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COMPUTER AIDED DESIGN OF VIBRATION ISOLATORS REGARDING SOIL. INTERACTION (VID)

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ABSTRACT

The main objective of this paper is to help designers of vibration isolators for a more exact solution of isolation problem taking into account soil interaction. A computer aided design technique using the machinery and soil information is introduced.

KEYWORDS

Vibration, isolation, transmissibility, response, spectrum.

INTRODUCTION

In the classical design procedure of vibration isolators soil effects are neglected, assuming a perfectly stiff soil[1,2]. In fact, soil stiffness changes from one place to another. So, soil interaction is expected to have varying effects on the isolation procedure. Both machine and foundation responses, change by this interaction at various degrees according to the soil parameters.

For this reason, a more exact solution for machinery isolation was introduced.

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THE SUGGESTED MATHEMATICAL MODEL :

Fig. (1) show the suggested mathematical model, for more realistic approach to machinery isolation problem.

Development of Equations of Motion :

The equations of motion which describe the behavior of the mathematical model Fig. (1) "natural frequencies, mode shapes, transmissibility, and vibration response" are developed using the method of dynamic equilibrium equations [3] taking into consideration the following assumptions :
Isolator stiffness is linear, soil stiffness is linear, rigid inertia block, infinite stiffness of concrete block, the excitation is due to a known unbalance weight, the motion of the machine and foundation is restricted to the vertical and horizontal directions only, and no vibration transmitted to the foundation from the neighborhood.

The condition of equilibrium of a mass at any instant of time under the influence of forces and reactions is considered. In order to account for dynamic equiblibrium, the mass inertia force is included.
For the vertical excitation of the system (the machine, inertia block, and soil mechanism), the dynamic equilibrium equations are derived as follows :

$$m_1\ddot{z}_1 + K_{v1}(z_1-z_2) + C_{v1}(\dot{z}_1-\dot{z}_2) = F_z(t) \qquad (1)$$

$$, \quad m_2\ddot{z}_2 + C_{v2}\dot{z}_2 + C_{v1}(\dot{z}_2-\dot{z}_1)+K_{v1}(z_2-z_1)+K_{v2}z_2 = 0 \qquad (2)$$

Substitute $Fe^{i\omega t}$ for $F_z(t)$, $Z_1e^{i(\omega t-\phi_1)}$ for z_1, and $Z_2e^{i(\omega t-\phi 2)}$ for z_2.

Rearranging the terms of equations (1) and (2) and dividing all through by $e^{i\omega t}$, the equations of motion become

$$(K_{v1}-m_1\omega^2 + i\omega C_{v1})Z_1e^{-i\phi_1} - (K_{v1}+ i\omega C_{v1})Z_2e^{-i\phi_2} = F \qquad (3)$$

$$(K_{v2}+K_{v1}-m_2\omega^2 + i\omega C_{v2} + i\omega C_{v1})Z_2e^{-i\phi_2} - (K_{v1}+i\omega C_{v1})Z_1e^{-i\phi_1}=0 \qquad (4)$$

, The damping ratio term is ignored while calculating the natural frequencies and modes of the system. However, the influence of damping is considered in response calculations.

The phase angles between the exciting force and the response z_1, z_2 are given by :

$$\phi_{1v} = \tan^{-1} [\omega(A_2 \cdot A_6 - A_1 \cdot A_7)/A_9] \qquad (5)$$

,

$$\phi_{2v} = \tan^{-1} [\omega(K_{v1}.A_6 - C_{v1}.A_7)/A_{10}] \qquad (6)$$

The undamped natural frequencies of the system are

$$\omega_{1v} = Q_1^{\frac{1}{2}} \qquad (7)$$

$$, \; f_{n1v} = \omega_{1v}/2\pi \qquad (8)$$

$$, \; \omega_{2v} = Q_2^{\frac{1}{2}} \qquad (9)$$

and

$$f_{n2v} = \omega_{2v}/2\pi \qquad (10)$$

where :

$$Q_1 = [B_v + (B_v^2 - 4 A_{11} C_z)^{\frac{1}{2}}]/2 A_{11} \qquad (11)$$

$$, \; Q_2 = [B_v - (B_v^2 - 4 A_{11}.C_z)^{\frac{1}{2}}]/2 A_{11} \qquad (12)$$

The steady state response of the system can be given as :

$$, \; Z_1 = F./\sqrt{(\omega^2.(A_2.A_6-A_1.A_7)^2+(A_2.A_7+\omega^2.A_1.A_6)^2)/A_8} \qquad (13)$$

$$, \; Z_2 = F./\sqrt{((K_{v1}.A_7+\omega^2.C_{v1}.A_2)^2+\omega^2(K_{v1}.A_6-C_{v1}.A_7)^2)/A_8} \qquad (14)$$

The response of both base/bed system are

$$vZ_1 = \omega Z_1 \qquad (15)$$

$$vZ_2 = \omega Z_2 \qquad (16)$$

and the absolute transmissibility is $T = (vZ_2/vZ_1)100$ (17)

The characteristics of this model in the horizontal direction are similar to the above model except that all the parameters are related to the horizontal axis.

Method of Analysis :

The application of computer programs in obtaining the performance of vibration isolators in terms of transmissibility spectra, and also the response of both base/bed system at different frequencies are calculated for both vertical and horizontal mode. In addition, these programs have sufficient built-in flexibility in input/output operation so that design and performance of isolators can be performed in single run. A flow chart of a typical application is shown in Fig. (2).

Table (1) represents a specimen of the results obtained from this program.

DISCUSSIONS OF RESULTS :

Figs.(3) and (4) represent the response of both base/bed system for two cases of soils, a stiff soil Fig.(3) and an elastic soil Fig. (4). From these figures it is clearly noticed that in case of rigid foundation the base response has a higher value of vibration displacement, with only one mode of vibration, while the elastic foundation reflects lower values for base vibration amplitude with more modes. A contradictory effect is noticed for the bed, with lower values of vibration amplitudes at all modes in case of stiff soil.

