APPROACH FOR STUDYING FOUNDATION SUBJECTED TO VIBRATION: FROM THEORETICAL STUDIES IN NEAR FIELD TO MODELING IN FAR FIELD, FROM LAB MODEL TO IN-SITU TEST

by Duong Hong Tham[1]

ABSTRACT

This article suggests approaches for studying soil foundation subjected to dynamic effects:

a) *Theoretical studies in near field about mobilized soil bearing capacity of foundation and its response when receiving the vibration propagating through soil medium from a source in far field;*
b) *Experimental studies for studying the mobilized coefficient of internal friction of soil with a self made apparatus 'Modified shearbox' and a small scale model for studying the additional settlement due to vibration;*
c) *Site plate bearing test with open standpipes installed around it for investigating the increase of pore water pressure when subjected to dynamic effects and the mechanism for developing the additional settlement under vibration.*

Some results obtained are: A formula for the bearing capacity of soil foundation subjected to dynamic effects; a system of governing differential equations for vibration of source - soil medium - receiver footing ; an apparatus for studying the mobilized shear strength due to vibration; and procedure for studying the additional settlement by using Matlab programming, small scale model and site test.

Keywords: Dynamic effects, Mobilized shear strength, Modified shearbox, Open standpipe.

OVERVIEW

Soil mechanics is one among three main columns supporting to construction mechanics, alongside fluid mechanics and solid mechanics. Besides using several assumptions and hypothesis of classical mechanics like Theories of Elasticity, Plasticity and continue medium mechanics... etc, and with many semi-empirical results, a huge mass of fundamental theories of soil mechanics was established. For instance: Formulas for estimating the settlement (i.e. definite integral of vertical deformation over depth of change in additional pressure) were taken from results of confined compression tests in oedometer; or time elapsed for finalizing a part of estimated settlement in consolidation test and using it for estimating the settlement of real construction works …That is to say, soil mechanics is an experimentally based system of theories; experiments in bigger test box or device, softly or more rigidly confined, faster or slower speed of shearing...will definitely give rather different results, then in turn resulting in various theories. Therefore lab tests play a very important role to soil mechanics.

[1]*Faculty of Civil and Electrical Engineering, HCMC Open University.*

Theories of modern soil mechanics have based upon more sophisticated and state of the art apparatus: pure triaxial compression apparatus, shearbox in sprung table, dynamic oedometer… And the other important part is mathematical model of rheologic characteristic behavior that three phases were taken into account. An important issue of the advanced soil mechanics is critical state soil mechanics where soil compressibility and strength were unified in many different ways.

There has been theory of soil foundation where soil properties are time-independent_i.e. not vary with respect to time_saturated and small deformation whilst other theories on the contrary view time-dependent soil properties and unsaturated soil.

There is currently a topic which considers soil properties under vibration. When imposed load was directly applied to footings, we say the problem is dynamically applied loadings; when the construction under consideration is statically stood, then a vibration from a source propagates to the construction foundation and stirs it, then we face the problem of *dynamic effects*.

Both cases above-mentioned are objectives of soil dynamics [1]. Dynamic loadings are vast topics with various mode of operation (rolling, rocking, reciprocating, torsing...) and frequencies (low frequency range, medium and high frequency ranges). Dynamic effects that are applied to an objective(s) may generally come from a source in its vicinity for example: due to pile driving, excavating for basement construction, or vehicle mobility…

Dynamic effect is a very challenging topic. And there were few practical approaches for studying it. Two issues are identified: a) Undisturbed soil samples were designed some way to receive an as-it-is state of loading like in its real condition of site, b) devices for testing them will be modified suitably. The most important matter is how to measure it and understand it properly during using data acquisition system for recording data in real time domain. A research in earthquake and dynamic loadings benefits a wide range of development about data collectors and data acquisition systems, unfortunately, there are a few of devices and instrumentations for lab tests on dynamic effects. If in dynamic loadings only try to find out the proper way to excite (loading) and record its response, dynamic effects try to create both the source (loadings) and simulated receiver footing foundation. So, we can figure out how the pure triaxial works [2]; or test for determining the dynamic characteristics of soil using dynamic oedometer [3]; or to simulate the reciprocating process of foundation and footing as a system, sprung table was developed or centrifuge for postulating the liquefaction due to dynamic effects [4].

In Vietnam now this trend of research is not so many, except a few site tests were conducted [5].

