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SYNOPSIS: It has been proved that the propagation law of elastic surface wave emanating from machinery foundations has bearing not only on distances from vibration source but also on frequencies and depth of vibration source and external pressure acting on soil surface of wave receivers. Based on plenty of tests the calculation formulas for elastic surface wave are put forward and the computation precision of which is satisfactory.

INTRODUCTION

At present many researchers attach importance to the investigation of propagation law of elastic surface wave in soil because it has great significance to resonably taking the area of factory zone, saving agriculture fields and arranging the precise instruments and devices. Espetialy, the environment request to persons is becoming more and more strict, which makes researchers pay more attention to the investigation of this discipline.

In the process of research of this discipline, the authors mainly adopted test method. It is because most of theoritical research is developed on the basis of the theory of elastic semi-infinite body, which does not coincide with fact because the bases are always formed of some strata of soils and the elastic properties of which, sometimes, are far from each other. Owing to the elastic constants of soils are related not only to normal stress acting on soil but also to initial stress existing in soil particles and other factors, then the relationship between stress and strain in soil disagrees with Hooke's law. All of these cases makes the propagation theory of elastic wave in soil based on elastic theory do not very well agree with practice [1]. Due to this case the authors try to put forward semi-empirical formula for computing the propagation law of elastic surface wave in soils by a number of tests. Therefore, on the ground of work carried out in the past the authors measured again lots of propagation law of elastic wave in recent years. The tested foundations involve in some special model foundations and actual machine foundations in operation. All tests are perforbmed under the condition of stable exciting forces with frequencies changing from 5 to 400 Hz. The amplitudes of model foundations do not exceed 200 μm and of actual machine foundations change from 300 to 600 μm.

In order to make readers further understand the general cases tested the soil conditions and sizes of these model foundations are listed in Table I.

TAB. I. The Magnitude of Foundations and Their Soil Conditions

Sizes of Model Foundations (m)	Soil Conditions
3.5*3.5*1.5	Slight Clay Loam
2.0*3.0*1.5	Slight Clay Loam
1.6*1.6*2.2	Hard Clay Soil
1.6*1.6*0.7	Hard Clay Soil
1.0	Clay Soil
0.11	Loessial Clay Loam

The actual foundations measured involve in five hammer foundations with weight of falling part 3 tons, two hammer foundations with weight of falling part 5 tons, four hammer foundations with 10 tons, 16 tons and two 1 ton and some foundations under compressors. These foundations are built on clay soil, clay loam, loessial clay loam, rock base and piles.

In the whole analysis, the authors employed the measured results performed in sixty times done by themself and lots of measured results done by some home and abroad experts. All together 149 measured curves of attenuation of amplitudes of vibration by forming of 1500 data are analysed in detail. From this the calculation formula of propagation of elastic surface wave in soils are put forward. The formula that shall be discussed in the following possesses following four main characteristics as comparison with the calculation formulas published at home and abroad:

1) The effect of frequencies is considered.
2) The effect of embedded depth of vibration sources is taken into account.

3) The influence of pressure acting on soil surface is considered.

4) And the effect of different distances is noted.

I. The Effect of Frequencies of Vibration Sources

To this problem the famous professor B. Gorizin of Russian ever put forward following calculation formula of propagation of elastic surface wave:

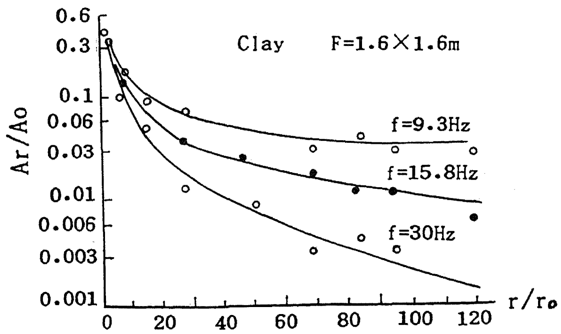
$$Ar = Ao(r_o/r)^{0.5}\exp[-\alpha(r-r_o)] \qquad (1)$$

Where: Ao = amplitude at distance ro
Ar = amplitude at distance r
ro = equevarent radius of foundation served as vibration source, $ro=(F/\pi)^{0.5}$ (m)
F = base area of foundation (m^2)
α = coefficient of energy absorption (m^{-1})

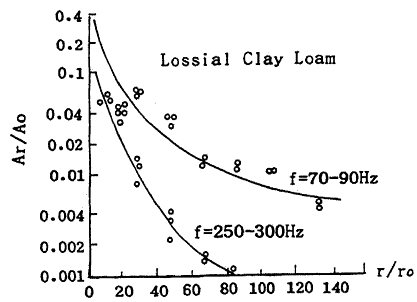
The coefficient α changes from 0.04 to 0.12 m^{-1} to different soils. So far the formula 1 is widely used in many contries.