This means that erecting a machine foundation on an elastic soil will decrease the isolation effeciency and help vibration transmission to other machinery. This fact should be taken into consideration for designing a good isolator.
This conclusion can be clearly demonstrated from the results taken from VID program representing transmissibility spectra and shown in Fig.(5) for the vertical direction and Fig.(6) in the horizontal direction.

SUGGESTED DESIGN PROCEDURE FOR ISOLATORS :

For more accurate design of isolators that takes into consideration the soil interactions, the following procedure is suggested :

a] Data required :

Soil information

1] Shear modulus of soil G.

2] Poisson's ratio of soil ν.

3] Soil unit weight γ.

Foundation information :

1] Concrete unit weight γ_c.
2] Area of foundation A_f.
3] Foundation hight H_f.

These should be stated using the recommendation given below and used for calculating the foundation mass.

Machine information :

1] Machine weight W_1.
2] Machine dimensions.
3] Forcing frequencies of machine f.
4] Machine center of gravity co-ordinates.

RECOMMENDATIONS REGARDING THE FOUNDATION DIMENSIONS & MASS :

The following items apply to block-type foundation resting on soil [4,5] :

1] A rigid block-type foundation resting on soil should have a mass of two to three times the mass of the supported machine for centrifugal machines. However, when the machine is reciprocating, the mass of the foundation should be three to five times the mass of the machine.
2] The top of the block is usually kept 30 cm above the finished floor or pavement elevation to prevent damage from surface water runoff.
3] The vertical thickness of the block should not be less than 60 cm., or as dictated by the length of anchor bolts used. The vertical thickness may also be governed by the other dimensions of the block in order that the foundation be considered rigid. The thickness is seldom less than one fifth of the least dimension or one tenth the largest dimension.
4] The foundation should be wide to increase damping in the rocking mode. The width should be at least 1 to 1.5 times the vertical distance from the base to the machine centerline.
5] Once the thickness and width have been selected, the length is determined according to (1) above, provided that sufficient plan area is avaibalbe to support the machine plus 30 cm

clearance from the edge of the machine base to the edge of the block for maintenance purposes.

6] The length and width of the foundation are adjusted so that the center of gravity of the machine plus equipment coincides with center of gravity of the foundation. The combined center of gravity should coincide with the center of resistances of the soil.

7] For large reciprocating machines, it may be desirable to increase the embedded depth in soil such that 50% to 80% of the depth is embedded. This will increase the lateral restraint and the damping ratios fox all modes of vibration.

8] Should the dynamic analysis predict resonance with the acting frequency, the mass of the foundation is increased or decreased so that, generally, the modified structure is overtuned or undertuned for reciprocating and centrifugal machines, respectively.

b] Design steps :

With this program together with the above design data in hand, the following steps are requested to be followed :

1] Given the machine mass (m_1) together with the calculated values of (m_2) and K_{v2} of the foundation, the main program VID will calculate the transmissibility spectra for different isolator to soil stiffness ratio K_{v1}/K_{v2}.

2] Traces of family of K_{v1}/K_{v2} ratio's as transmissibility spectra can be obtained from the same program Fig. (7).

3] With the forcing frequency of the machine in question on the abscissa and the required transmissibility on the ordinate of the above traces, their intersection will determine the required value of the stiffness ratio K_{v1}/K_{v2} as shown in Fig. (7).

4] Since the value of K_{v2} "soil stiffness" is already known, the required solator stiffness that fulfills the proposed isolation efficiency is hence determined.

5] To check the resonant frequencies of the designed system the traces shown in Fig. (8) can be obtained from the same program for the soil stiffness in question. These traces represent the natural frequencies of the major modes as function of stiffness ratio's K_{v1}/K_{v2}.

Given the value of K_{v2} and the designed ratio K_{v1}/K_{v2}, the frequencies of the major modes can be obtained.

CONCLUSIONS :

As far as the results of the theoretical work reported here in, are concerned, the following conclusions are drawn :

1] Soil interaction plays a great role in the vibration isolation process, and should be taken very seriously during the design stage.

2] A computer aided design procedure for vibration isolation taking into consideration the soil interaction has been created as a part of this work.

3] Stiff soil is much more favourable in vibration isolation than elastic soils, piles, are thus recommended for elastic soils whenever it is economically feasible.

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NOMENCLATURE :

A_{00}	$= m_2 \omega^2.$
A_0	$= m_1 \omega^2.$
A_1	$= C_{v1} + C_{v2}.$
A_2	$= K_{v1} + K_{v2} - A_{00}.$
A_3	$= K_{v1} . (K_{v2} - A_{00}).$
A_4	$= C_{v1} . (K_{v2} - A_{00}).$
A_5	$= C_{v1} . C_{v2} . \omega^2.$
A_6	$= A_4 + (C_{v2} . K_{v1}) - (A_0 . A_1).$
A_7	$= A_3 - (A_0 . A_2) - A_5.$
A_8	$= [(A_7)^2 + (\omega A_6)^2]^2.$
A_9	$= A_2 . A_7 + \omega^2 . A_1 . A_6.$
A_{10}	$= K_{v1} . A_7 + \omega^2 . C_{v1} . A_6.$
B	= Mount width
C_{v1}	$= 2 . \xi_1 \sqrt{K_{v1} . m_1} .$
C_{v2}	$= 2 . \xi_2 \sqrt{K_{v2} . m_2} .$
D	= Mount diameter.
F	$= m\ e\ \omega^2 .$
H	= Mount height.
L	= Mount length.
ξ_1, ξ_2	= Isolator and soil damping factor.
ω	$= 2\pi\ f .$

