# KEY POINTS FOR NUMERICAL SIMULATION OF INCLINATION OF BUILDINGS ON LIQUEFIABLE SOIL LAYERS

**Jin Xu[1], Xiaoming Yuan[2], Jianyi Zhang[3] ,Fanchao Meng[1]**

[1] *Student, Dept. of Geotechnical Engineering, Institute of Engineering Mechanics, Harbin. China*
[2] *Professor, Dept. of Geotechnical Engineering, Institute of Engineering Mechanics, Harbin. China*
[3] *Assistant, Dept. of Geotechnical Engineering, Institute of Disaster Prevention Science and Technology, Sanhe. China*
*Email: jxu0086@gmail.com, yxmiem@163.com, b532@163.com, iemmfc@163.com*

**ABSTRACT :**

The earthquake-induced asymmetrical settlement of buildings on saturated soil layer is one of the typical phenomena in earthquake damages, which will lead to the inclination and the function loss of the buildings. Developing numerical methods for simulating the liquefaction-induced uneven settlements of the buildings is significant for seismic design of buildings and engineering disasters reduction. However, most researches are focused on the mechanism of liquefaction and assessment of liquefaction potentials or the lateral spreading of liquefaction. The corresponding numerical simulation methods for the liquefaction-induced uneven settlements of the buildings are few. The reason is that the physical process of the problem is not well understood and the key points for analyzing still are not attained. To search for the key points of the potential numerical method for calculating the building inclination due to soil liquefaction, the relationship of the inputting waves, the vertical dynamic stresses, the pore water pressures and the building settlements is investigated by the shaking table tests in the paper. The testing results indicate: (1) The pore water pressure model used in the potential method must be suitable for simulating the process of water pressure rising during the irregular loads and can exactly calculate the difference of the pore water pressures under the incident loads with same peak amplitude but different forms; (2) The pore water pressure model should be able to describe the pore water pressure variation due to the anisotropic property of soils and can distinguish the difference of the water pressures due to the compression and extension stresses; (3) The pore water pressure model should be able to calculate the effect of the consolidation ratios on the pore water pressure variation and can attain the actual process of water pressure for the soils below the buildings; (4) The potential method should be able to follow the tracks of the deformation process of the soil layers with the increasing of the pore water pressure.

**KEYWORDS:** Liquefaction, Building, Inclination, Calculation Method

## 1. INTRODUCTION

The former research of settlement on liquefiable soil layers concerning the impact of seismic wave mainly used the method of equivalent range, which means taking 0.6 times of the seismic wave peak value as the range of simple harmonic wave. However, the mechanism of earthquake-induced differential settlements of buildings is actually the synergistic effects of several impact factors such as foundation soil layer, loads distributed on buildings, and input of seismic waves, among which the impact of asymmetry and irregularity of seismic wave is unneglectable.

S.J. Meng has systematically analyzed the impact of seismic wave on differential settlements on clay layers, put forward a method that could analyze the differential settlements concerning time-history response of clay, and verified by shaking table test. R. Sun proposed a pore pressure model that could also reflect the time-history response, and the reliability was verified by dynamic triaxial test. All these research make possible analyzing the earthquake-induced differential settlements of buildings on liquefiable sand layers under earthquake wave.

This paper applies the pore pressure model proposed by Sun. Meanwhile based on the relationship between pore pressure variation and sand module variation caused by pore pressure proposed by W.L. Feng, the equation about sand module softening caused by pore pressure increase, which could reflect the time-history response under irregularity effects, was deduced and applied in the calculation of differential settlements.

## 2. THE METHOD OF CALCULATING DIFFERENTIAL SETTLEMENTS ON SAND LAYERS

### *2.1. Pore Water Pressure Model*

The pore pressure model used in this paper is proposed by Sun.

$$\begin{cases} u_i = u_{i-1} + \delta u_i & i = 1, 2, ......M \\ \delta u_i = \dfrac{C_{1,0}}{(N_{eq}^i)^{C_{2,0}}} \left(\overline{\tau_i}\right)^{A_{4,0}} \bullet \left[1 - C_{1,a}\left(k_c - 1\right)^{C_{1,b}}\right] \end{cases} \quad (2.1)$$

The equivalent cycle number is

$$N_{eq}^i = \sum_j^i \left[\frac{\sigma_j}{\sigma_i}\right]^\alpha \quad (2.2)$$

Where $u_i$ is the accumulated pore pressure ratio after the (i)th stress cycle, $u_{i-1}$ is the accumulated pore pressure ratio after the (i-1)th stress cycle, $\delta u_i$ is increment caused by the (i)th stress cycle, $\overline{\tau_i}$ is the (i)th effective shear stress ratio, $C_{1,a}, C_{1,b}, A_{4,0}, C_{1,0}, C_{2,0}$ are test parameters, for the situation of loose, mid-dense, and dense sand, $C_{1,a}$ are 0.38, 0.28, and 0.25, respectively, $C_{1,b}$ are 0.55，0.47 and 0.38, respectively.

