ANALYSIS OF INFLUENCE FACTORS FOR EARTHQUAKE-INDUCED DIFFERENTIAL SETTLEMENT OF BUILDINGS

Shangjiu Meng[1], Longwei Chen [2] , Xiaoming Yuan[3]

[1] *Professor, Heilongjiang Engineering College, Harbin. China*
[2] *Graduate, Dept. of Geotechnical Engineering, Institute of Engineering Mechanics, Harbin, China*
[3] *Professor, Dept. of Geotechnical Engineering, Institute of Engineering Mechanics, Harbin, China*
Email: iemmsj@163.com, l.chen@meees.org, yxmiem@163.com

ABSTRACT :

The earthquake-induced differential settlement of building on weak subsoil is one of the typical damages caused by earthquake. Generally, the earthquake-induced differential settlement depends on the condition of subsoil, the distribution of building load and the inputted seismic waves. In static situation, either the unbalanced building or the non-uniform distribution of subsoil underlying can cause inclination of building. For the seismic loads, however, the situation is complicated. On one side, the differential settlement occurs even for balanced building load and even subsoil, and on the other side most of the existing methods can not simulate the earthquake-induced differential settlement even for obviously unbalanced building and significantly uneven subsoil.

In this paper, the influence factors of earthquake-induced differential settlement of building are investigated by a numerical method which has been improved and proved by shaking table tests and earthquake investigation data. Considering various combinations of influence factors (i.e. building, subsoil and seismic wave), the quantitative evaluation on the influence factors of earthquake-induced differential settlement has been obtained. The results herein indicate: (1) The most important factor causing differential settlement of building is the asymmetry and irregularity of seismic wave; (2) Even for the obviously unbalanced building and the significantly uneven subsoil, the properties of asymmetry and irregularity of seismic waves are still dominant in the differential settlement; (3) Although the asymmetry and irregularity of seismic wave play a dominant role in differential settlement, the significant settlement of building depends on the soft extent of subsoil and the amplitude of ground acceleration; (4) For the specific building and subsoil, there is a threshold of peak ground acceleration beyond which the settlement and the differential settlement of subsoil and building increase significantly.

KEYWORDS: Earthquake-induced differential settlement, comprehensive analysis, influence factors, building

1. INTRODUCTION

The earthquake-induced differential settlement of building on weak subsoil is one of the typical damages caused by earthquake. Generally, the earthquake-induced differential settlement depends on the condition of subsoil, the distribution of building load and the inputted seismic waves. In static situation, either the unbalanced building or the non-uniform distribution of subsoil underlying can cause inclination of building. For the seismic loads, however, the situation is complicated. On one side, the differential settlement occurs even for balanced building load and even subsoil, and on the other side most of the existing methods can not simulate the earthquake-induced differential settlement even for obviously unbalanced building and significantly uneven subsoil.

Generally, the earthquake-induced differential settlement of buildings on natural subsoil basically depends on three factors: the wave type of seismic ground motion, the property and distribution of soil layer underneath the building and the weight distribution of the building and foundation. Recently, the effect of asymmetry and irregularity of inputted seismic waves on the earthquake-induced differential settlement of the buildings on natural subsoil is investigated by

Yuan et al (2003) in terms of the earthquake damage phenomena, theoretical analyses, dynamic triaxial tests and shaking table tests. The research has shown that the asymmetry and irregularity of the inputted seismic waves themselves can cause the remarkable differential settlement of the subsoil and structure in some cases and the asymmetrical and irregular character of the inputted seismic waves themselves is a necessary factor to be considered in reasonable evaluation for the problem of the earthquake-induced differential settlements. Other researches (Ishihara et al, 1973, 1984; Nagase et al, 1987) also show that the effect of the asymmetry and irregularity of the seismic loads is significant on the dynamic behavior of the soil in many cases, especially on the permanent deformation of the soft clay soil and the saturated sand.

