Composite Computational Model for Portland Cememt Concrete Pavement

Bo Tian and Kai-min Niu

ABSTRACT: It is well known that there are two models in pavement calculation, one is Winkler model and the other is multi-layered elastic model. In this paper, a new bi-parameter computational model is presented for analyzing layered base and subgrade in the Portland cement concrete pavement. In the new model the subgrade is represented by a group of the springs with k-vaule, and subbase/base are modeled by elastic multi-layer there has several elastic layers on Winkler foundation. However either Winkler model or Boussinesq and Burmister model only use one material parameter, the modulus of reaction k or elastic modulus E. So the new model has the merit of the two classical models. Finally result of the new model is compared with the enhanced k-value method in PCA, FAA, etc.

Key Words: Portland cement concrete pavement, Model, Subbase, Transfer matrix method

INTRODUCTION

There are many foundation models for analyzing pavement, such as Winkler, Burmister (or Boussinesq), Pasternak and Kerr foundation. When subbase is used in PCC pavement, adjustment of subgrade modulus is required in order to apply existed design method. PCA, AASHTO, FAA and USACE define their modified method respectively. There are some methods to solve multilayered half space problems, and transfer matrix method is used in the paper.

Foundation model

Winkler Foundation

Winkler foundation is described with a group of springs. The corresponding force-deflection relationship is defined by

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$$p(x, y) = kw(x, y) \qquad (1)$$

Boussinesq and Burmister Foundation

Mechanical property of infinite half elastic space can be described by elastic modulus E and Poisson ratio υ. The relationship between vertical deflection and uniform circular load is solved by Boussinesq, and is expressed as:

$$w(r) = \frac{2(1-\upsilon_0^2)}{E_0}\int_0^{\infty}\overline{p}(\xi)J_0(\xi r)d\xi \qquad (2)$$

There is also a similar relationship between the vertical deflection and uniform circular load by using Burmister foundation.

Pasternak Foundation

Winkler foundation is considered as a group of separate springs, and there is no interaction among the springs. The more realistic model introduced by Pasternak also considers the shear forces between springs, as shown in Figure 1. However the shearing modulus is hard to determine. The response expression is

$$p = kw - G_b\nabla^2 w \qquad (3)$$

Kerr Foundation

Kerr observed that the results of vertical displacement and stress in the edge of slab were abnormal when free slab was applied on the Pasternak foundation, also there were some computational difficulties encountered when concentrated load was applied on the slab by using Pasternak model. Thus Kerr modified the Pasternak model by adding a spring layer as shown in Figure. 2. The corresponding governing equation is shown in :

$$(1+\frac{k}{c})p - \frac{G_b}{c}\nabla^2 p = kw - G_b\nabla^2 w \qquad (4)$$

Modified Modulus Methods

If there is subbase or base in the pavement structure, the foundation of subgrade should be modified or enhanced. Therefore, methodologies for estimating the composite modulus of multilayered system underneath the concrete slab are included in the design method. PCA, USACE and FAA give the separate relationships for untreated and treated base materials. Uzan and Witczak (Uzan, 1985) consider that the relationships for the granular materials are almost same, while differ to some extent for stabilized base materials.

For cement treated base, PCA (PCA, 1984) method recommends the determination of composite modulus from field plate bearing tests, which is performed on the surface of base course by using a 30-in. diameter plate. For untreated base, two layers Burmister system is employed to modify the composite modulus.

FAA and USACE also give their modified method based on their experiment and theoretical research studies. FAA (FAA, 1995) recommends the typical table for the composite modulus of granular base, and considers that the composite modulus of treated base is 1.2~1.6 times than granular one. USACE (Army T.M. 1979) gives nomographic for composite modulus of treated and untreated one.

If the slab is placed directly on the subgrade without subbase. AASHTO (AASHTO, 1993) suggested the following theoretical relationship based on an analysis of plate bearing of plate bearing test , $k = \frac{M_R}{19.4}$. This equation gives a too large k-value. If there is subbase in pavement, two layers Burmister system theory is employed with a 30-in. diameter load plate and a 69-kPa (10psi) uniform pressure. There is also a chart for estimating modulus of subbase reaction in *AASHTO Guide for Design of Pavement Structures*.