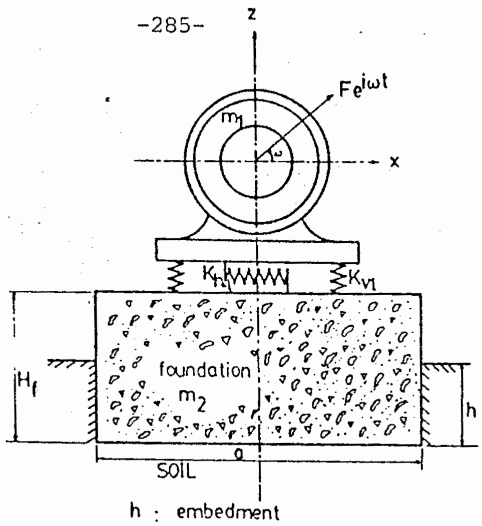

Fig. (3-7) Machine supported on concrete foundation and vibration isolated from foundation.

m_1 Equivalent machine mass.
m_2 Equivalent foundation mass.
k_{v1} Equivalent isolator stiffness.
k_{v2} Equivalent soil stiffness.
c_{v1} Isolator damping coefficient.
c_{v2} Soil damping coefficient.

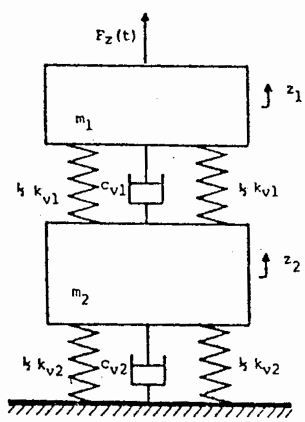

Fig. (3-7a) VERTICAL EXCITATION.

m_1 Equivalent machine mass.
m_2 Equivalent foundation mass.
k_{h1} Equivalent isolator stiffness.
k_{h2} Equivalent soil stiffness.
c_{h1} Isolator damping coefficient.
c_{h2} Soil damping coefficient.

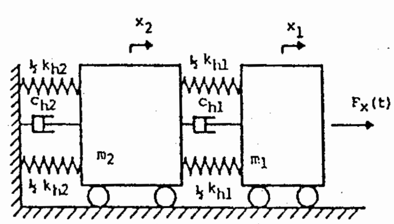

Fig. (3-7b) HORIZONTAL EXCITATION.

Fig. (1) MATHEMATICAL MODEL.

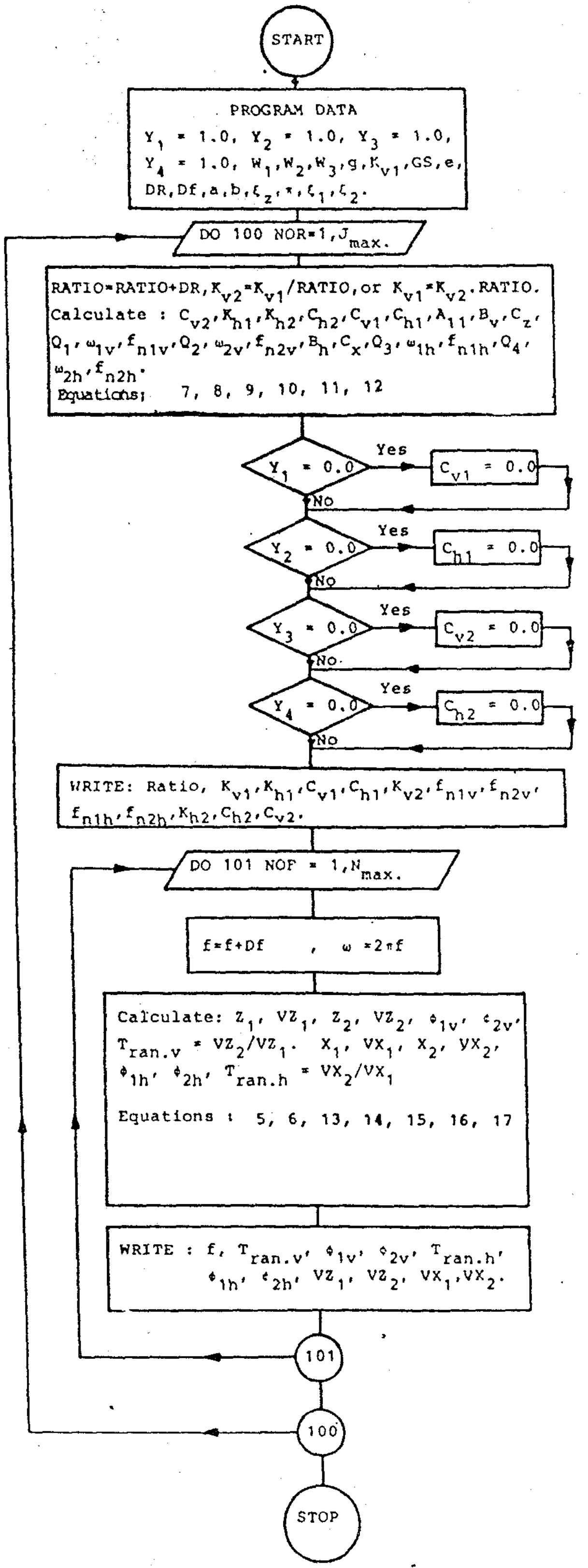

Fig.(2) Flow chart(VID PROGRAM) for designing isolator or performance of isolator considering soil interaction effect.