This model could reflect the impact of both different consolidation ratios and irregular effects on the increase of pore pressure.

### *2.2. Variation of Compression Module along with Variation of Pore Water*

According to Feng, the shear module

$$\begin{cases} G_{\max} = A_1\left(\overline{\sigma_0}\right)^{C_3} \\ G_{\max \bullet N} = G_{\max \bullet N-1} \bullet \left(\dfrac{\overline{\sigma_{0 \bullet N}}}{\overline{\sigma_{0 \bullet N-1}}}\right)^{C_3} \end{cases} \quad (2.3)$$

Where $\overline{\sigma_0}$ is average effective normal stress, $C_3$ is test parameters.

According to the relationship between compression module and shear module

$$E = 2G(1+\nu) \quad (2.4)$$

Assuming that the total stress is constant during the process of liquefaction, thus from (2.3) and (2.4)

$$E_i = E_{i-1} \bullet \left(\frac{\overline{\sigma_{0 \bullet i}}}{\overline{\sigma_{0 \bullet i-1}}}\right)^{C_3} = E_{i-1} \bullet \left(\frac{1-u_i}{1-u_{i-1}}\right)^{C_3} \quad (2.5)$$

When a certain sand element is determined having liquefied, that is $u_i \geq 1.0$, based on Z.J. Shi's critical value concept, for sand,

$$G_{Liq} = 0.0125 G_{\max} \quad (2.6)$$

Thus, at this time

$$E_{Liq} = 0.0125 E_0 \quad (2.7)$$

Integrate (2.5) and (2.7), the relationship of the variation of compression module along with the variation of pore water is

$$\begin{cases} E_i = E_{i-1} \bullet \left( \dfrac{1-u_i}{1-u_{i-1}} \right)^{C_3} & (u_i < 1) \\ E_i = 0.0125 E_0 & (u_i \geq 1) \end{cases} \tag{2.8}$$

### *2.3. Overall Flow and Calculating Steps*

This paper simplifies the sand-structure system as a two-dimensional problem, combined the earthquake-induced differential settlements analyses with the static and dynamic finite element analysis. The initial stress state of every single element can be acquired from static analysis, while the dynamic stress can be acquired from dynamic analysis. A calculating method can be given by combining the element dynamic stress with the pore water pressure model that is fit for the irregular effects, also assisting with the relationship of sand element module decrease caused by liquefaction. The overall flow and calculating steps are shown in figure 1.