PROBLEMS TO BE STUDIED

In reality, there were many construction activities over very soft soil like pile driving, excavating... This causes so many damages to construction and buildings in the vicinity; or during dimensioning land for housing, the short distance from the house to the road (usually over soft soil) resulted in vibration transmitted through soil medium and attack the footings of the house. More seriously, perturbation at very low frequencies can damage electronic products during their manufacturing them [6,7,8].

This comes to an urgent mission that is how to tackle the problem in Vietnam. It means there is a need for finding some relevant approaches for studying the change of soil properties and compressibility under vibration effects.

In Vietnam condition, when there were rarely devices or lab tests for this topics, then how to conduct experiments or theories for the topic? What is the approach? What is the suitable procedure?

OBJECTIVES AND RESULTS

Firstly, mathematical model is necessary for every academic research in engineering. In near field, a formula of dynamic bearing capacity is addressed, whilst other target is the vibrational response of Receiver Footings in far field.

Secondly, experimental studies were conducted to clarify and quantify the effect of vibration on soil strength.

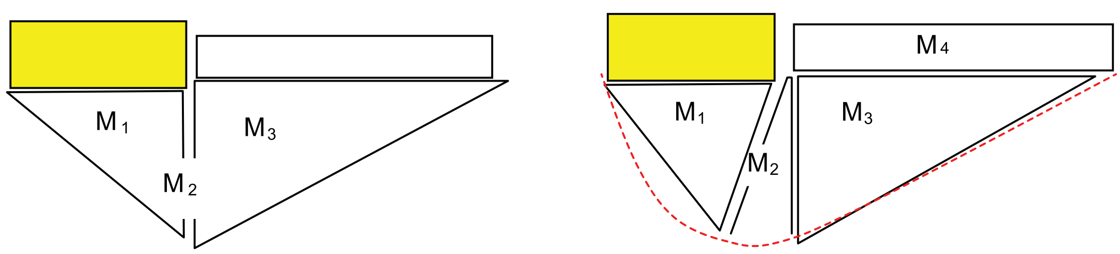
Thirdly, a site test is planned to study the mechanism of additional settlement to double check a so-called implicit relationship between the excess pore water pressure and its attenuation, contact pressure and intensity of vibration.

Some approaches and results have been suggested as follow:

- *Bearing capacity for soil foundation subjected to dynamic effects*

A two-block model developed by a Russian academic scholar Gercevanov (recently still agreed with some other European scientists) where sliding mass was simplified by two blocks: a wedge and its added mass, lying right beneath footing and passively sliding part. Transit sliding block_which locates amid added mass and passively sliding mass_was temporarily neglectable in the model. This is a necessary item to make the model as simple as possible so as to compute analytical confining coefficient of lateral pressure and other parameters. Problem was solved via two steps: (1) Determining the coefficient of lateral pressure K_{dyn}; (2) Establishing the formula for calculating the ultimate value of vertical loading in term of acceleration and intensity of vibration.

Fig 1. Two block Model as per Gercevanov was developed into three block model subjected to pseudo-static loading [9,10]



$$P_{ult}^{dyn} = \frac{E_o^{"} + Bc\tan\alpha[\sin\alpha.\tan(\alpha-\varphi)+\cos\alpha] - \Phi_1[\sin\alpha - \cos\alpha\tan(\alpha-\varphi)]}{(1\pm\overline{m})\tan(\alpha-\varphi)\pm\overline{m}.t}$$

(1)

Where E_o" is mobilized lateral passive pressure, B is width of footing, angles α, φ_{mob} are angles of inclination between sliding surface and mobilized angle of internal friction; Φ_1 is filtration force or seepage due to excess pore water pressure and a hydraulic gradient; m and t relate to acceleration and percentage of additional loading (to be normalized into dimensionless number).

Denominator of the expression of soil bearing capacity indicates that, under an increase in vibration acceleration, soil bearing capacity decreases, together with a reduction in lateral earth resistance (coefficient of lateral earth pressure K_{dyn}) in E_o''[10].

In more details as compared to previous model, three-block model aims at considering factors contributing to the dynamic bearing capacity of subsoil foundation. They are to: (1) investigate curve failure surface; (2) take into account the transit slide zone; and (3) use appropriate values of the coefficient of lateral pressure for different zones of failure mass.

