/秒) C	f_x (次/秒) C	f_φ (次/秒) C	C_z (吨/米³) D	C_φ (吨/米³) D	C_x (吨/米³) D	C_ψ (吨/米³) D	D_φ (吨/米³) D
1	−1.5米处天然黄土 E	33.45	25.6	—	9,000	1,345	9,400	16,650	1,405
2	−1.5米处天然黄土经过人工夯实 F	35.50	—	16.55	10,130	1;520	7,800	18,800	1,170
3	在编号2上虚铺0.3米回填土并经夯实 G	32.10	22.5	—	8,300	1,242	6,100	15,350	913
4	在编号3上再虚铺0.3米回填土并经夯实 H	32.00	—	—	8,250	1,235	—	15,250	—
5	在编号4上再虚铺0.3米回填土并经夯实 I	31.90	22.6	—	8,200	1,228	6,280	15,150	940

A) No.; B) test trench conditions; C) vibrations/sec; D) ton/m^3; E) natural loess at −1.5 m; F) natural loess at −1.5 m with manual tamping; G) 0.3 m of fill shoveled over No. 2 and tamped; H) another 0.3 m of fill shoveled over No. 3 and tamped; I) another 0.3 m of fill shoveled over No. 4 and tamped.

Table 7 indicates that loess refill foundations have isotopic compression moduli and anisotropic compression moduli slightly lower than those of natural foundations composed of the same soil.

It is also seen from Fig. 9 that the complex foundation modulus approaches a definite limit as the fill depth increases.

It is also known from experiment that the complex modulus of a refill foundation depends heavily on the tamped mass, which is closely related to water content, so that the latter must be strictly controlled and the layer tamped individually during refilling and compacting. Whenever the fill contains large quantities of organic matter and rubble, it should not be used for dynamic machinery foundation building.

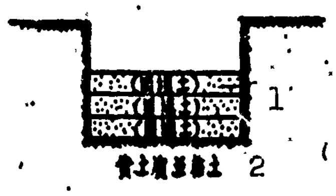

Fig. 8. 1) Fill; 2) loess.

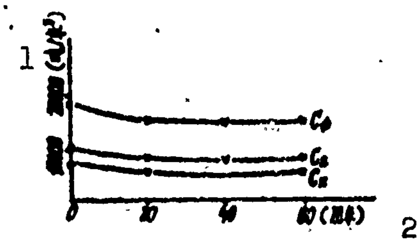

Fig. 9. Coefficients C_f, C_z and C_x as a function of artificial refill thickness. 1) tons/m^3; 2) cm.

V. CONCLUSION

1. The advantage of reinforcing weak soils with sand footings is quite striking when dynamic machinery foundations are built on soft soils (except in the case of the drop-hammer foundation).

2. The influence of the underlying strata on the foundation complex modulus must be taken into consideration in the compression zone if these layers are stratified. We suggest here that the isotropic compression modulus of the foundation be obtained in accordance with the magnitude of the external loads, the depth of the compressed layer, the complex foundation moduli for the various soil layers and the thicknesses of these layers.

3. An artificial-refill foundation composed of loess has isotropic compression and anisotropic compression moduli slightly lower than those of a natural foundation composed of the same soil type (with the tamping conditions used in this study).

4. The foundation complex modulus varies with depth in the soil, increasing with increasing depth.

5. Measured with a compression model, the complex foundation modulus increases gradually with time, approaching a definite limit.

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Manu-script Page No.	[Footnotes]
1	Comrades Men Fung-nin, Chan Chuan and Liu Dao-shun also participated in the experiment work for the present study.
2	See O.A. Savinov, "Principles of Machinery Foundation Design"

for the adjustment and geometry of the heavy-machinery compression model.

3 The frequency was measured with a Philips Hall-emf instrument.

Manuscript Page No.	[Transliterated Symbols]
2	Φ = f [not identified].