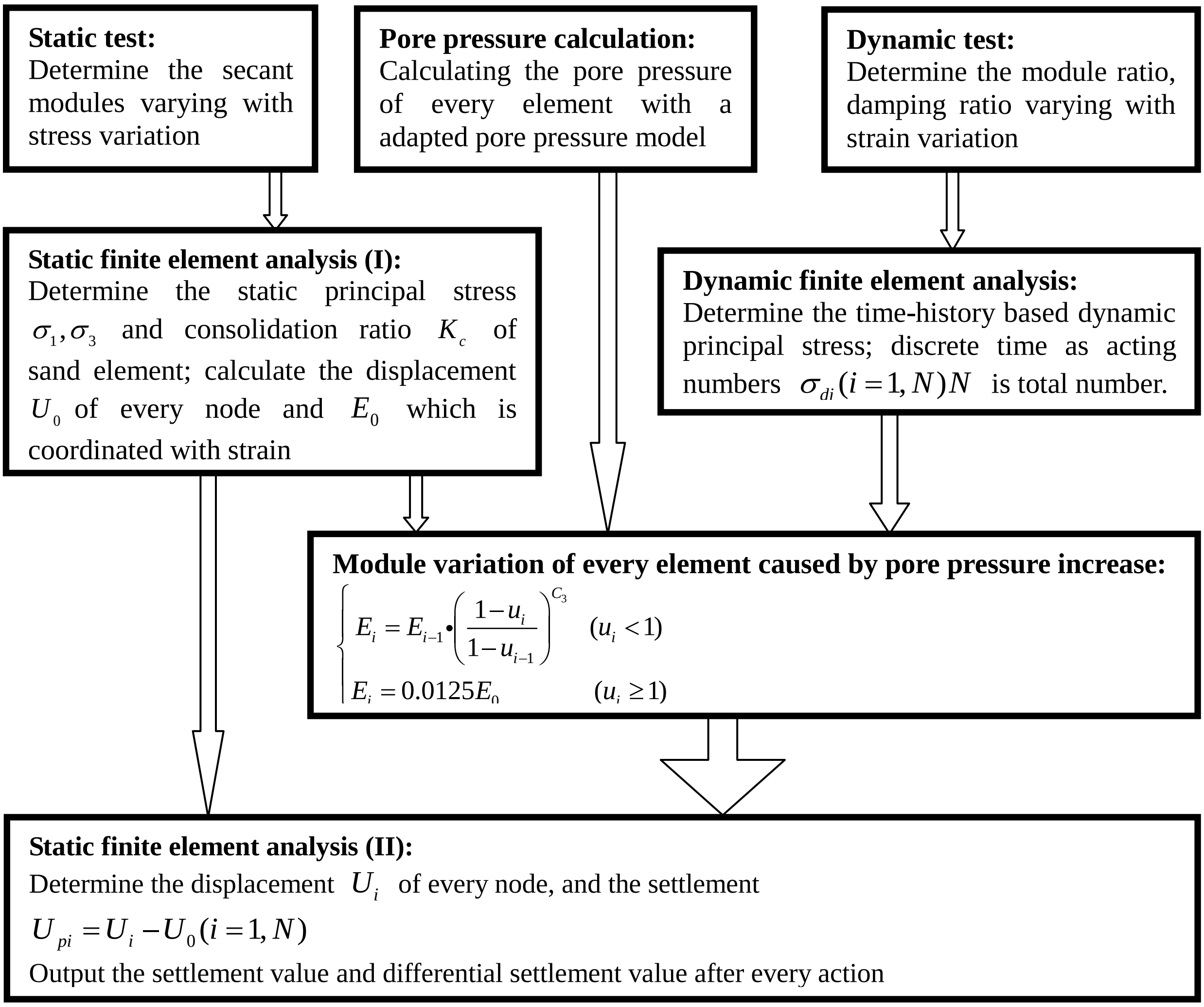


Figure 1 Overall flow and calculating steps

## 3. NUMERICAL SIMULATION TEST

In this paper the computer program compiled by Fortran Language is used, simulating different working conditions. Assume the foundation sand is uniform distributed, and the loads acted on the building are equivalent. Consider two working conditions: input waves are (1) sine wave and (2) El Centro wave, shown in figure 2. The calculating model of sand-structure system is shown in figure 3. This paper mainly investigates responses of two symmetric positions, namely NO.170 and NO.179 elements in figure 3. The calculating parameters are shown in table 3.1 and table 3.2.