2. SIMPLIFIED ANALYTIC METHOD FOR CALCULATING DIFFERENTIAL SETTLEMENT

The simplified analytic method for calculating the earthquake-induced differential settlement is proposed according to the mechanism of differential settlement, which results from the combinations of subsoil condition, loading distribution of buildings and inputted seismic wave. The asymmetry and irregularity of inputted seismic wave have noticeable influence on differential settlement. These factors can control the earthquake-induced differential settlement on specific conditions of uniform subsoil condition and uniform loading distribution of buildings. Figure 1 illustrates the diagram of inputted seismic wave and building. When seismic waves (horizontally shearing) are vertically inputted on buildings, the seismic response (acceleration and dynamic stress) of footings will distribute anti-symmetrically in similar forms to the inputted waves. However, if the inputted seismic waves (positive values, negative values) are not equally distributed about the neutral axis, the dynamic stress on the symmetric footings will be different. This kind of difference of dynamic stress will cause differential deformation if the base consists of sensitive soft soil, and probably results to differential settlements of the buildings. Referring to previous analytical methods (Shi, et al, 1988; Zhou, 2003) for settlement, seismic loads are equivalently converted to sinusoidal loads. Thus the residual deformation of base caused by the asymmetry and irregularity of seismic loads will be neglected. This will be proper for assessment of even settlement but not proper for differential settlement. The simplified analytical method employs residual stress–strain model of soil under irregular load and soil softening model to calculate the earthquake-induced differential settlement according to the real seismic loading on the soil elements. This method has not taken into account of the equivalent conversion but the influence of seismic load on earthquake-induced differential settlement.

In the simplified method, the weight of building acts on the two symmetric footings, and then the corresponding settlements could be calculated. The difference of these settlements will generate differential settlement. The dynamic compressive stress relationships of the two footings are corresponding to the positive and negative values of inputted seismic waves respectively. Therefore, the combinations of influence factors of subsoil condition, load distribution of building and seismic waves will be taken into account for differential settlement. In this method, the time history analysis for differential settlement can be carried out; furthermore, it does not need much data and computing time. The reliability of this method has been verified by shaking table tests (Meng, Yuan, 2003). Based on this method, qualitative analysis of the combinations of influence factors are presented hereafter.

3. CALCULATION MODELS AND PARAMETERS

3.1. Typical soil-structure model

Comprehensive analysis of influence factors requires considerations of every combination of these factors, thus a referring model has to be chosen for analysis. Based on this model, influence of the factors on the differential settlement can be analyzed. In this paper, Tanggu area near Tianjin city has been chosen as typical region, the subsoil as typical soil and the department building as typical building. Because many department buildings in this area have been seriously damaged due to the inclination and cracks of the buildings caused by the obviously uneven subsidence of the subsoil during Tangshan Earthquake in 1978. In the simplified analytical method, the influence of buildings on differential settlement can be represented by the difference vertical stress distribution caused by the symmetric footings.

Therefore, the applied loadings resulted from the symmetric footings on the underlying soil can be 120.47kN per unit length corresponding to a 3-stoty building (figure 2). Figure 3 presents time history of the inputted seismic wave. These loads distribute equivalently on the footings to keep equilibrium of the loads. Table 3.1 outlines the typical static parameters of soil. S_1, C_6, C_7, S_6, S_7 are settlement parameters, representing soil settlement. The physical relationships of these settlement parameters with respect to soil parameters and lab test method can be referred to reference (Shi, et al, 1988) for detail. Table 3.2 lists settlement parameters of typical soils. In this paper, 40 cases are presented to calculate differential settlements by the adjusting parameters of underlying soil, the number of story of building, the inputted seismic wave shape and amplitude, and the combinations of these influence factors.

Table 3.1 Soil parameters of typical soils

Soil type	Soil classification	Depth /m	K_s /kPa	n_s	φ /degree	C /kPa	R_f
I	Loam	1～3	152	1.0	23.8	5	0.364
II	Silty soil	3～6	396	0.729	22.9	20	0.402
III	Silty soil	6～10	1237	0.465	23.2	38	0.478
IV	Silt	10～50	422	0.665	21.5	10	0.447

Table 3.2 Typical soil settlement parameter

Soil type	S_1	C_6	C_7	S_6	S_7
I	-0.128	0.61	0.186	0.208	0.0
II	-0.145	0.53	0.178	0.240	0.0
III	-0.203	0.38	0.150	0.350	0.0
IV	-0.159	0.49	0.160	0.220	0.0