Multilayered Half Space Problems

Since Burmister gave the Burmister system theory in 1943, there are several methods to solve the problem. Wang(1996) gave one resolvent with transfer matrix method, in which every layer can be described with one matrix. Tian(1998) improves the model into static elastic, static viscoelastic, dynamic elastic and dynamic viscoelastic one.

THEORETICAL APPROACH OF NEW MODEL

Methodology with Transfer Matrix Method

The new model is similar with Burmister system, except that the half elastic space is substituted by springs. Then the new model includes two parameters, one is the elastic modulus E (and Poisson ratio, thickness of each layer in Burmister system), the other is the reaction modulus k of spring, shown in Figure 3.

In the classical theory of multilayered elastic system, there is the governing differential equation for each layer:

$$\frac{\partial \sigma_r}{\partial r}+\frac{\partial \tau_{zr}}{\partial z}+\frac{\sigma_r-\sigma_\theta}{r}=0 \qquad (5)$$

$$\frac{\partial \sigma_z}{\partial z}+\frac{\partial \tau_{zr}}{\partial r}+\frac{\tau_{zr}}{r}=0 \qquad (6)$$

The main mathematical tools used in our multi-layer system analysis are Laplace, Hankel integral transformation and the Transfer Matrix Method.

Laplace and Hankel integral transformation are applied in eq. 5 and Eq. 6. Then

$$\frac{d}{dz}\begin{bmatrix}\bar{u}\\ \bar{w}\\ \bar{\tau}_{zr}\\ \bar{\sigma}_z\end{bmatrix}=[A(\xi)]\begin{bmatrix}\bar{u}\\ \bar{w}\\ \bar{\tau}_{zr}\\ \bar{\sigma}_z\end{bmatrix} \qquad (7)$$

Where,

$$[A(\xi)]=\begin{bmatrix}0 & \xi & \frac{2(1+\upsilon)}{E} & 0\\ \frac{-\upsilon}{1-\upsilon}\xi & 0 & 0 & \frac{(1+\upsilon)(1-2\upsilon)}{E(1-\upsilon)}\\ \frac{E\xi^2}{1-\upsilon^2} & 0 & 0 & \frac{\upsilon}{1-\upsilon}\xi\\ 0 & 0 & -\xi & 0\end{bmatrix}, \text{ is a } 4\times 4 \text{ matrix}$$

The result for Eq. 7 is

$$\begin{bmatrix}\bar{u}(\xi,z)\\ \bar{w}(\xi,z)\\ \bar{\tau}_{zr}(\xi,z)\\ \bar{\sigma}_z(\xi,z)\end{bmatrix}=\begin{bmatrix}4\times 4\\ Matrix\end{bmatrix}\begin{bmatrix}\bar{u}(\xi,0)\\ \bar{w}(\xi,0)\\ \bar{\tau}_{zr}(\xi,0)\\ \bar{\sigma}_z(\xi,0)\end{bmatrix}=[\exp(z[A(\xi)])]\begin{bmatrix}\bar{u}(\xi,0)\\ \bar{w}(\xi,0)\\ \bar{\tau}_{zr}(\xi,0)\\ \bar{\sigma}_z(\xi,0)\end{bmatrix} \qquad (8)$$

In brief, $\overline{X}(\xi,z)=[\exp(z[A(\xi)])]\bar{x}(\xi,0)=[T_i]\bar{x}(\xi,0)$ (9)

$[T_i]$ is a 4×4 exponential matrix, referred to as layer transfer matrix. For the exponential matrix, we have

$$[\exp(A(\xi))] = [\exp([m](\lambda)[m]^{-1})] = [m]\exp(\lambda)[m]^{-1} \qquad (10)$$

which is equivalent to

$$[\exp(A(\xi))] == [m]\begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \lambda_3 & \\ & & & \lambda_2 \end{bmatrix}[m]^{-1}$$

And $\overline{x}(\xi, z)$ can be solved by using the boundary condtion.

Finally Hankel inverse integral transformation is applied to obtain the displacement and stress.