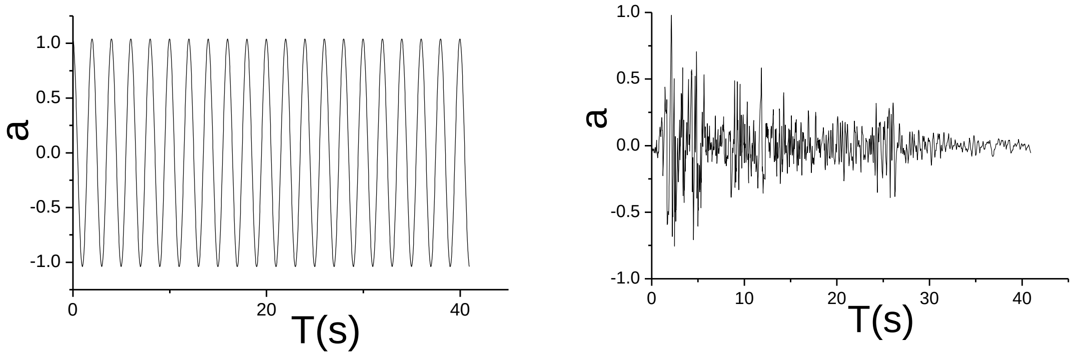


Figure 2 Waveform of input waves

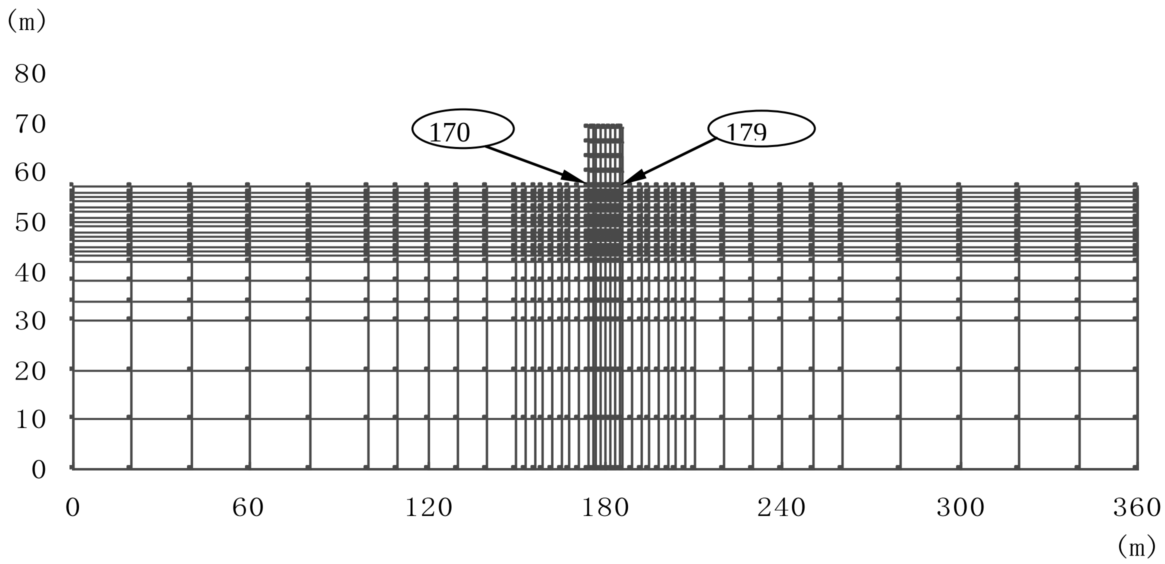


Figure 3 Model of sand-structure system

## 4. CALCULATION AND ANALYSIS

The output results are a lot, among which this paper concerns are three types of data: (1) The pore pressure variation of two symmetric positions (NO.170 and NO.179 elements); (2) The module variation of two symmetric positions; (3) The settlements of two symmetric positions.

Table 3.1 Static calculating parameters

<table>
<tr><td rowspan="2">Soil types</td><td colspan="5">Duncan parameters</td><td colspan="5">Liquefaction parameters</td></tr>
<tr><td>$K_a$ (kPa)</td><td>$n_s$</td><td>Φ (deg)</td><td>C (kPa)</td><td>$R_f$</td><td>$C_{1,a}$</td><td>$C_{1,b}$</td><td>$C_{1,0}$</td><td>$C_{2,0}$</td><td>$A_{4,0}$</td></tr>
<tr><td>Mid-dense sand</td><td>18000</td><td>0.953</td><td>24</td><td>0</td><td>0.4</td><td>0.28</td><td>0.47</td><td>4.52</td><td>1.25</td><td>2.43</td></tr>
<tr><td colspan="6">Initial max shear module（kPa）</td><td colspan="5">Density（g/cm$^3$）</td></tr>
<tr><td colspan="2">Mid-dense sand</td><td colspan="2">Brick</td><td colspan="2">Concrete</td><td colspan="2">Mid-dense sand</td><td colspan="2">Brick</td><td>Concrete</td></tr>
<tr><td colspan="2">20000</td><td colspan="2">1000000</td><td colspan="2">10000000</td><td colspan="2">1.6</td><td colspan="2">2.0</td><td>2.5</td></tr>
</table>

Table 3.2 Dynamic calculating parameters

| Shear strain | $5\times10^{-6}$ | $1\times10^{-5}$ | $5\times10^{-5}$ | $1\times10^{-4}$ | $5\times10^{-4}$ | $1\times10^{-3}$ | $5\times10^{-3}$ | $1\times10^{-2}$ | Poisson ratio |
|---|---|---|---|---|---|---|---|---|---|
| Soil types | Module ratio | | | | | | | | Sand |
| Sand | 0.965 | 0.935 | 0.775 | 0.660 | 0.300 | 0.250 | 0.105 | 0.090 | 0.398 |
| Building | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | Brick |
| | Damping ratio | | | | | | | | 0.2 |
| Sand | 0.006 | 0.010 | 0.030 | 0.045 | 0.088 | 0.103 | 0.124 | 0.130 | concrete |
| Building | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.167 |

### *4.1. Input Sine Waves*

Two tests are executed, the ranges of input waves are $0.01m/s^2$, $0.02m/s^2$, respectively. The results are shown in figure 4, 5, 6, and 7.