It is seen from formula 1 that the propagation law of elastic wave in soils is only related to radius r and the coefficient of energy absorption, and has no bearing on frequencies of vibration source. It is worthy pointing out that up to now the effect of frequencies on propagation of wave has not been considered in many contries yet. However, it shows from experiments that not to consider the effect of frequencies is unresonable because the soils are visco-elastic body, the dispersion of vibration energy of which is almost propotional to the vibration frequency. The tests done by the authors fully demonstrate that the propagation law of elastic surface wave has markedly bearing on the frequencies of vibration source. In order to show the phenomena the three typical test curves as shown in Fig. 1 are cited from many curves. It follows from Fig.1 that the higher the frequencies, the faster the amplitude decreasing with distances. For example, it follows from Fig. 1a that at r/ro = 50 the relative amplitudes of vibration Ar/Ao equal 0.045, 0.020 and 0.007 corresponding to exciting frequencies 9.3, 15.8 and 32 Hz. In the case of very high frequencies as shown in Fig.1 c the phenomenon is especially obvious. Here, it should be pointed out that the Fig.1a-1b describe the relationship between exciting frequencies and the vertical components of vibration amplitudes under the vertical vibration source and the Fig. 1c describes the relation between exciting frequencies and horizontal amplitudes of vibration under the action of horizontal vibration source.

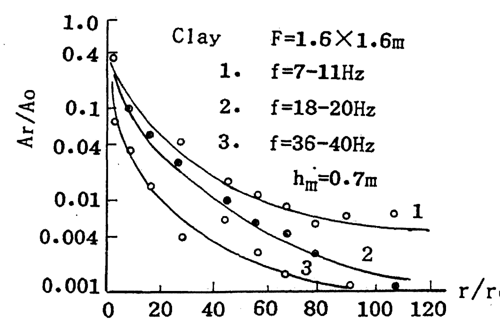
Owing to the influence of frequencies of vibration source is not taken into account by the formula 1, hence the computation results are often far from the measured results.



a) Attenuation of Vertical Wave under Vertical Vibration Sourrce



b) Attenuation Law of High Exciting Frequency



c) Attenuation of Horizontal Wave under Horizontal Vibration Source

Fig.1 Effect of Frequency of Vibration Source on Propagation of Wave

II. The Effect of Embedded Depth of Foundations on Propagation of Wave

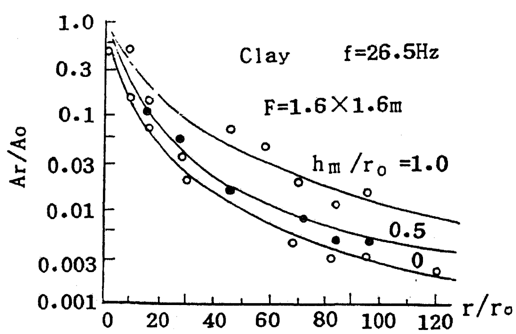
Actual machinery foundations always possess a certain embedded depth. There fore, researching the effect of embedded depth of foundations on propagation of elastic wave has much more actual meaning. However, the factor has not been taken into account so far. For instance, the design code of machinery foundations (CHиП II 19-79) of USSR published in 1979 years put forward following calculation formula for propagation of elastic surface wave:

$$A_r = A_o \left\{ \frac{1}{\delta\left[1+(\delta-1)^2\right]} + \frac{\delta^2-1}{(\delta^2+1)\sqrt{3\delta}} \right\} \qquad (2)$$

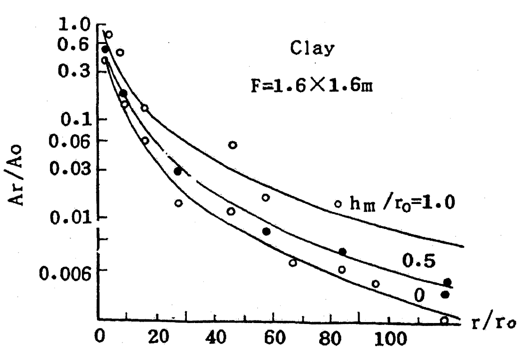
Where:

$$\delta = r/r_o$$

It shows from formula 2 that the attenuation of amplitudes of vibration with distances has only bearing on geometric parameter r/ro and no bearing on embedded depth of foundations served as vibration source and other factors. However, the experiments show that the embedded depth of vibration source gives apparent influence to propagation of elastic wave. For instance, the figure 2a shows that at r/ro = 50 and when hm = 0, 0.5 ro and 1.0 ro (hm = embedded depth of foundation as vibration source) , then the measured relative amplitudes Ar/Ao equal 0.01, 0.018 and 0.40 respectively. Since the formula 2 does not consider the effect of embedded depth of vibration source on propagating wave and other factors, and then it makes the computation results do not coincide with measured results as shown in Table II.