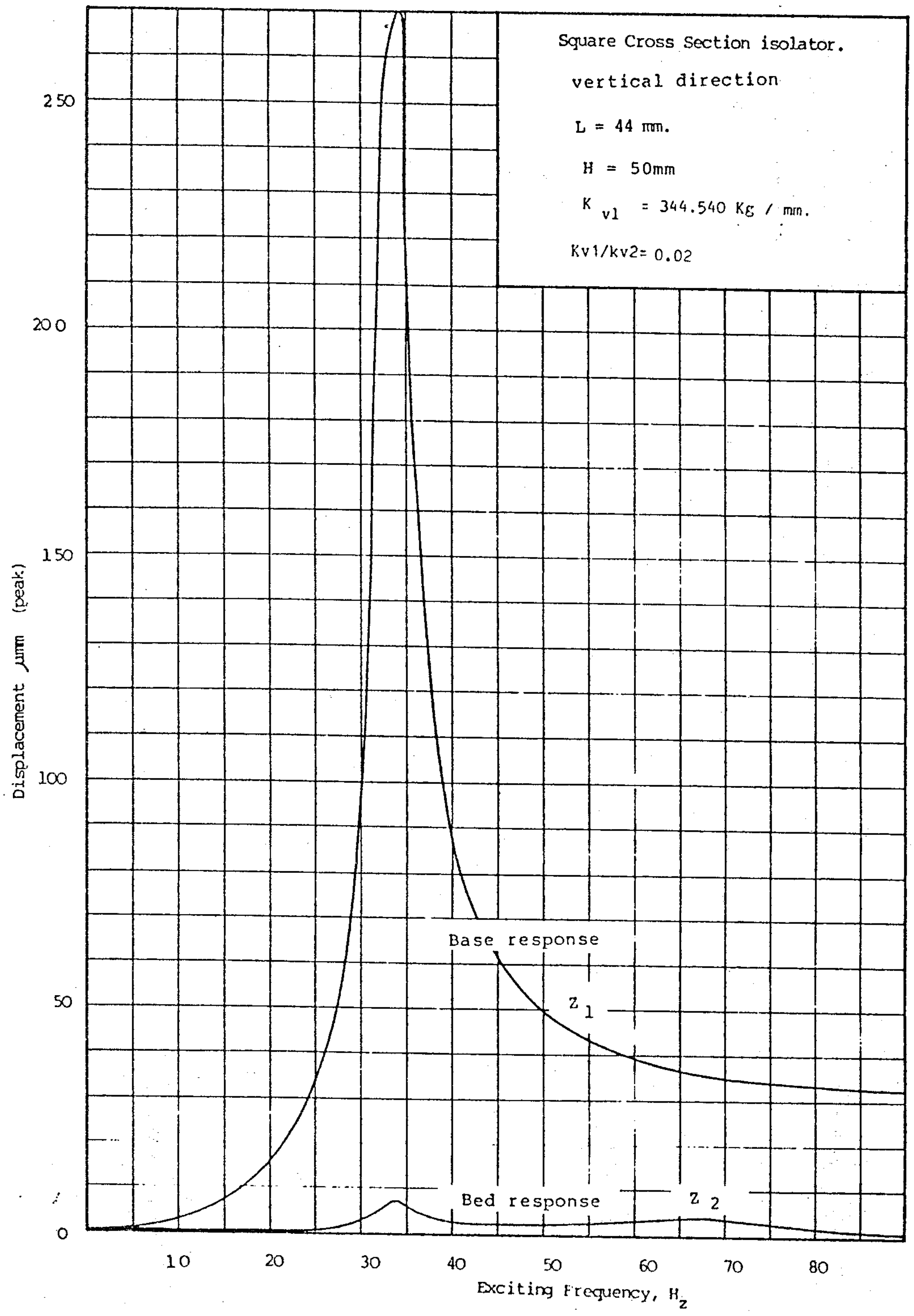

Fig. (3) Motion response for the case of rigid soil.