In figure 4 and 5 the sand has not liquefied yet, the pore pressure increase and the module decrease of the two symmetric positions are symmetric; the foundation settlements are uniform, too. While in figure 6 and 7 the sand has already liquefied, however the pore pressure increase and the module decrease of the two symmetric positions are still symmetric, the module has decreased to about 1/80 of the initial module, the foundation settlements are still uniform, too.

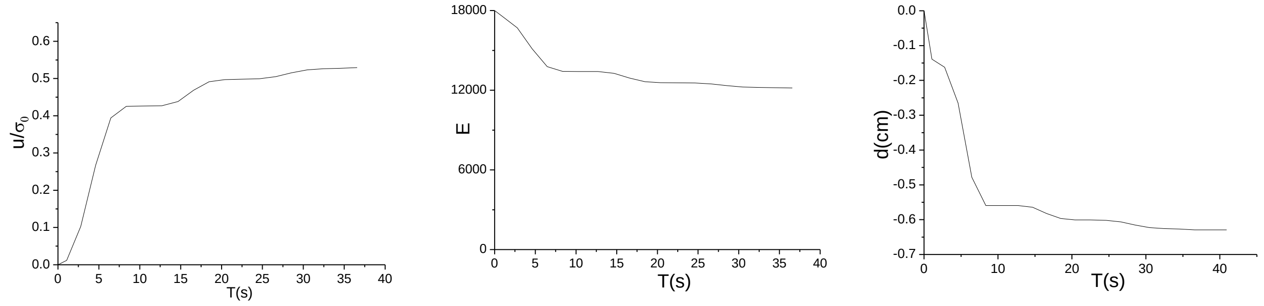


Figure 4 Left element response under input range $0.01m/s^2$

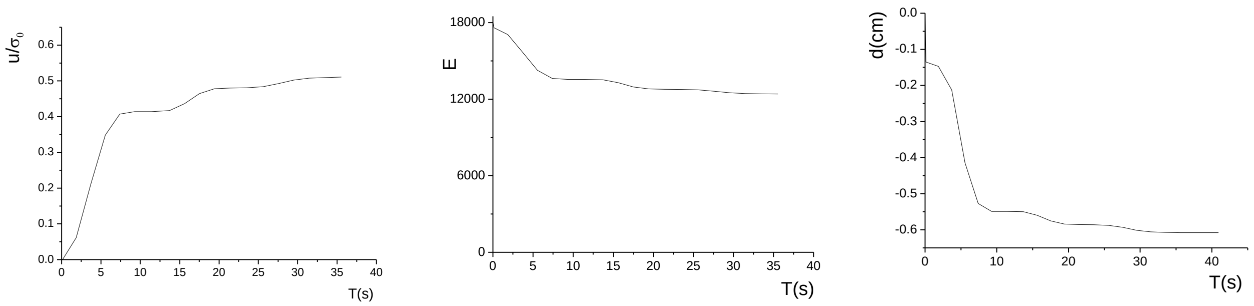


Figure 5 Right element response under input range $0.01m/s^2$

### *4.2. Input El Centro Waves*

Three tests are executed, the peaks of input waves are $0.05m/s^2$, $0.07m/s^2$, $0.1m/s^2$ respectively. The results are shown in figure 8, 9, 10, 11, 12, and 13.

In figure 8 and 9 the sand has not liquefied since the earthquake acceleration is small. However the pore pressure increase and the module decrease of the two symmetric positions presents the trend of asymmetric, the foundation settlements are obvious uneven. In figure 10 and 11, the left of the two symmetric positions the sand has liquefied, while the right one has not. Both of the pore pressure increase and the module decrease of the two symmetric positions presents obvious asymmetric, the foundation settlements are especially notable. In figure 12 and 13, both of the two symmetric positions have liquefied. Because the pore pressure ratio increases sharply and immediately reaches 1.0, along with the module decreases to 1/80 of the initial module, the pore pressure increase and the module decrease of the two symmetric positions presents seems symmetric again. However the foundation settlements retain asymmetric since the time-history based response is different. The value of settlements is much more than which is before liquefaction, and will go on increasing sharply along with the increase of earthquake acceleration.