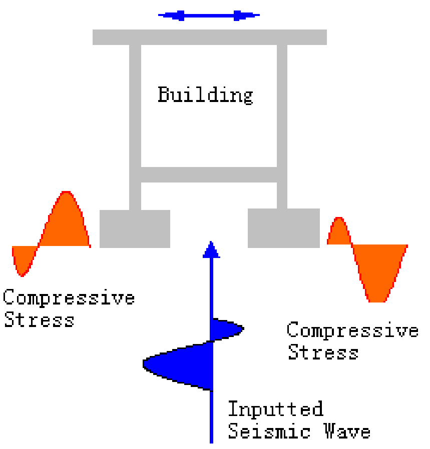

Figure 1 Inputted seismic wave and building

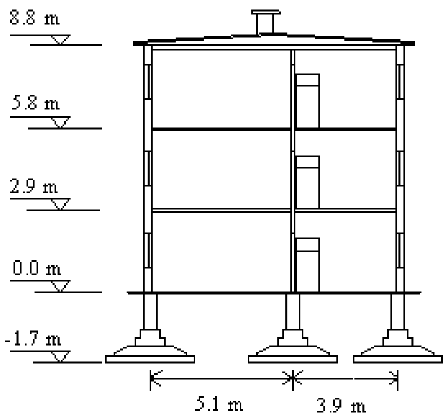

Figure 2 Typical building

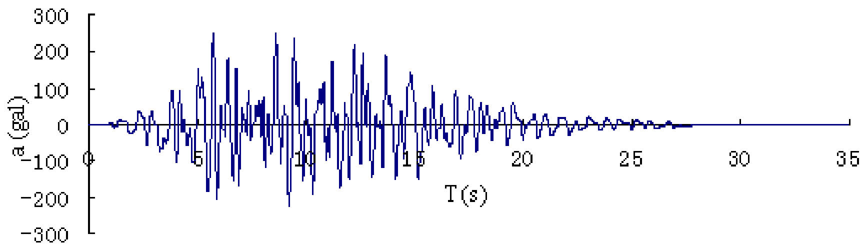

Figure 3 Time history of the inputted seismic wave

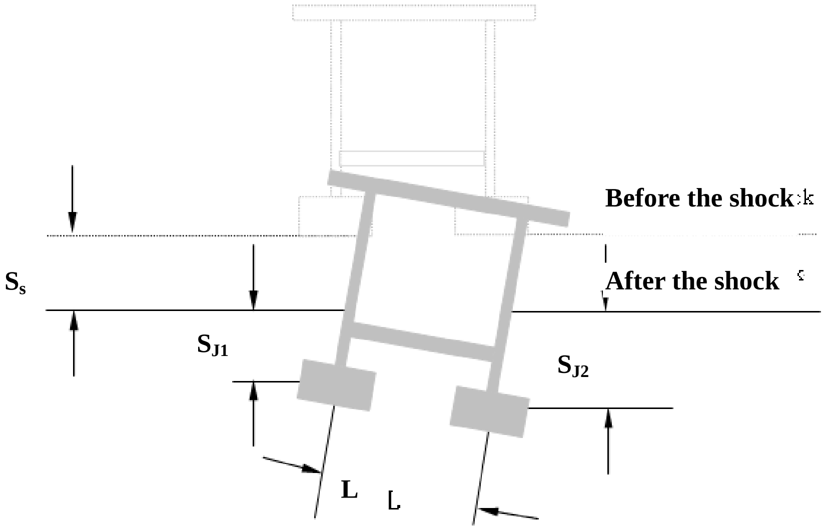

Figure 4 Settlements of building and subsoil before and after the shock

3.2. Calculating variables

The variables required to calculate are including:
1) The settlements of the symmetric footings: S_{J1}, S_{J2};
2) The difference of the footing settlements (i.e. differential settlement) $|S_{J1} - S_{J2}|$;
3) The settlement of the subsoil S_s;
4) The inclination of building: $|S_{J1} - S_{J2}| / L$.

The settlement of building (i.e. differential settlement) is a value with respect to the subsoil underneath. However, the actual settlements of building and subsoil take place simultaneously. The relative difference of the two settlements has been especially concerned. The inclination of building representing the seismic risk of structures, including high rising structures, is defined as differential settlement divided by the distance between footings in permillage (‰). Figure 3 illustrates the relations of the variables.

4. CALCULATION ANALYSIS

The influence factors of differential settlement are correlated and jointly affect the differential settlement. Thus to find out the worst influence factor or combination of the factors could be of great importance.