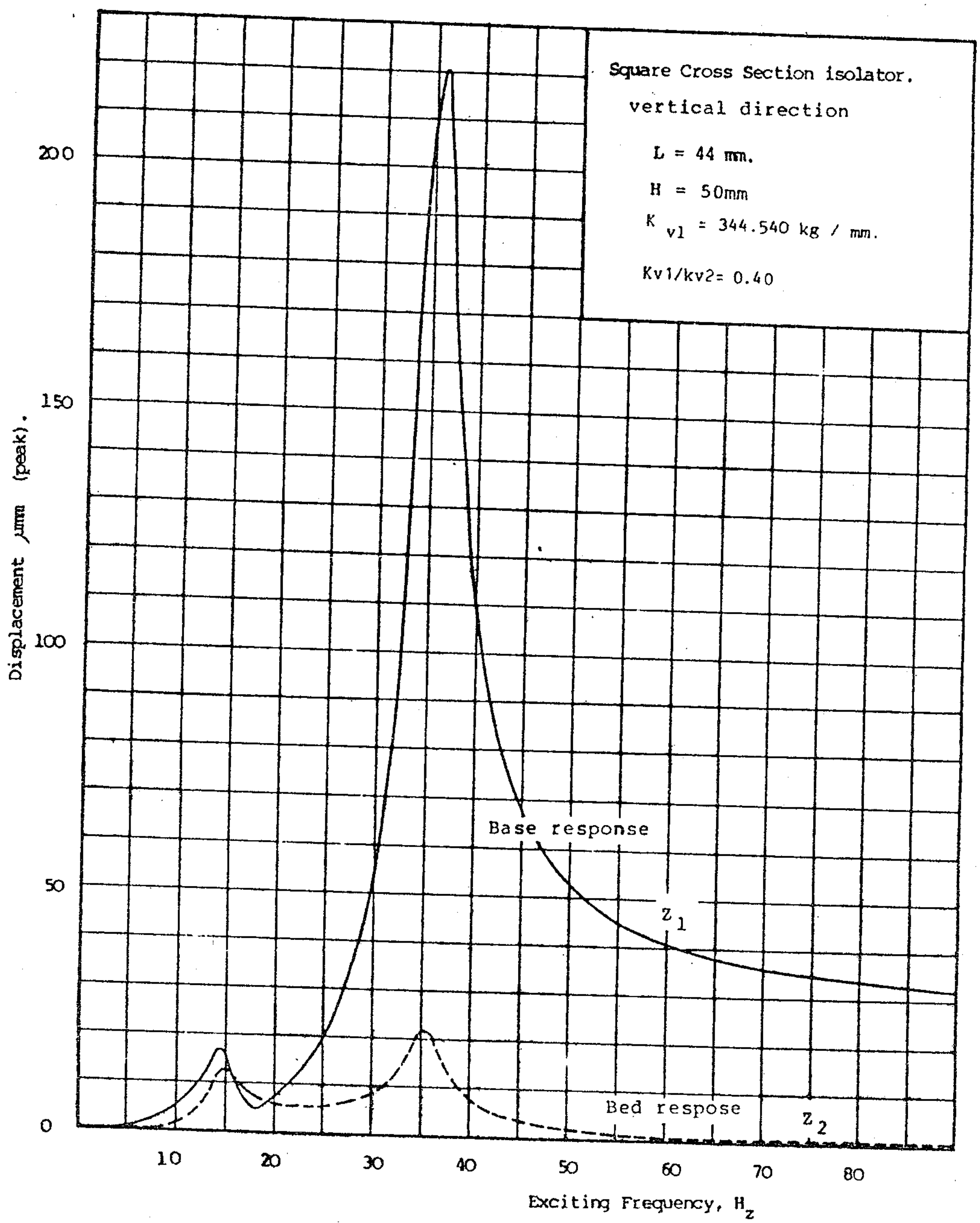

Fig.(4) Motion response for the case of elastic soil.

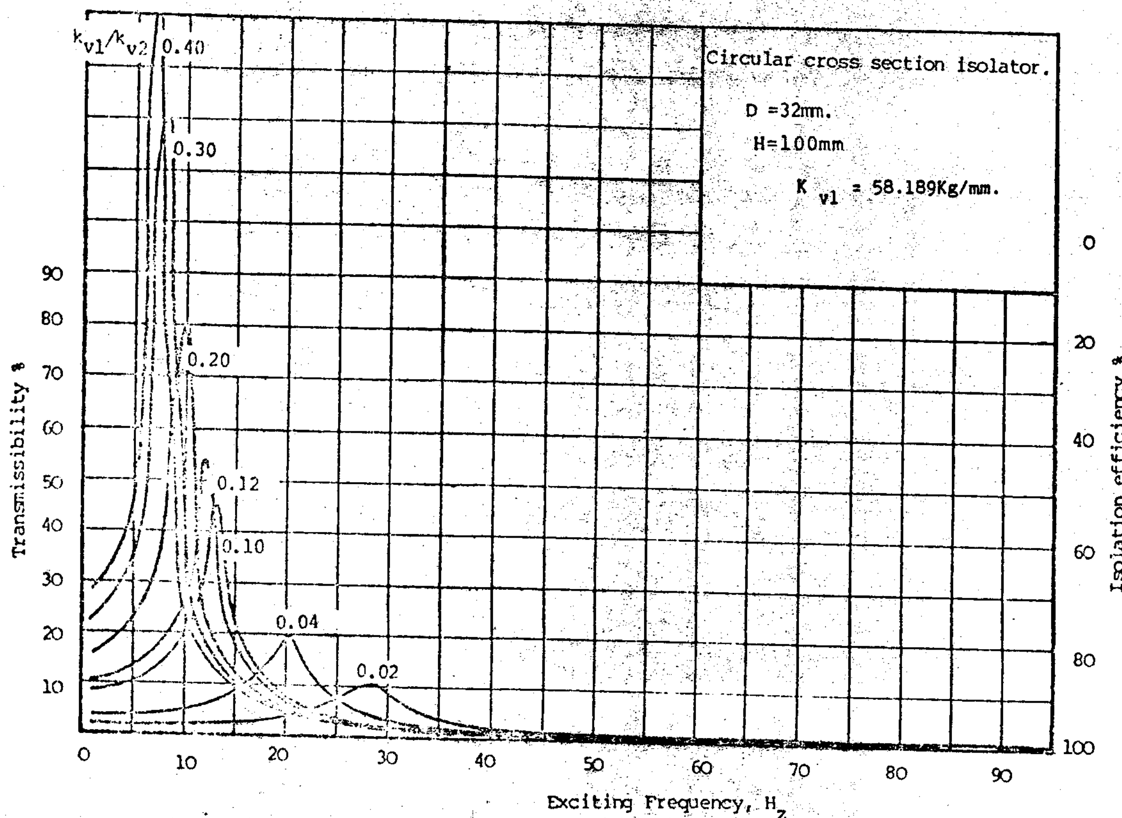

Fig.(5) Soil interaction effect in the vertical direction.