If there are n layers in pavement with one layer spring, We have

$$\overline{X}(\xi, z_n) = \prod_{i=n}^{1}[T_i]\overline{X}(\xi, 0) \qquad (11)$$

One Layer Model Approach

One layer model means that there are one elastic layer, which is represented by the elastic modulus E_1, Poisson ratio υ_1 and thickness h_1 , and one layer spring with reaction modulus k, as shown in Figure 4.

The boundary equations are

(1) At the surface of pavement

For z=0, $\sigma_z\big|_{z=0} = -p(r)$ and $\tau_{zr}\big|_{z=0} = 0$

(2)At the interface between elastic layer and spring

For z=h_1, $\begin{matrix} \sigma_z = -kw \\ \tau_{rz} = 0 \end{matrix}$.

Then $\overline{X}(\xi, h_1) = \prod_{i=1}^{1}[T_i]\overline{X}(\xi, 0)$, which becomes

$$\begin{bmatrix} \overline{u^1} \\ \overline{w^1} \\ \overline{\tau_{zr}^1} \\ \overline{\sigma_z^1} \end{bmatrix} = [T_1]\begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ \overline{\tau_{zr}^0} \\ \overline{\sigma_z^0} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}\begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ \overline{\tau_{zr}^0} \\ \overline{\sigma_z^0} \end{bmatrix}$$

$$\begin{bmatrix} \overline{u^1} \\ \overline{w^1} \\ 0 \\ -k\overline{w^1} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}\begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ 0 \\ \overline{P^0}(\xi) \end{bmatrix} \qquad (12)$$

So the vertical deflection on surface in the Hankel domain is

$$\overline{w^0} = \frac{a_{31}(ka_{24}+a_{44})-a_{34}(ka_{21}+a_{41})}{a_{32}(ka_{21}+a_{41})-a_{31}(ka_{22}+a_{42})}\overline{P}^0(\xi) \qquad (13)$$

N-Layer Model Approach

N-layer model means that there are N elastic layers, characterized by their elastic modulus(E_1, E_2, …E_i, …E_n), Poisson ratio(υ_1, υ_2, … υ_i, … υ_n) and thickness(h_1, h_2, …h_i, …h_n), and one layer spring with reaction modulus k, as shown in Figure 3.

The corresponding boundary equation are

(1) At the surface of pavement

For z=0, $\sigma_{z1}\big|_{z=0} = -p(r)$ and $\tau_{zr1}\big|_{z=0} = 0$

(2) interface contact condition

Between two elastic layers

For $z \neq H_n$, $\sigma_{z_k}\big|_{z=H_k} = \sigma_{z_{k+1}}\big|_{z=H_k}$ $\quad \tau_{zr_k}\big|_{z=H_k} = \tau_{zr_{k+1}}\big|_{z=H_k}$ $\quad U_k\big|_{z=H_k} = U_{k+1}\big|_{z=H_k}$ $\quad w_k\big|_{z=H_k} = w_{k+1}\big|_{z=H_k}$

Between elastic layer and Spring

For z=H_n, $\sigma_z = -kw$,

$\tau_{rz} = 0$

then, $\overline{X}(\xi, h_n) = [T_n]\times[T_{n-1}]\times[T_{n-2}]\times....\times[T_2]\times[T_1]\overline{X}(\xi,0) = \prod_{i=n}^{1}[T_i]\overline{X}(\xi,0)$ (14)

where, $\prod_{i=n}^{1}[T_i]$ is a 4×4 matrix,

$$\prod_{i=n}^{1}[T_i] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$

then,

$$\begin{bmatrix} \overline{u^n} \\ \overline{w^n} \\ \overline{\tau_{zr}^n} \\ \overline{\sigma_z^n} \end{bmatrix} = \prod_{i=n}^{1}[T_i] \begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ \overline{\tau_{zr}^0} \\ \overline{\sigma_z^0} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ \overline{\tau_{zr}^0} \\ \overline{\sigma_z^0} \end{bmatrix}$$

$$\begin{bmatrix} \overline{u^n} \\ \overline{w^n} \\ 0 \\ -k\overline{w^n} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \overline{u^0} \\ \overline{w^0} \\ 0 \\ \overline{p^0}(\xi) \end{bmatrix} \qquad (15)$$