a)



b)

Fig.2 Effect of Embedded Depth of Vibration Source on Propagation of Wave

TAB. II. The Comparision of Total Errors % of Amplitudes of Vibration (According to 1500 test data)

Calculation formula	For Model Foundations	For Actual Foundation
By Expresion 2	337	321
By Code of China	65	90
By Formulas 3 and 4	39	41

III. The Effect of Pressure at Wave Receivers on Propagating Wave

In fact the persons take most care of the propagating law of wave under the action of external pressure at wave receivers because all foundations of structures and precise instruments, Without exception, give the base a certain pressure. Therefore, the research of effect of pressure on propagation law of elastic wave is especially important.

However, so far the effect of external pressure acting on the soil surface of wave receivers is scarcely researched. In order to clarify this problem a number of field tests is carried out by the authors. Experiments indicate that the amplitude under the action of pressure at wave receivers are much less than those of free soil surface as shown in Fig. 3.

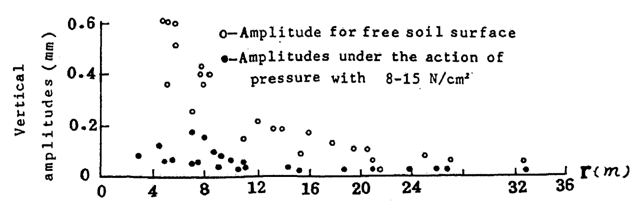
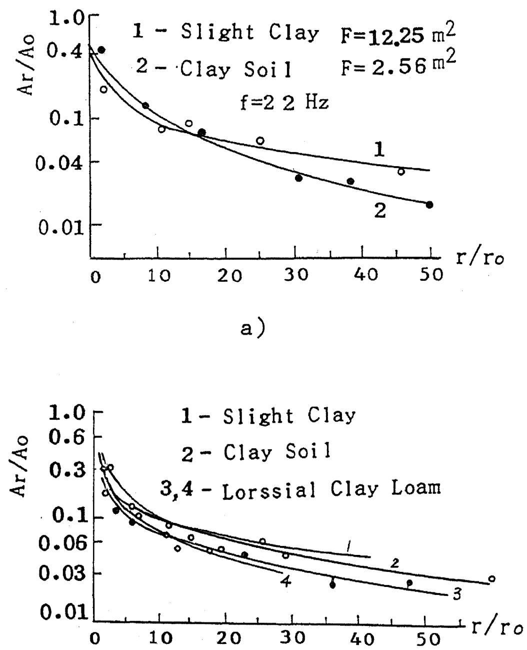


Fig.3 Effect of Pressure Acting on Soil Surface on Propagation of Wave

For example, at r=16 m the amplitude equals 0.07 mm for free soil surface and only equals 0.02 mm for existing of pressure which equals 12 N/cm^2 , while the total acting force corresponding to pressure equals 1080 kN. Meanwhile, it follows from Fig. 3 that the ratio of vibration amplitudes under the action of external pressure to the amplitudes under free soil surface is different. Generally speeking, the shorter the distance from vibration source, the smaller the ratio. However, the ratios are not less than 0.4 within the range tested. The test results as shown in Fig. 3 are obtained under the action of pressure which equals 8-15 N/cm^2 , and which is induced by industrial factory building with one story. In the case of other pressures the ratio of amplitudes of vibration shall generate variation to some extent.

IV. The Effect of Different Soils

According to the propagation theory of elastic wave in absolutly isotropic homogeneous elastic body the attenuation law of amplitudes of vibration should be different for soils. In the period of research the authors ever paid attention to the effect of soils on propagating of wave and did to try to consider this factor. However, the practice does not coincide with expectation of authors. For instance, the figure 4 shows that the attenuation law of vibration amplitudes is different only in a



b)

Fig.4 Effect of Different Soils on Propagation of Wave

small degree. Even, the inverse phenomenon is obtained in test results. For example, the attenuation of vibration amplitudes with distances for slight clay loam with smaller bearing capacity 15 N/cm² and smaller elasticity is more slow and moderate as compared with clay soil with larger bearing capacity 25 N/cm² and elasticity. The phenomenon like the kind of example above was ever introduced in literature [1], which points out that the coefficient of energy absorption for gray water-surturated sand with laminae of peat and organic silt equals 0.04 m^{-1} , while the coefficient for yellow water-saturated fine-grained sand with larger elasticity inversely equels 0.1 m^{-1} . On the ground of these cases we hold that the effect of soils on propagating of surface wave may be ignored to a first approximation under the soils tested. In this respect the treatment method of this paper is, in principle, is in agreement with the design code of machinery foundation (CHиП II 19-79) of USSR.