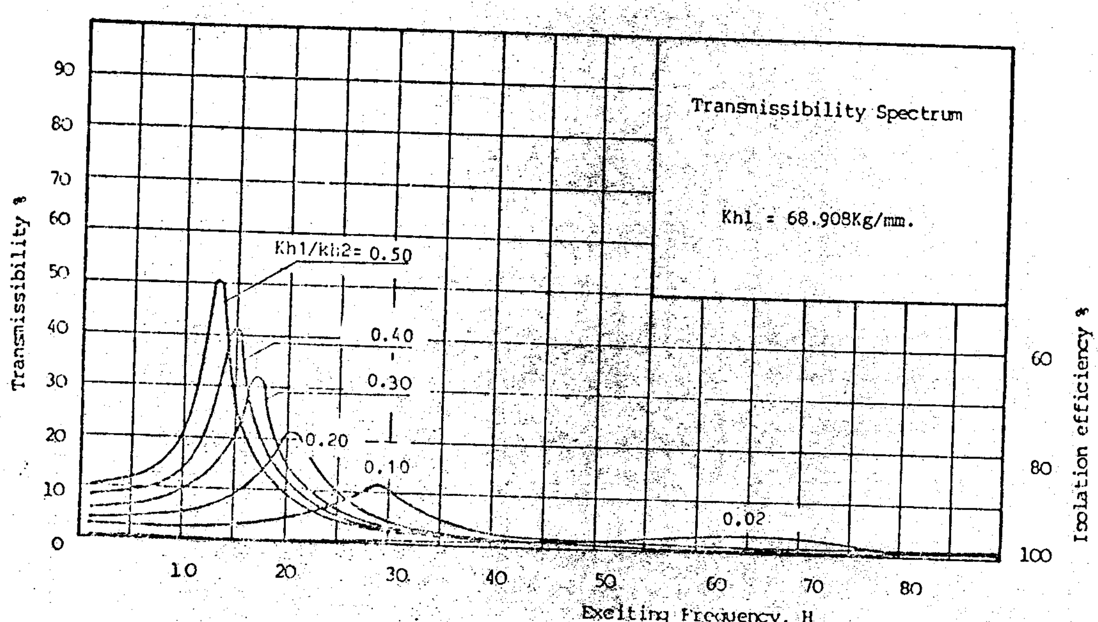

Fig.(6) Soil interaction effect in the horizontal direction.

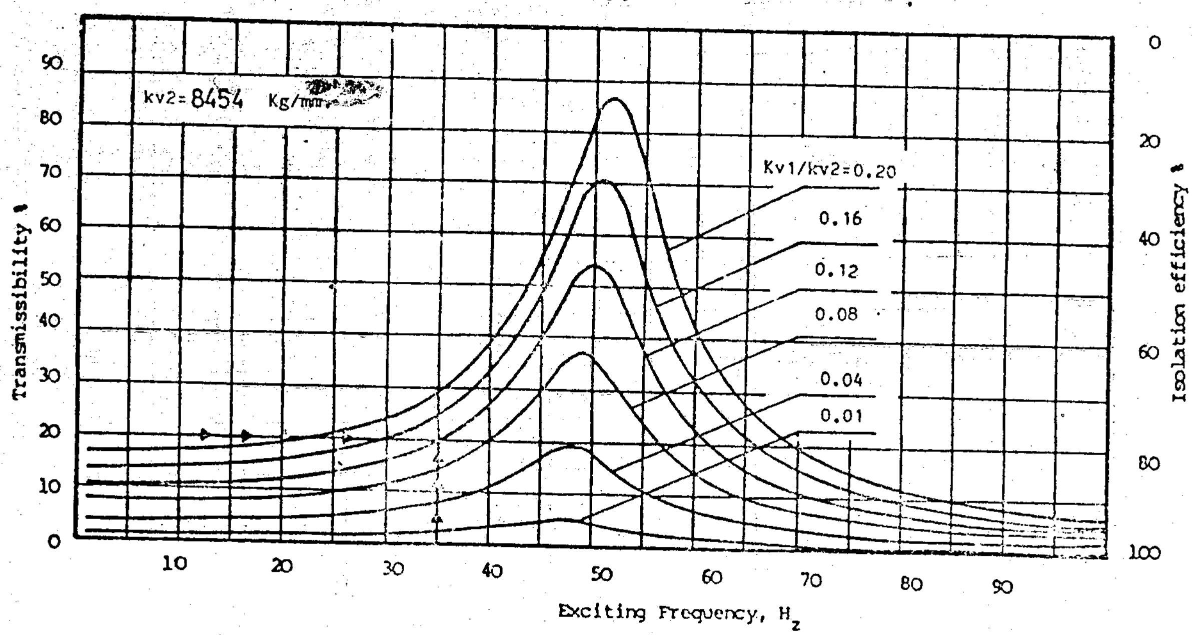

Fig. (7) Design curves considering soil interaction effects.

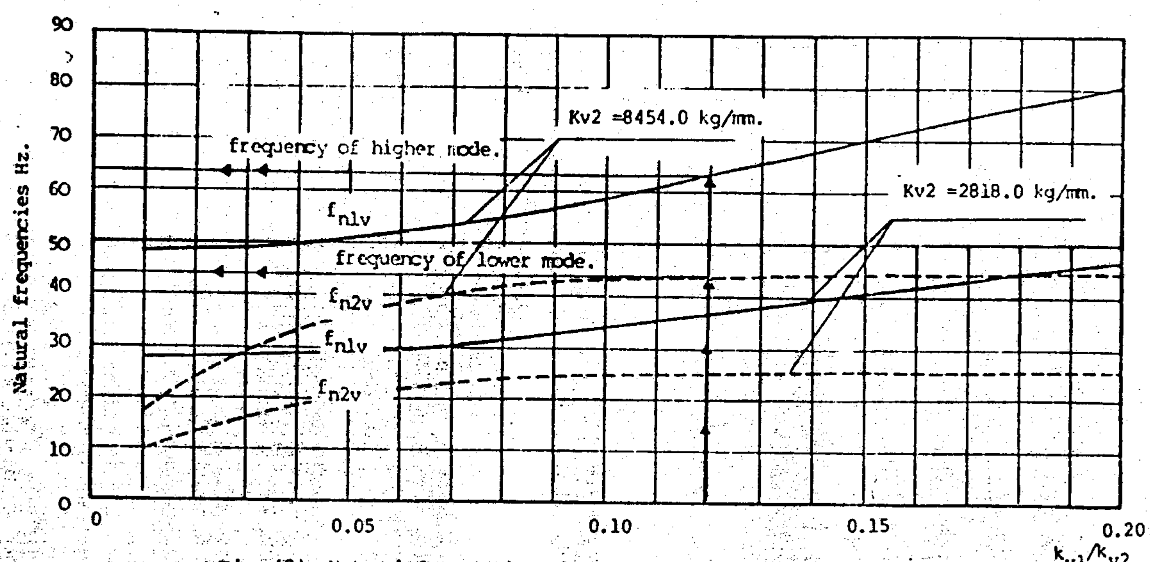

Fig. (8) Natural frequencies of the system considering soil interaction effect (CHECK CURVES).

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Table(1) Specimen of the results obtained from(VID)program.