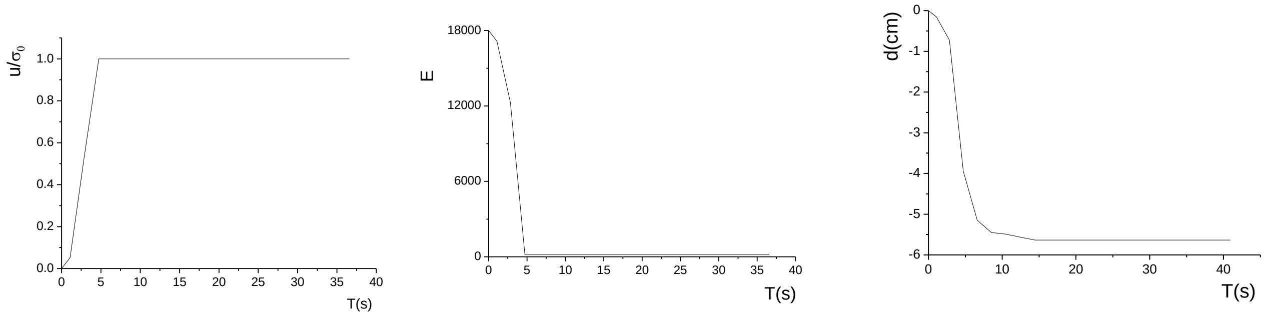


Figure 6 Left element response under input range $0.02m/s^2$

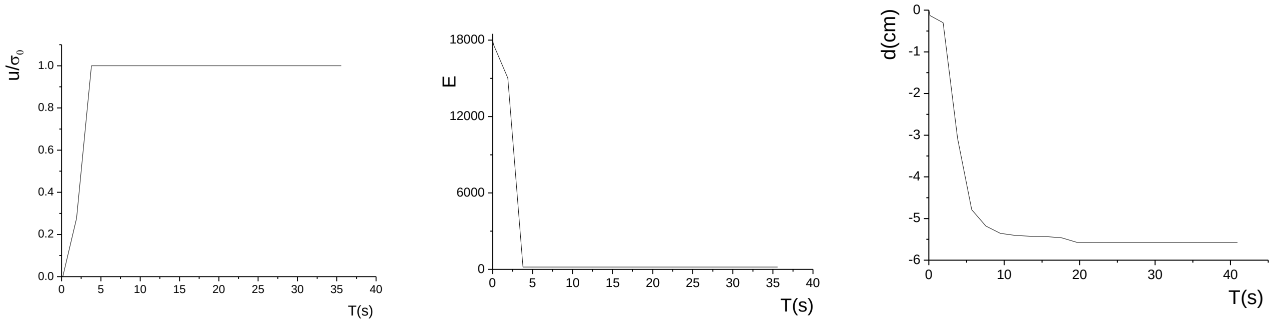


Figure 7 Right element response under input range $0.02m/s^2$

### *4.3. Data Contrast and Analysis*

Through the contrast of two groups of numerical simulation tests above the result is apparent. When the input wave is symmetric, the reaction of sand foundation, including pore pressure and settlement, is symmetric; When the input wave is obvious asymmetric, the reaction of sand foundation is not symmetric either, and the settlements will be uneven due to the uneven increase of pore pressure.

In this paper in order to clearly analyze the time-history based soil element reaction and the relation between it and the differential settlements, the acceleration of input waves are small. Actually when the earthquake acceleration is large, the foundation sand layer will be liquefied in a short time, and the settlements will be apparently uneven since the different increase progress of pore pressure.

## 5. CONCLUSION

(1) The pore water pressure model used in this paper and the equation about sand module variation along with the pore pressure variation deduced by this paper can successfully present the time-history response of soil, and are adapted for the calculation of differential settlements of buildings. (2) The finite element method used in this paper can effectively calculate the time-history response of soil and settlements, which is fit for any kind of input waves, no matter symmetric or asymmetric. (3)For the buildings on which loads are equivalent and the foundation soil layer is also uniform distributed, it is still possible to appear the differential settlement. Whether it happens is related to the waveform and peak value of input waves. When the input wave is sine wave, which

is uniform, the reaction of sand foundation is symmetric, so are the settlements. When the input wave is asymmetric, the reaction of sand foundation is also asymmetric, leading to the differential settlements.