V. The New Formula for Calculation of Propagation of Elastic Surface Wave

According to the discussion above we have known what factors should be considered. And then how to consider these factors becomes especially important problem. In the process of research the authors did try to adopt uniform computation formula for different distances and analyse five computation formulas. The analysed results show that the total errors on average are not satisfied when using uniform calculation formula. In order to decrease the errors, finary, two expressions are developed for short and long distances. The treatment method like this has theoritical ground. Because it is well known that the action of longitudinal and transverse waves is predominant near the source of vibration and the elastic surface wave is predominant under long distances. In order to establish the point distinguishing short from long distances the great computation work is carried out by virtue of elactic computor. It indicates from analysis that the distinguishing point should be adopted to equal 8 r_o . When $r \leqslant 8$ ro , then the computation formula for short distance should be used, otherwise the formula for long distance should be used. Through the detail analysis the final calculation formulas of propagation of elastic surface wave may be written as follows:

for $r \leqslant 8$ ro

$$A_r = \xi A_o \frac{r_o}{r} \frac{e^{-\alpha_1 f(r-r_o)}}{1+\beta(1-r_o/r)} \quad (3)$$

for $r > 8$ ro

$$A_r = \frac{2.83\,\xi A_o}{8+7\beta} e^{-7\alpha_1 f r_o} \sqrt{\frac{r_o}{r}}\, e^{-\alpha_2 f(r-8r_o)} \quad (4)$$

Where: ξ = correction coefficient of pressure acting, which may be adopted to equal 0.4

f = frequencies of vibration source (Hz)

β = coefficient of embedded depth of vibration source:

$$\beta = \frac{1}{2.0+0.5\,h_m/r_o} \quad (5)$$

hm = embedded depth of foundation served as a source of wave (m)

α_1 = attenuation coefficient of short distance, which may be adopted to equal 0.001 for soils studied

α_2 = attenuation coefficient of long distance:

$$\alpha_2 = \frac{1}{600+4\,r/r_o} \quad (6)$$

It should be indicated that the parameters in the coefficients α_1, α_2 and β, such as 0.001, 2.0, 0.5, 600 and 4, are obtained by virtue of analysis of elastic computor. In order to compare the errors computed by formulas 3 and 4, by formula 2 and by the design code of machinery foundations (GBJ 40-79) of china, a great computing is carried out. The precision of computation is determined by the errors as follows:

$$\mathcal{E} = \frac{1}{N} \sum_{i=1}^{N} \left| \left(1 - \frac{A_{c,i}}{A_{m,i}} \right) \right| \cdot 100 \quad (7)$$

where: $\mathcal{E}$ = total error on average

N = total number of measured points

$A_{c,i}$ = computation amplitude of point i

$A_{m,i}$ = measured amplitude of point i

On the basis of analysis to 1500 data the total errors computed by three formulas are obtained as listed in Table II. It follows from Table II that the computation precision of formulas 3 and 4 is much better than those computed by formula 2 and by design code of China.

Finally. it should be pointed out again that the computation formulas 3 and 4 are put forward under these soils as mentioned above. In order to fully understand the resonableness of formulas put forward by the authors the comparison of computation precision for other soils is performed and may be seen from Table III.

TAB. III. Comparison of Errors Computed by Three Formulas with Measured Results for Weak Soil, Rock Bace And Pile Foundations

Vibration Sources and Conditions	by Formula 2	by Code of China	by Expression 3 and 4
1	67.7	32.2	30.3
2	81.5	61.4	31.2
3	65.5	45.9	17.9
4	123.0	70.0	51.0
5	545.0	67.0	49.0
6	622.0	65.0	56.0

note: 1 includes following cases: hammer foundation with weight 5 tons, clay loam with silt, pile foundation and 9 points measured. 2: hammer with 2 tons, clay loam with silt, pile foundation and 7 points. 3: hammer with 3 tons, fine-grained base, pile foundation and 4 points. 4: hammer with 3 tons, silt base, pile foundation and 9 points, 5: hammer with 0.75 tons, rock base and 9 points. 6: hammer with 5 tons, rock base and 6 points measured. It follows from Table III that the calculation precision computed by formulas 3 and 4 is also better than those computed by other formulas of computation.

Conclusions

Through the detail analysis above some principal conclusions can be drawn as follows:

1) The propagation law of elastic surface wave emanating from machinery foundations is related not only to distances from vibration sources but also very markedly to frequencies and embedded depth of vibration source and to magnitude of pressure acting on soil surface at wave receivers.

2) The compatation precision of attenuation formulas for amplitudes of vibration put forward by the authors is much better than others above mentioned.

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