4.1 Analysis of single influence factor and case study

Case study and analysis are carried on typical calculation model with even subsoil profile and uniform load distribution. Table 3 presents the differential settlement by adjusting the amplitude of inputted waves. Obviously, the settlement and differential settlement of building increase nonlinearly with increasing wave amplitude, and 0.2g of amplitude can be threshold value. If the inputted amplitudes exceed this value, the settlement and differential settlement increase noticeably. The inclination of building caused by earthquake also exceeds the allowance value (5‰).

Table 4 presents obtained differential settlements by adjusting the weight of building from one story to five stories respectively. From the results, the settlement and inclination of building are far less sensitive to building weight than to inputted wave amplitude. The amplitude of inputted seismic wave increases from 0.1g to 0.2g, the settlement can increase to about 40 times. This is due to subsoil effect, since the response of soil-structure interaction has been magnified when the inputted wave amplitudes increase. Thus the settlement will be larger than that by increasing the weigh of building.

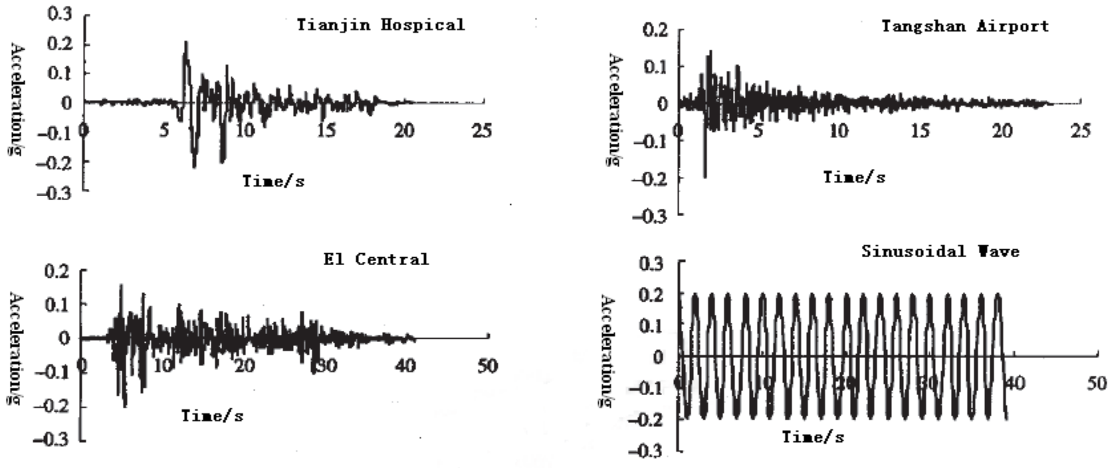

Figure 5 Typical inputted seismic waves

Table 5 presents obtained differential settlements by adjusting the subsoil properties. Settlements of common clay are so small that it can be neglected. However, settlements of silt or silty clay are noticeably large. From the calculation results, the maximum inclination of building reaches nearly 20%0, far larger than the allowance value. Therefore, in the high seismic risk soft soil regions, potential risk of settlement and differential settlement to buildings can be quite high. It is necessary to properly estimate settlement and differential settlement and take proper measures. Meanwhile, the calculation results are consistent with the real seismic damage.

Table 6 presents obtained differential settlement by adjusting the inputted seismic waves which have been shown in figure 5. Although the amplitudes of these waves are the same, the final settlements and inclinations of building remain quite large difference. When the inputted wave is sinusoidal, there is no differential settlement and no inclination of building. Because sinusoidal wave is regular and symmetric, and the dynamic stress and loading times on the symmetric footings are equal which results to no differential settlement. According to equivalent conversion method, all the inputted waves can be converted to equivalent sinusoidal waves with same amplitude and same cycles. The calculation results are the same as those presented in table 6, but there is no differential settlement but settlement only. The influence of irregularity and asymmetry of inputted waves has been neglected. This explains the reason that previous method (Shi, et al, 1988; Zhou, 2003) can calculate settlement but can not calculate differential settlement.

4.2 Analysis of multi influence factor and case study

Table 7 presents the effect of combinations of multi influence factors on differential settlement. In this paper, suppose that the distribution of the modulus of subsoil underlying and the weight of building on the two footing are different. The values of one footing are larger than those of the other respectively by 100%. The calculations are carried out on the 8 possible combinations of influence factors, the worst of which (case 23) generates 11.99cm of differential settlement and 13.32‰ of inclination of building comparing to 0.1cm of differential settlement and 0.11‰ of inclination out of the most advantageous combination (case 26).