Finally, the surface deflection in Hankel domain is

$$\overline{w_0} = \frac{a_{31}(ka_{24} + a_{44}) - a_{34}(ka_{21} + a_{41})}{a_{32}(ka_{21} + a_{41}) - a_{31}(ka_{22} + a_{42})} \overline{P}^0(\xi) \qquad (16)$$

VERIFICATION

Verification of New Model by Itself

In order to verify the new model, N-layer model is compared with one-layer model. There exist two structures. One is the one-layer (thickness H, Modulus E, Poisson ratio υ) on spring K; The other is N-layer structure on spring K, which comes from the one-layer divided into N layers.

Because the two models indeed are the same one, the answers based on N-layer model should be equal to those derived from one-layer model. An example is shown in Table 1, indicating that the vertical deflection for the 100-layer and one layer are same in the load center. And the answers for 3-layer and one layer are also equal.

New Model vs. Infinite Slab on Winkler Foundation

The one-layer new model is indeed the same with infinite slab on Winkler foundation, except that the compression deformation is negligible in infinite slab. Thus the deflection for one-layer new model should be greater than infinite slab on Winkler foundation. Table 2 shows that the deflection basin for one-layer new model is a little bit larger.

New Model vs. Unbounded Subbase

In order to compare the new model with FAA, USACE and PCA, two unbounded moduli, 345MPa(50,000psi) and 207MPa(30,000psi), are adopted respectively. Because the definition of reaction modulus is defined as the ratio of an applied pressure q to deflection w_0 , a 762-mm(30-in), 0.069-MPa(10-psi) uniform pressure and 0.3-Possion ration are calculated in the new model. The calculation answer and three modified results are shown in the table 3, which suggests that they are so close. The former is a little bit lower with thin base layer and low reaction modulus, while a little bit larger with thick base layer and high reaction modulus.

New Model vs. Treated Subbase

In PCA Plate-loading test (Childs, 1967) is used to determine k values of cement treated base for full-scale test slabs, the compression modulus of treated base is 9092MPa (1,300,000psi). Three plate diameters, 76.2/ 86.4/ 96.6 cm, are adopted in new model. The results are shown in the table 4.

When the 76.2cm-plate is used, our results are much higher than the modified values in PCA. Only when 96.6cm-plate is used, our results are close to PCA modified values.

As to FAA modified method, there is no modulus of treated base in AC-150/5320-6D, and the composite modulus of treated base is simply assumed to be 1.2~1.6 times of that for the granular one, thus no comparison can be made between our new model and FAA. However our results are in the range of values used in FAA modified method when 96.6-cm load plate is used in the calculation.

USACE modified method is based on Burmister system, the thickness for stabilized base varies from 15.24cm to 38.1cm, from 69MPa to 6900MPa in base modulus. The results are listed in table 5, showing that the two answers are close when the base modulus is low. While the result is larger than USACE modified method when higher modulus is used.

SUMMARY AND CONCLUSIONS

1. The new model combines the Winkler foundation with Burmister foundation , it has better property to model cement concrete slab foundation. It can be derived by using the Transfer Matrix Method.

2. Numerical experiments between one-layer new model and N-layer new model, one-layer new model and infinite slab on Winkler foundation are conducted, and the results show that our model is correct.

3. Our new model and the modified PCA, FAA methods gives similar results for PCC with untreated base, While to treated base, the deflection in the new model are greater than those generated by the others modified methods.

ACKNOWLEDGMENTS

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APPENDIX II NOTATION

The following symbols are used in this paper:

p= the unit pressure

k= the reaction modulus

c= the modulus of new spring layer in Kerr Model

G_b =shearing modulus

$\overline{p}(\xi)$ = load in Hankel transfer

$J_0(\xi r)$ =Bessel function of first kind and order 0

r = radial distance from load center

z= the variable parameter in thickness direction

x= the variable parameter in x direction

y= the variable parameter in y direction

ξ =the variable parameter in Hankel domain

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

M_R =modulus of subgrade

σ_r =stress in r direction

σ_θ =stress in θ direction

σ_z =stress in z direction

τ_{zr} =shear stress in zr direction

u=horizontal deform

w =vertical deflection.

