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Composite Model for Dynamic Pore Water Pressure Developing Process of Soft Soil under Cyclic Loading

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ABSTRACT: Dynamic pore water pressure developing process (DPDP) is an important issue in soft soil dynamic mechanic study. Based on soft soil dynamic pore pressure development mechanism, its basic behavior was analyzed, and four properties that its mathematical model should meet were presented. Relationship between hyperbolic model and exponential model was investigated by using Taylor series expansion. A three-parameter composite model of dynamic pore pressure development was proposed. Mathematical analysis shows that the exponential model and hyperbolic model are the special cases of the new model. Finally, correctness of the composite model was verified by measured data of both disturbed and undisturbed soil.

KEYWORDS: Dynamic pore water; Soft soil; Composite model.

INTRODUCTION

With the rapid economic development, construction of highways, high-speed railways, magnetic levitation transportation systems, urban underground railways and other important transportation infrastructure gradually increased in China's coastal areas, such as the Hangzhou Bay bridge, Wenzhou airport, Hangzhou-Ningbo expressway. Meanwhile, these infrastructures also promote further economic development in coastal areas. Because the geological conditions are unique, most of these projects are built on deep soft soil foundation. This kind of soft soil has high water content and low strength, often with significant structural property. When disturbed by vibration, its flock structure will gradually be destroyed, and then the soil's strength will significantly reduce too [1-2]. Some infrastructures built on soft soil need to withstand the dynamic loading by the wave's erosion, and some need to withstand continuous vibration loading when high-speed trains passed. Their appearance have promoted regional economic development, but at the same time, there are several technical problems in the design and operation process, such as the settlement is too large after open to traffic, the original design of the structure has big difference with the measured result. And some problems directly impact on the function of the normal use of the project [3-5]. In the future, China will build a large number of high-speed railways, highways and subways on the deep coastal soft soil areas, especially in Zhejiang, Shanghai, Jiangsu and other economically developed provinces. In addition to withstand normal vibration loading, these critical infrastructure will also withstand the potential earthquake hazards. How to ensure these facilities' safe operation under vibration loading is a hot issue in civil engineering. The key to solving these problems is to establish the appropriate soil dynamic constitutive law, [6] and make reasonable mathematical simulation of the soft soil's dynamic property.

BASIC PROPERTIES OF DYNAMIC PORE WATER PRESSURE MODEL

The mathematical description of dynamic pore water pressure (p) developed with the vibration cycle (N) is a prerequisite to the establishment of built of soft soil dynamic constitutive law. Many researchers have done a thorough study and get good research results on this issue [1, 2]. Zeng studied the effect of silt particle content to DPDP by a series of dynamic cyclic tests of saturated and disturbed silt [7]. Liu and Chen investigated dynamic properties of recently deposited soils and vibratory liquefaction of sands in area of Nanjing and its neighbor [8]. Wang presented a core function for DPDP of seashore soft soil based on energy dissipating theory and differential governing equation [9]. Okur reported one evaluation of cyclic behavior of fine-grained soils using the energy method [10]. Zhang made experimental study on dynamic properties of the silt soil in Shanxi province, China [11]. Ravichandran studied the micro-scale modeling of saturated sandy soil behavior subjected to cyclic loading [12]. Xenaki discussed the dynamic properties and liquefaction resistance of two soil materials in an earthfill dam by laboratory resonant column and cyclic triaxial tests on specimens of two compacted soils [13].

From above investigations we can get that, in the vibration process of the fixed confining pressure σ_3, the dynamic pore water pressure increases as the vibration gradually increased N; as N approaches infinity, the soil liquidation is destroyed, the dynamic pore water pressure reaches a maximum P. As the dynamic pore pressure can not be greater than the confining pressure, so $P \le \sigma_3$. In fact, in the experiment, the vibration cycle was limited, we often take N_f at termination of the vibration, and discuss the relation between vibration cycle ratio x ($x = N / N_f$) and the dynamic pore water pressure p. When the confining pressure is fixed, the typical *p-x* curve is shown in Figure 1.