SEG NONM
SEG SORT
SEG ATAN

KVI... 0.01   KV1= 0.84540E 02   KH1= 0.16904E 02   CV1= 0.80047E 01   CH1= 0.35807E-01   KV2= 0.94540E 04
...1V ...79522 02   FN2V= 0.16710E 02   FN1H= 0.44715E 01   FN2H= 0.75064E 01   KH2= 0.74251E 04   CH2= 0.52691E 01   CV2= 0.56437E 01

I	TRANV 1	PHI1V	PHI2V	TRANH 1	PHI1H	PHI2H	VZ1	VZ2	VX1	VX2
1.0	0.97054E 00	0.34117E 00	0.24165E 00	0.22735E 00	0.77495E 01	0.70322E 01	[illegible]	0.62072E-05	0.31539E-02	0.71696E-05
2.0	0.99186E 00	0.68775E 00	0.49136E 00	0.22772E 00	0.16354E 01	0.63013E 00	0.50075E-04	0.50263E-04	0.26669E-01	0.60730E-04
3.0	0.99407E 00	0.10537E 01	0.75772E 00	0.22832E 00	0.27155E 01	0.12060E 01	0.17415E-01	0.17314E-03	0.99440E-01	0.22710E-03
4.0	0.99719E 00	0.14421E 01	0.10505E 01	0.22931E 00	0.42446E 01	0.22364E 01	0.42173E-01	0.42258E-03	0.27616E 00	0.63326E-03
5.0	0.10012E 01	0.18661E 01	0.13816E 01	0.23052E 00	0.63092E 01	0.43069E 01	0.85671E-01	0.65785E-03	0.69122E 00	0.15934E-02
6.0	0.10062E 01	0.23401E 01	0.17659E 01	0.23201E 00	0.12446E 02	0.94570E 01	0.15470E 00	0.15566E-02	0.18097E 01	0.41985E-02
7.0	0.10121E 01	0.28833E 01	0.22236E 01	0.23378E 00	0.35496E 02	0.32023E 02	0.25942E 00	0.26256E-02	0.66352E 01	0.15512E-01
8.0	0.10190E 01	0.35233E 01	0.27828E 01	0.23586E 00	-0.38045E 02	-0.41993E 02	0.41577E 00	0.42185E-02	0.91982E 01	0.21695E-01
9.0	0.10270E 01	0.43007E 01	0.34852E 01	0.23826E 00	-0.15284E 02	-0.19699E 02	0.63918E 00	0.65663E-02	0.49797E 01	0.11865E-01
10.0	0.10360E 01	0.52798E 01	0.43958E 01	0.24095E 00	-0.97300E 01	-0.14600E 02	0.96864E 00	0.10035E-01	0.39416E 01	0.94986E-02
11.0	0.10462E 01	0.65680E 01	0.56229E 01	0.24405E 00	-0.72575E 01	-0.12572E 02	0.14570E 01	0.15242E-01	0.35651E 01	0.87009E-02
12.0	0.10575E 01	0.83604E 01	0.73626E 01	0.24749E 00	-0.58505E 01	-0.11596E 02	0.22042E 01	0.23309E-01	0.34237E 01	0.84733E-02
13.0	0.10701E 01	0.11051E 02	0.10010E 02	0.25132E 00	-0.49363E 01	-0.11098E 02	0.34106E 01	0.36496E-01	0.33920E 01	0.85248E-02
14.0	0.10840E 01	0.15565E 02	0.14492E 02	0.25557E 00	-0.42906E 01	-0.10852E 02	0.55376E 01	0.60027E-01	0.34205E 01	0.87419E-02
15.0	0.10993E 01	0.24611E 02	0.23516E 02	0.26027E 00	-0.38079E 01	-0.10751E 02	0.93664E 01	0.10846E 00	0.34858E 01	0.90724E-02
16.0	0.11162E 01	0.48768E 02	0.47667E 02	0.26546E 00	-0.34318E 01	-0.10735E 02	0.20274E 02	0.22629E 00	0.35751E 01	0.94902E-02
17.0	0.11346E 01	-0.70820E 02	-0.71913E 02	0.27117E 00	-0.31295E 01	-0.10771E 02	0.28745E 02	0.32616E 00	0.36810E 01	0.99817E-02
18.0	0.11549E 01	-0.33629E 02	-0.34699E 02	0.27746E 00	-0.28806E 01	-0.10835E 02	0.18893E 02	0.21825E 00	0.37990E 01	0.10541E-01
19.0	0.11770E 01	-0.21028E 02	-0.22055E 02	0.28438E 00	-0.26714E 01	-0.10910E 02	0.13644E 02	0.16058E 00	0.39261E 01	0.11165E-01
20.0	0.12012E 01	-0.15322E 02	-0.16284E 02	0.29199E 00	-0.24929E 01	-0.10984E 02	0.11133E 02	0.13373E 00	0.40601E 01	0.11855E-01
21.0	0.12276E 01	-0.12120E 02	-0.12996E 02	0.30037E 00	-0.23385E 01	-0.11046E 02	0.97540E 01	0.11974E 00	0.41995E 01	0.12614E-01
22.0	0.12566E 01	-0.10077E 02	-0.10839E 02	0.30962E 00	-0.22035E 01	-0.11088E 02	0.89218E 01	0.11211E 00	0.43434E 01	0.13448E-01
23.0	0.12883E 01	-0.86600E 01	-0.92794E 01	0.31982E 00	-0.20842E 01	-0.11100E 02	0.83918E 01	0.10811E 00	0.44908E 01	0.14362E-01
24.0	0.13230E 01	-0.76180E 01	-0.80613E 01	0.33110E 00	-0.19780E 01	-0.11074E 02	0.80452E 01	0.10644E 00	0.46412E 01	0.15367E-01
25.0	0.13612E 01	-0.68184E 01	-0.70480E 01	0.34360E 00	-0.18827E 01	-0.11001E 02	0.78182E 01	0.10642E 00	0.47941E 01	0.16473E-01