$\overline{u}$ = horizontal deform at Hankel domain

$\overline{w}$ =vertical deform at Hankel domain

$\overline{\tau_{zr}} = \tau_{zr}$ at Hankel domain

$\overline{\sigma_z} = \sigma_z$ at Hankel domain

υ =Poisson ratio. υ_1, υ_2, … υ_i, … υ_n mean Poisson ratio at layer 1,layer2, layer i,…,layer n

E=Elastic modulus. E_1, E_2, …E_i, …E_n means modulus at layer 1,layer2, layer i,…,layer n

h=the thickness of layer. h_1, h_2, …h_i, …h_n mean thickness at layer 1,layer2, layer i,…,layer n

$H_{n-1} = \sum_{i=1}^{n-1} h_i$, the sum thickness from layer 1 to layer n-1

$\overline{x}(\xi,0) = [\overline{u}(\xi,0), \overline{w}(\xi,0), \overline{\tau_{zr}}(\xi,0), \overline{\sigma_z}(\xi,0)]^T$, $\overline{x}(\xi,0)$ is vector at the z=0;

$\overline{x}(\xi,z) = [\overline{u}(\xi,z), \overline{w}(\xi,z), \overline{\tau_{zr}}(\xi,z), \overline{\sigma_z}(\xi,z)]^T$, $\overline{x}(\xi,z)$ =vector at the z;

$[T_i]$= 4×4 Matrix, named as Transfer Matrix, $[T_i]$= $\exp(z[A(\xi)])$

$\prod_{i=n}^{1}[T_i]$ = a 4×4 Matrix, named as structure Transfer Matrix.

λ =eigenvalue of matrix $A(\xi)$,

$[m]$= the eigen matrix,

$[m]^{-1}$= the inversion eigen matrix.

LIST OF TABLE TITLES

TABLE 1 Comparison between One Layer Model and N-layer Model

Reaction Moudlus $k(MN/m^3)$	Deflection on load centre(μm)			
	Subgrade modulus E_1=500*MPa*			
	15*cm*		20*cm*	
	3 layers	1 layer	100layers	1 layer
50	888.3	888.3	680.9	680.9
100	549.6	549.6	440.5	440.5
150	409.5	409.5	338.5	338.5
250	278.9	278.9	240.9	240.9

Note. Load diameter is 76.2 cm, uniform pressure is 0.069MPa, Poisson ration is 0.3

TABLE 2 Deflection Basin of one Layer New Model and Infinite Slab on Winkler Foundation in μm

Reaction modulus $k(MN/m^3)$		E_1=500*MPa* , H_1=15*cm*					
		Offset (*cm*)					
		0	20	30	40	65	80
50	**One layer**	888.3	776.1	647.3	484.6	169.0	67.2
	Infinite slab	868.7	757.2	631.4	482.6	171.3	67.0
100	**One layer**	549.6	471.8	381.6	265.2	65.9	15.5
	Infinite slab	530.5	452.9	365.0	262.1	66.9	14.9

Note. Load diameter is 76.2 cm, uniform pressure is 0.069MPa, Poisson ration is 0.3.

TABLE 3 Comparison of USACE, FAA, PCA and New Model Modified Methods on Untreated Subbase

Modulus of Subgrade (MN/m^3)	k-value of subbase (MN/m^3)			
	Subbase thinckness(*cm*)	10.16(4in)	15.24(6in)	30.48(12in)
13.55(50pci)	PCA	17.6	20.3	29.8
	USACE	17.1	19.2	30.4
	FAA	22.8	32.5	59.6
	New model(345 MPa)	20.1	29.8	65.0
	New model (207 MPa)	17.3	24.7	51.2
54.2(200pci)	PCA	59.6	62.3	86.7
	USACE	65.0	70.5	79.9
	FAA	75.9	84.6	108.4
	New model (345 MPa)	56.6	74.0	136.9
	New model (207 MPa)	51.8	63.7	108.4
81.3(300pci)	PCA	86.7	89.4	116.5
	USACE	88.1	91.5	98.2
	FAA	94.9	103.0	119.2
	New model (345 MPa)	79.1	98.4	170.7
	New model (207 MPa)	73.4	85.9	135.5