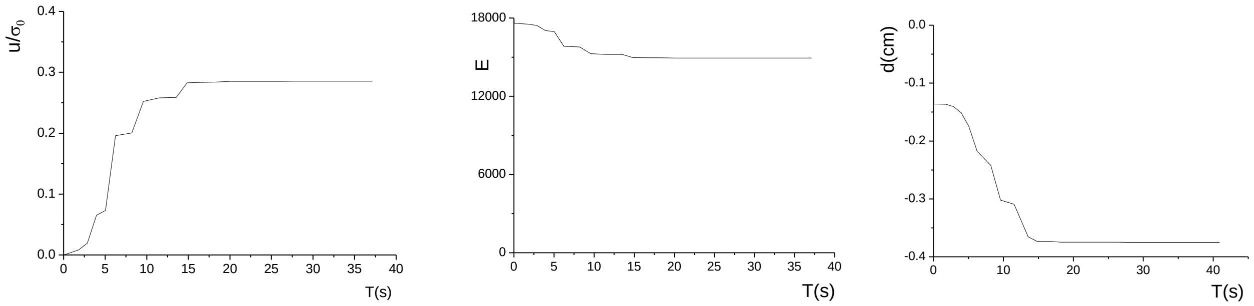


Figure 8 Left element response under input peak $0.05m/s^2$

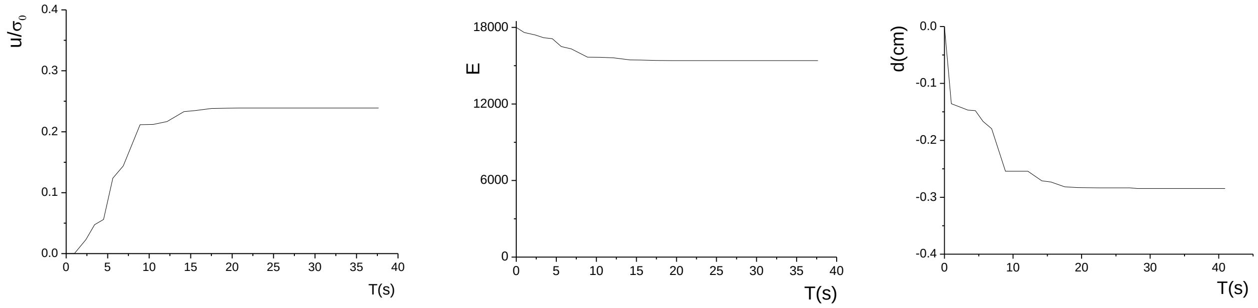


Figure 9 Right element response under input peak $0.05m/s^2$

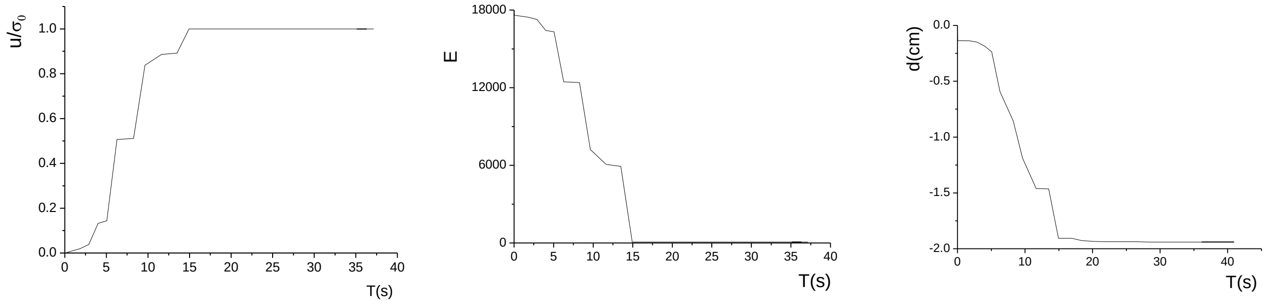


Figure 10 Left element response under input peak $0.07m/s^2$

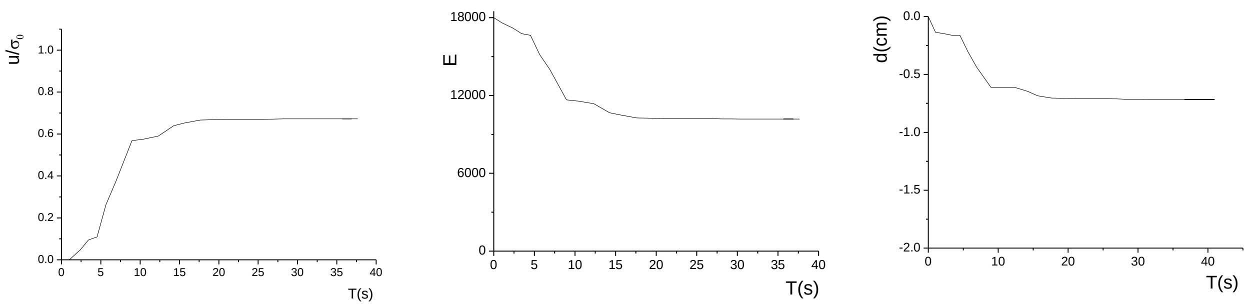


Figure 11 Right element response under input peak $0.07m/s^2$

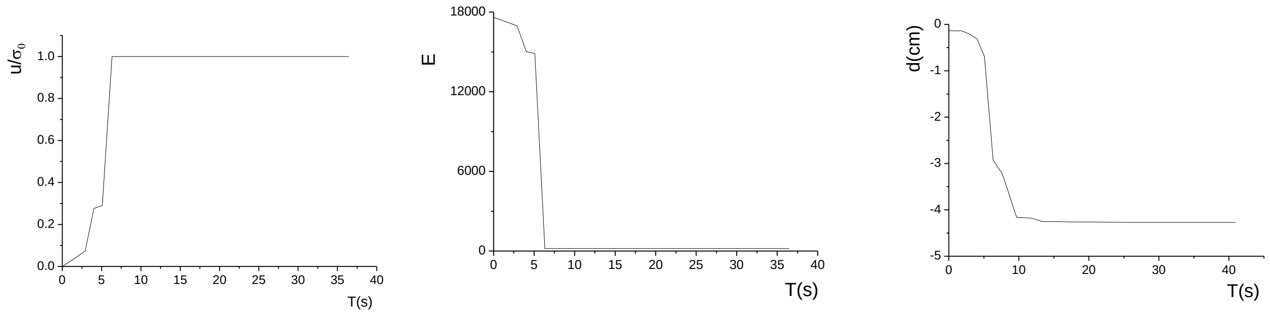


Figure 12 Left element response under input peak $0.1m/s^2$

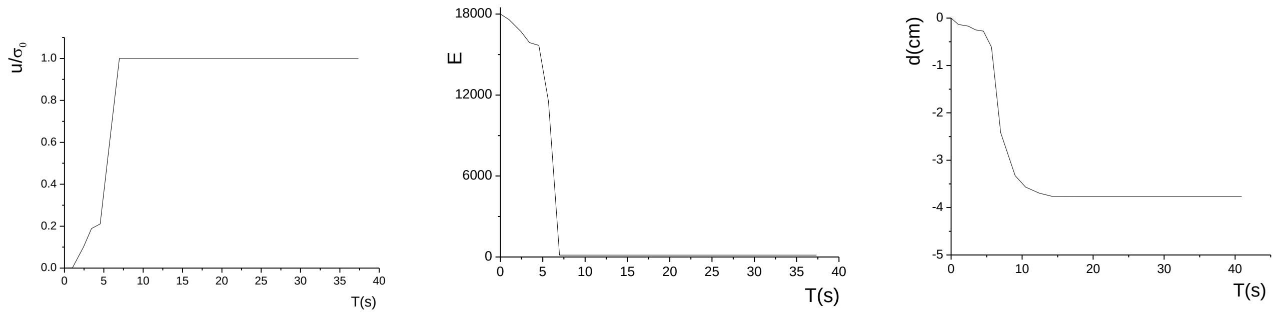


Figure 13 Right element response under input peak $0.1m/s^2$

## REFERENCES

[1] S.J. Meng. (2002). Study on Residual Deformation of Soils under Irregular Dynamic Loading and Earthquake-induced Differential Settlements of Building. Doctoral Dissertation.

[2] R. Sun. (2006). Study on Seismic Ground Motion on Liquefiable Soil Layer and Site Liquefaction Detection. Doctoral Dissertation.

[3] W.L. Feng, Z.J. Shi. (1987). Pore water pressure analysis method of investigating horizontal soil layers liquefaction potentials. Research Report of Institute of Engineering Mechanics.

[4] S.J. Meng, X.M. Yuan. (2004). Analysis of influence factors for earthquake-induced differential settlements of buildings. *Earthquake Engineering and Engineering Vibration* **24:1**, 111-116.

[5] X.M. Yuan, R. Sun, S.J. Meng. (2003). Effects of asymmetry and irregularity of seismic waves on earthquake-induced differential settlement of buildings on natural subsoil. *Soil Dynamics and Earthquake Engineering* **23:2**, 107-114.

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