26.0	0.14031E 01	-0.61845E 01	-0.61577E 01	0.35750E 00	-0.17946E 01	-0.10870E 02	0.76732E 01	0.10766E 00	0.49491E 01	0.17693E-01
27.0	0.14493E 01	-0.56688E 01	-0.53370E 01	0.37299E 00	-0.17185E 01	-0.10671E 02	0.75871E 01	0.10996E 00	0.51059E 01	0.19044E-01
28.0	0.15003E 01	-0.52407E 01	-0.45479E 01	0.39032E 00	-0.16473E 01	-0.10389E 02	0.75446E 01	0.11319E 00	0.52642E 01	0.20547E-01
29.0	0.15567E 01	-0.48791E 01	-0.37613E 01	0.40979E 00	-0.15819E 01	-0.10009E 02	0.75353E 01	0.11730E 00	0.54239E 01	0.22226E-01
30.0	0.16194E 01	-0.45694E 01	-0.29521E 01	0.43175E 00	-0.15218E 01	-0.95122E 01	0.75519E 01	0.12230E 00	0.55847E 01	0.24112E-01
31.0	0.16894E 01	-0.43010E 01	-0.20977E 01	0.45665E 00	-0.14662E 01	-0.88739E 01	0.75890E 01	0.12821E 00	0.57466E 01	0.26242E-01
32.0	0.17676E 01	-0.40662E 01	-0.11753E 01	0.48504E 00	-0.14147E 01	-0.80646E 01	0.76428E 01	0.13509E 00	0.59094E 01	0.28663E-01
33.0	0.18554E 01	-0.38590E 01	-0.16056E 00	0.51758E 00	-0.13669E 01	-0.70466E 01	0.77101E 01	0.14306E 00	0.60731E 01	0.31433E-01
34.0	0.19546E 01	-0.36750E 01	0.97387E 00	0.55513E 00	-0.13223E 01	-0.57710E 01	0.77886E 01	0.15224E 00	0.62374E 01	0.34625E-01
35.0	0.20671E 01	-0.35107E 01	0.22601E 01	0.59870E 00	-0.12806E 01	-0.41742E 01	0.78766E 01	0.16282E 00	0.64024E 01	0.38331E-01
36.0	0.21953E 01	-0.33636E 01	0.37373E 01	0.64956E 00	-0.12416E 01	-0.21722E 01	0.79726E 01	0.17502E 00	0.65680E 01	0.42662E-01
37.0	0.23422E 01	-0.32317E 01	0.54539E 01	0.70919E 00	-0.12052E 01	0.34635E 00	0.80752E 01	0.18914E 00	0.67340E 01	0.47757E-01
38.0	0.25114E 01	-0.31137E 01	0.74717E 01	0.77922E 00	-0.11710E 01	0.35323E 01	0.81837E 01	0.20553E 00	0.69005E 01	0.53771E-01
39.0	0.27071E 01	-0.30086E 01	0.98703E 01	0.86114E 00	-0.11392E 01	0.75816E 01	0.82971E 01	0.22461E 00	0.70675E 01	0.60861E-01
40.0	0.29341E 01	-0.29163E 01	0.12753E 02	0.95547E 00	-0.11097E 01	0.12748E 02	0.84148E 01	0.24690E 00	0.72348E 01	0.69126E-01
41.0	0.31972E 01	-0.28371E 01	0.16254E 02	0.10601E 01	-0.10827E 01	0.19330E 02	0.85362E 01	0.27292E 00	0.74024E 01	0.78474E-01
42.0	0.35000E 01	-0.27720E 01	0.20546E 02	0.11672E 01	-0.10573E 01	0.27608E 02	0.86611E 01	0.30314E 00	0.75704E 01	0.88363E-01
43.0	0.38426E 01	-0.27224E 01	0.25843E 02	0.12598E 01	-0.10364E 01	0.37690E 02	0.87894E 01	0.33774E 00	0.77389E 01	0.97498E-01
44.0	0.42151E 01	-0.26698E 01	0.32388E 02	0.13131E 01	-0.10164E 01	0.49259E 02	0.89214E 01	0.37605E 00	0.79079E 01	0.10384E 00
45.0	0.45895E 01	-0.26739E 01	0.40402E 02	0.13067E 01	-0.99694E 00	0.61430E 02	0.90570E 01	0.41571E 00	0.80775E 01	0.10555E 00
46.0	0.49105E 01	-0.26693E 01	0.49966E 02	0.12413E 01	-0.97662E 00	0.73032E 02	0.92003E 01	0.45178E 00	0.82475E 01	0.10238E 00
47.0	0.51004E 01	-0.26630E 01	0.60846E 02	0.11384E 01	-0.95552E 00	0.83172E 02	0.93494E 01	0.47685E 00	0.84178E 01	0.95826E-01
48.0	0.50925E 01	-0.26378E 01	0.72377E 02	0.10231E 01	-0.93450E 00	-0.88482E 02	0.95044E 01	0.48401E 00	0.85882E 01	0.87865E-01
49.0	0.48794E 01	-0.25538E 01	0.83624E 02	0.91223E 00	-0.91348E 00	-0.81829E 02	0.96626E 01	0.47148E 00	0.87587E 01	0.79899E-01
50.0	0.45203E 01	-0.25052E 01	-0.86227E 02	0.81322E 00	-0.89315E 00	-0.76588E 02	0.98209E 01	0.44393E 00	0.89292E 01	0.72614E-01
51.0	0.40975E 01	-0.24146E 01	-0.77588E 02	0.72774E 00	-0.87369E 00	-0.72462E 02	0.99775E 01	0.40666E 00	0.90999E 01	0.66227E-01
52.0	0.35758E 01	-0.23433E 01	0.70484E 02	0.65507E 00	-0.85511E 00	-0.69191E 02	0.10132E 02	0.37244E 00	0.92707E 01	0.60775E-01