The calculated results presented in table 7 are not of practical meaning because of the assumption of different distribution of modulus of subsoil and weight of building. It is not consistent with the real case. The differences of the selected parameters do not exceed 5%, which could be the real case in practice. Table 8 presents the calculation results. Following the same procedures, the worst of which (case 31) generates 5.11cm of differential settlement and 5.68‰ of inclination of building comparing to 0.15cm of differential settlement and 0.17‰ of inclination out of the most advantageous combination (case 38).

Note that in table 8, the influence of the irregularity and asymmetry of seismic wave on differential settlement was very high. Therefore, the differential settlement obtained preciously is resulted from irregularity and asymmetry of inputted wave. From the actual calculation, the seismic load was dominant, which proves that the influence of inputted wave is higher than those of subsoil and building. It can lead to improper or incorrect conclusions for differential settlement if the influence of seismic wave type was neglected (Shi, et al, 1988). If seismic wave was converted to sinusoidal wave according to the equivalent method, the differential settlement is still small (0.80cm) even under the worst combination case. Meanwhile, the permanent deformation cased by the laterally uneven distributed subsoil can not be obtained according to the Seed effective repeating method, which will cause unexpected deviation to the real differential settlement. However, there has been no effective method proposed yet.

Table 3 Differential settlement with different amplitudes of inputted waves

Amplitude / g	One side settlement / cm	Other side settlement / cm	Differential settlement / cm	Subsoil settlement / cm	Inclination $/^0/_{00}$	Case
0.05	0.015	0.0079	0.0071	0.010	0.0079	1
0.10	0.48	0.25	0.22	0.30	0.20	2
0.15	3.88	2.05	1.82	2.40	2.02	3
0.20	17.59	9.29	8.30	10.71	9.22	4
0.25	57.93	30.49	27.44	34.95	30.49	5

Table 4 Differential settlement with different stories of building

Story	One side settlement / cm	Other side settlement / cm	Differential settlement / cm	Subsoil settlement / cm	Inclination $/^0/_{00}$	Case
1	9.82	4.22	5.61	10.71	6.23	6
2	15.02	7.63	7.39	10.71	8.21	7
3	21.79	11.96	9.83	10.71	10.92	8
4	30.43	17.62	13.09	10.71	14.54	9
5	41.32	23.93	17.38	10.71	19.31	10

Table 5 Differential settlement on different subsoil

Subsoil	One side settlement / cm	Other side settlement / cm	Differential settlement / cm	Subsoil settlement / cm	Inclination $/^0/_{00}$	Case
Dense sand	0.40	0.15	0.24	0.80	0.27	11
Medium sand	1.77	0.97	0.80	1.00	0.89	12
Clay	0.49	0.27	0.23	0.43	0.26	13
Silty sand	7.50	4.15	3.35	4.25	3.72	14
Silt	34.69	19.11	15.58	18.64	17.3	15

Table 6 Differential settlement on different inputted waves

Wave	One side settlement / cm	Other side settlement / cm	Differential settlement / cm	Subsoil settlement / cm	Inclination $/^0/_{00}$	Case
Beijing Hotel	17.59	9.29	8.30	10.71	9.22	16
Tianjin Hospital	10.39	11.20	0.81	10.71	0.90	17
Tangshan	10.10	12.68	2.59	10.71	2.88	18
El Centro	34.42	29.83	4.59	10.71	5.10	19
Sinusoidal wave	43.78	43.78	0.00	10.71	0.00	20

Table 7 Differential settlement on different combinations of influence factors

Amplitude $/g$	Subsoil profile	Weight distribution	Settlement of left side $/cm$	Settlement of right side $/cm$	Differential settlement $/cm$	Settlement of subsoil $/cm$	Inclination $/^0/_{00}$	Case
0.2	1[*]	I[**]	7.86	2.70	5.16	9.15	5.73	21
		II	3.74	6.93	3.19	9.15	3.54	22
	2	I	13.12	1.13	11.99	11.74	13.32	23
		II	6.83	3.96	2.87	11.74	3.19	24
0.2	Uniform	I	13.12	2.70	10.42	11.74	11.58	25
		II	6.83	6.93	0.1	11.74	0.11	26
	1	Even	7.86	6.93	0.93	9.15	1.03	27
	2		13.12	3.96	9.16	11.74	10.18	28