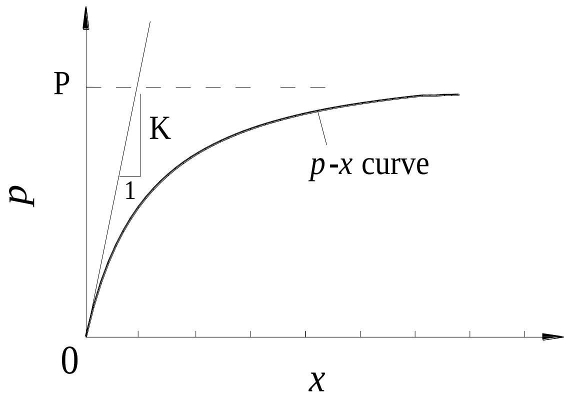

Figure 1. Dynamic pore water pressure developing process.

Seen from Figure 1, *p-x* mathematical model must have the following properties:

(1) Through (0, 0) point, that is, p (0) = 0;

(2) The function first derivative is greater than zero to ensure its monotonically increase;

(3) The function second derivative is less than zero to ensure that the function curve convex;

(4) The function has an upper bound, p (∞) = constant P.

Based on this, it is proposed to describe the *p-x* relation: hyperbolic model, exponential model. Expressions of these two models are:

$$p = \mathrm{f}_1(x) = \frac{x}{1/\mathrm{K} + x/\mathrm{P}} \tag{1}$$

$$p = \mathrm{f}_2(x) = \mathrm{P}(1 - e^{-\mathrm{K}x/\mathrm{P}}) \tag{2}$$

Where: K and P are positive undetermined parameters, P indicates the limit dynamic pore water pressure, K indicates the initial pore pressure development rate.

Although both Eq. (1) the hyperbolic model and Eq. (2) the exponential model meet the mathematical nature as shown in Figure 1, and have the same limit dynamic pore water pressure and initial pore pressure development rate, but the *p-x* development process are not the same.

It can be improved that when the limit dynamic pore water pressure and the initial pore pressure development rate corresponding to equal, the exponent model has been in the top of the hyperbolic model.

But both the engineering and laboratory tests show that, there are larger errors to simulate the *p-x* relation by the traditional model, sometimes it can not meet the actual needs of the project. Thus, the urgent need to establish a more rational *p-x* development model is very important.

This article will base on the demonstration of the traditional model's nature defects to establish a new *p-x* development model for the preparation of the establishment of the corresponding soil dynamic constitutive model.

A NEW MODEL

Basic Properties of the New Model

Based on the above analysis, the author introduces the third parameter, proposes a composite three-parameter model (CTP model) to simulate the development of soft soil *p-x*, the model is given by:

$$p = f_3(x) = (1-\alpha) f_1(x) + \alpha f_2(x) = \frac{(1-\alpha)x}{1/K + x/P} + \alpha P(1 - e^{-Kx/P}) \quad (3)$$

Where: α is a parameter between 0 and 1, and other two symbols have the meaning as in above Eq. (1) and Eq. (2). According to Figure 1, the basic property of Eq. (3) can be obtained as:

$$f_3(0) = (1-\alpha) f_1(0) + \alpha f_2(0) = 0 \quad (4)$$

$$\begin{cases} \dfrac{df_3}{dx} = \alpha K e^{-Kx/P} + \dfrac{(1-\alpha)KP}{(P+Kx)^2} > 0 \\ \dfrac{df_3}{dx}\Big|_{x=\infty} = K \end{cases} \quad (5)$$

$$\frac{d^2 f_3}{dx^2} = (1-\alpha)\frac{d^2 f_1}{dx^2} + \alpha \frac{d^2 f_2}{dx^2} = -\left[\frac{\alpha K^2}{P e^{Kx/P}} + \frac{(1-\alpha)K^2 P^2}{(P+Kx)^3} \right] < 0 \quad (6)$$

$$\begin{cases} f_3(\infty) = (1-\alpha) f_1(\infty) + \alpha f_2(\infty) = P \\ \dfrac{df_3}{dx}\Big|_{x=\infty} = 0 \end{cases} \quad (7)$$

Eq. (4)-(7) show that the Eq. (3) of new model $f_3(x)$ can meet the four mathematical properties as shown in Figure 1, and it has the same P and K to the exponent model and hyperbolic model. Meanwhile, it also shows that the physical meaning of parameters in the new model is relatively clear.