Note: 100pci=27.1MN/m^3, 1in=2.54cm

TABLE 4 Comparison of FAA, PCA and New Model Modified Methods on Treated Subbase

Subgrade k value k(MN/m^3)	Subbase k value(MN/m^3)			
	Thickness of base (cm)	10.16(4in)	15.24(6in)	30.48(12in)
13.55(50pci)	PCA	46.1	62.3	105.7
	New model	69.1/55.6/51.8	118.4/94.3/77.5	310.6/245.0/198.
	FAA	27.1~36.3	39.0~52.0	71.5~95.4
27.1(100pci)	PCA	75.9	108.4	173.4
	New model	102.4/83.5/70.5	172.4/138.4/114.6	441.7/349.6/284.8
	FAA	91.1~121.4	101.4~135.2	130.1~173.4
54.2(200pci)	PCA	127.4	173.4	/
	New model	154.5/127.4/108.9	253.1/204.3/171.3	629.3(38.1cm)
	FAA	113.8~151.8	123.6~164.5	143.1~190.8

TABLE 5 Comparison of USACE and New Model Modified Method on Treated Subbase

Thickness of subbase (*cm*)	Subbase moudlus (*MPa*)	Subgrade reaction modulus (MN/m^3)	Modified modulus(MN/m^3)	
			USACE	**New Model**
15.24(6in)	69	27.1(100pci)	25.7	28.5
	690		37.9	58.8
	2070		52.8	91.1
	6900		103.0	153.1
22.86(9in)	69	40.65(150pci)	54.2	46.9
	690		67.8	115.7
	2070		108.4	187.0
	6900		135.5	325.2
30.48(12in)	69	40.65(150pci)	67.8	55.6
	690		103.0	159.1
	2070		130.1	267.2
	6900		135.5	477.8

LIST OF FIGURE TITLES

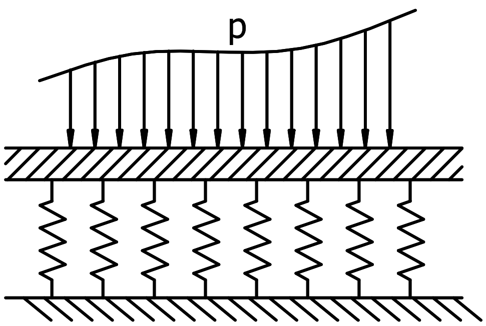

Figure 1 Pasternak Model

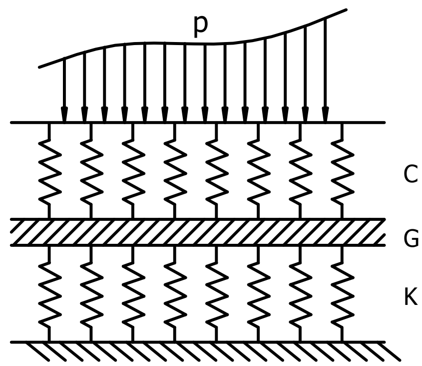

Figure 2 Kerr Model

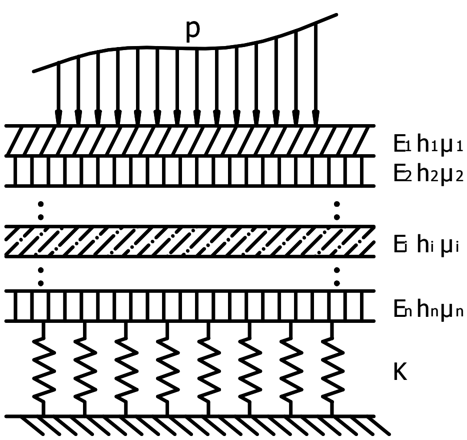

Figure 3 New Model

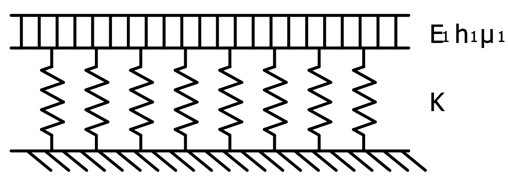

Figure 4 One-layer New Model