Table 8 Differential settlement of real cases

Amplitude $/g$	Subsoil profile	Weight distribution	Settlement of left side $/cm$	Settlement of right side $/cm$	Differential settlement $/cm$	Settlement of subsoil $/cm$	Inclination $/^0/_{00}$	Case
0.2	1	I	7.86	4.24	3.62	9.15	4.02	29
		II	7.39	4.58	2.81	9.15	3.12	30
	2	I	8.75	3.64	5.11	11.74	5.68	31
		II	8.24	3.96	4.28	11.74	4.76	32
	Uniform	I	7.86	3.64	4.22	9.15	4.69	33
		II	7.39	3.96	3.43	9.15	3.81	34
0.2	1	Even	7.86	4.58	3.28	9.15	3.64	35
	2		8.75	3.96	4.79	11.74	5.32	36
	Uniform	Even	7.86	3.96	3.90	9.15	4.33	37
Sinusoidal /0.13	1	I	8.15	8.56	0.41	5.59	0.46	38
		II	7.96	8.76	0.80	5.59	0.89	39
	Uniform	Even	8.15	8.15	0.00	5.59	0.00	40

[*]1 stands for left hard and right soft subsoil condition; 2 stands for left soft and right hard subsoil condition.
[**]I stands for left heavy and right light building; II stands for left heavy and right light building.

5. CONCLUSION

In this paper, the influence factors on earthquake-induced differential settlement have been discussed and analyzed by mean of the simplified method. The main conclusions can be outlined: (1) On the condition of uniform subsoil profile and even load distribution of building, the differential settlement is mainly controlled by the irregularity and asymmetry of inputted wave. (2) On the specific condition, the influence of irregularity and asymmetry of inputted wave on differential settlement is overwhelmingly larger than those caused by non-uniformity of subsoil and uneven distribution of building itself. However, some assumptions have been proposed in the paper. The real cases are more complicated, thus the limitations of these conclusions appear. However, the permanent deformation of soft clay is sensitive to and remarkably influenced by wave type. This kind of effect is very significant to the differential settlement of shallow foundation on soft subsoil. Therefore, it is necessary and proper to take into account of irregularity and asymmetry of seismic wave to calculate differential settlement. Furthermore, if the seismic waves are converted to sinusoidal waves according to equivalent conversion method, the equivalent loading cycles on soil elements resulted from the lateral uneven distribution of subsoil are different. The residual deformation and settlement will not be neglected, resulting to unreasonable results.

REFERENCES

Meng, S., Yuan, X., Sun, S. (2002). Study on mechanism of earthquake-induced differential settlement of building by shaking table test. *Chinese Journal of Geophysical Engineering* **6.** 747-751.
Meng, S. (2002). Study on Residual Deformation of Soils under Irregular Dynamic Loading and Earthquake-induced Differential Settlement of Building. *Doctor Thesis, Institute of Engineering Mechanics*, Harbin, China.
Yuan, X., Sun, R., Meng, S. (2003). Effects of asymmetry and irregularity of seismic waves on earthquake-induced differential settlement of buildings on nature subsoil. *Soil Dynamics and Earthquake Engineering* **23:2**, 107-114.
Shi, Z., Yan, J., Wang, S. (1978) Damage of building and ground motion close to fault. *Chinese Journal of Geophysics* **21:3**. 234-241.
Wang, J. (1982) Inclination of building and strong ground motion. *Acta Seismologica Sinica* **4:1**. 90-97.
Shi, Z., Yu, S., Weng, L. (1988) Calculation for earthquake-induced settlement in Tangshan area. *China Civil Engineering Journal* **4,** 24-33.
Zhou, J., Cai, H., Xu, C. (2000). Analysis of settlement of building on soft clay. *Earthquake Resistance Engineering* **3**. 39-42.
Meng, S., Yuan, X. (2003). Simplified analytical method for earthquake-induced differential settlement of building. *Earthquake Engineering and Engineering Vibration* **23:2**, 102-107.

ACKNOWLEDGEMENT

This research was supported by Heilongjiang Province Natural Science Fund, Project No.E200501, and also supported by Heilongjiang Province Education Department backbone teacher Fund, Project No.1055G036.
This research was supported by the Special item for Fundamental scientific research outlay of National Commonweal Institute, Grant No.2006B03. These support is gratefully acknowledged.