When the parameter $\alpha = 0$ or 1, we can get its minimum and maximum:

$$f_{3,\min} = f_3(x)\big|_{\alpha=0} = f_1(x) \quad (8)$$

$$f_{3,\max} = f_3(x)\big|_{\alpha=1} = f_2(x) \quad (9)$$

From the above, we can know that the exponent model and hyperbolic model are special cases of this CTP model, when the P and K are equal.

Table 1. Parameters of typical curves of CTP model.

Fitting No.	K	P	α	Note
1	200	100	1.0	Exponential model
2	200	100	0.8	
3	200	100	0.6	
4	200	100	0.4	
5	200	100	0.2	
6	200	100	0.0	Hyperbolic model

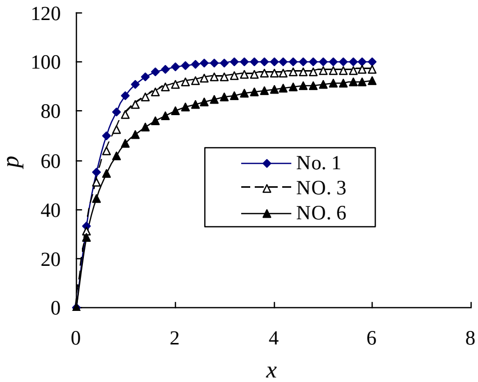

Figure 2. Typical curves of new CTP model.

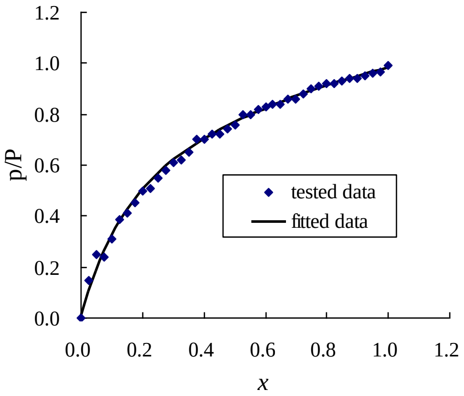

Figure 3. Tested and CTP model fitted curves.

Take K = 200, P = 100 for example, both the exponent model and the hyperbolic model can only give one of their curve equation as the optimal solution; while CTP model can give a curve family used for experimental data fitting and find the true optimal solution. The typical curves and their parameters are shown in Table 1 and Figure 2.

Verification by Investigation

Some lab tests on dynamic properties of Nanjing recently deposited soils were conducted by Liu and Chen, Jiangsu, China. [8] The soil sample is undisturbed soil, with 80 mm height and 39.1 mm. In their test, (*p*/P)-*x* relationship was investigated. One set investigated data and its fitted result with CTP model are shown as in Figure 3.

In order to study the effect of silt particle content, a series of dynamic cyclic tests of saturated and disturbed silt were conducted by Zeng [7]. The soil sample is 140 mm height with 61.8 mm diameter and 15% water content. One set investigated data and its fitted results with different models are shown as in Figure 4. Fitted errors are shown as in Figure 5, and the error is defined as:

$$error = (\,fitted\ data - tested\,data)\,/\,\% \tag{13}$$

It is evident from this Figure 3 to Figure 5 that fitting results of CTP model are very close to investigated data with negligible residual error, which are much smaller than those of hyperbolic model and exponent model.

CONCLUSIONS

(1) The traditional hyperbolic model and exponent model have larger errors in the simulation of the dynamic pore water pressure developing process.

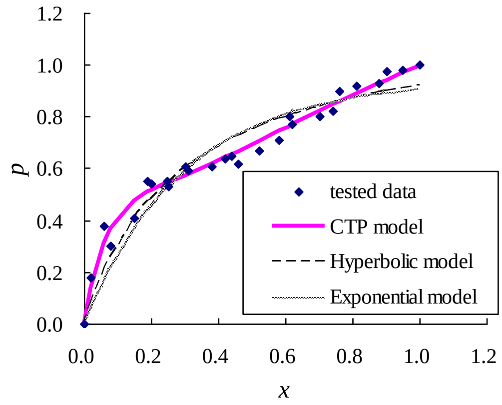

Figure 4. Tested and fitted curves of different models.

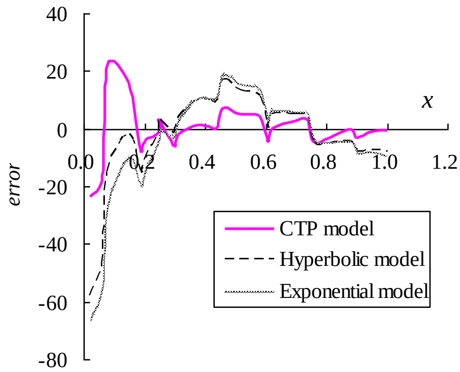

Figure 5. Fitted errors of different models.

(2)When the limit dynamic pore water pressure and the initial pore pressure development rate corresponding to equal, the exponent model has been in the top of the hyperbolic model.

(3) A new CTP model of dynamic pore water pressure development is established, and the model has the same P and K with the traditional model.

(4) The traditional hyperbolic model and the exponent model are the special case of this new CTP model in different situations.

(5) This new CTP model has good agreements with both disturbed and undisturbed soil.

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REFERENCES

[1] G. X. Chen and X. Z. Liu, *Chinese Journal of Geotechnical Engineering*, vol. 26, no. 79, 2004.
[2] Y. C. Cao and T. L. Wang, *Shanghai Dizhi*, vol. 67, no. 60, 1998.
[3] M. Rayhani1 and M. Naggarl, *Bulletin of Earthquake Engineering*, vol. 4, no. 571, 2007.
[4] V. Xenaki and G. Athanasopoulos, *Soil Dynamics and Earthquake Engineering*, vol. 28, no. 118, 2008.
[5] J. W. Meng, *Soil Dynamics and Earthquake Engineering*, vol. 27, no. 234 ,2007.
[6] W. H. Qi and J. S. Bo, *Journal of Earthquake Engineering and Engineering Vibration*, vol. 29, no. 169, 2009.

[7] C. N. Zeng, H. L. Liu and Y. D. Zhou, *Journal of Disaster Prevention and Mitigation Engineering*, vol. 26, no. 180, 2006.

[8] X. Z. Liu, "The study and test on dynamic properties of recently deposited soils and vibratory liquefaction of sands in area of Nanjing and its neighbor", Nanjing University of Technology, Nanjing, 2003.

[9] W. Wang G. J. Pan, Z. Pan, G. W. Zhou and H. Ling, *Advanced Science Letters*, vol. 4, pp. 1193-1196, 2011.

[10] O. Volkan and A. Atilla, *J. Earthqu. Eng.*, vol. 15, pp. 601-605, 2011.

[11] W. Zhang and A. H. Sun, *Electron. J. Geotech. Eng.*, vol. 16, pp. 1351-1367, 2011.

[12] N. Ravichandran, B. Machmer, H. Krishnapillai and K. Meguro, *Soil Dyn. Earthqu. Eng. vol.* 30, pp. 1212-1220, 2010.

[13] V. C. Xenaki and G. A. Athanasopoulos, *Soil Dyn. Earthqu. Eng.* vol. 28, no. 605, 2008.