Fig 2. a) Three blocks of sliding mass in a pseudo-static approach [11]

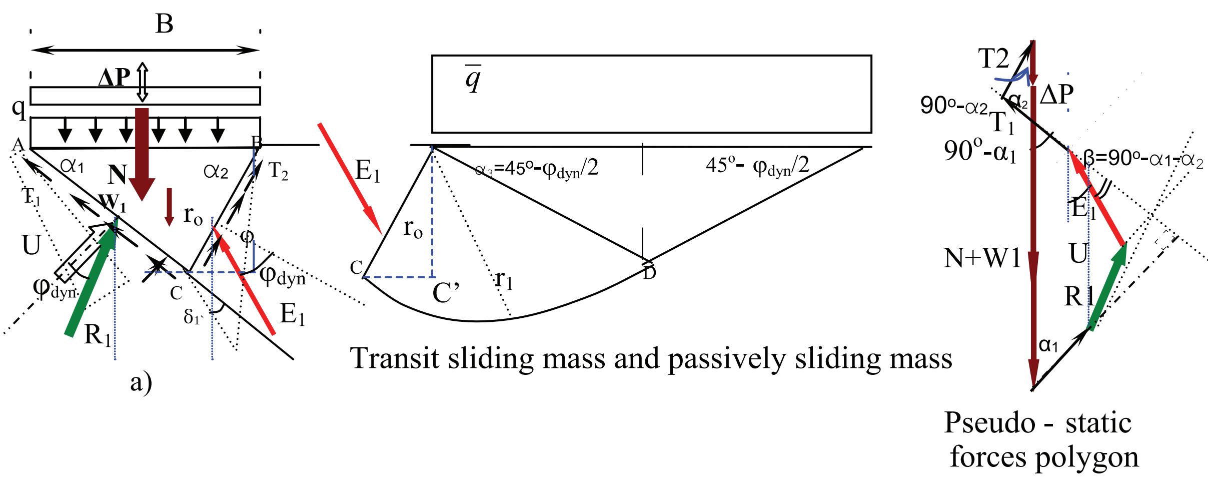
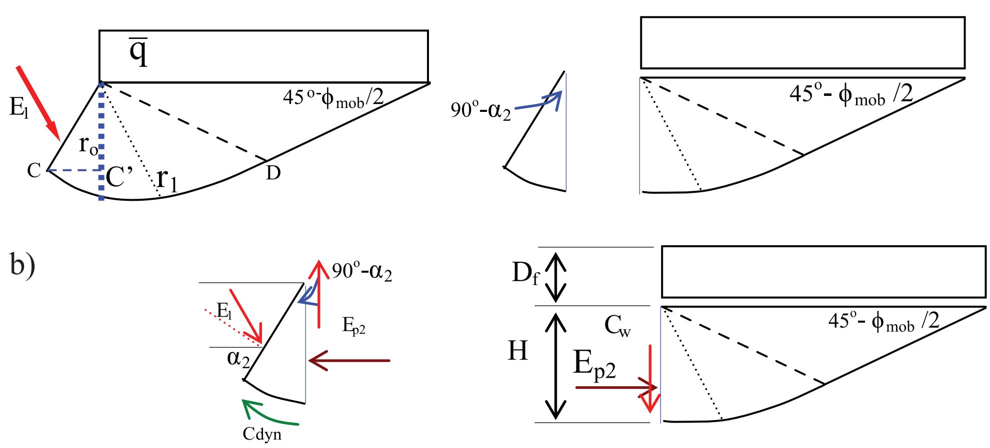


Fig 2 (continued). b) Pseudo static approach to determine lateral thrust, which is closely related to vertical ultimate load N+ΔP+ W1 [11]



$$(N+\Delta P+W_1)-U\cos P_1-E_1\cos(\alpha_2-\varphi)-R_1\cos(\alpha_1-\varphi_{dyn})=T_2.\sin\alpha_2+T_1.\sin\alpha_1$$

(2)

Where

$$E_1\sin(\alpha_2-\varphi_{dyn})-C_{dyn}.\sin\alpha_2=E_{p2}$$

$$E_{p2}=\frac{1}{2}K_{p,dyn}\gamma H^2+2\sqrt{K_{p,dyn}(1+\frac{c_w}{c_{dyn}})}.c_{dyn}(H+D_f)$$

Also $$K_{p,dyn} = \frac{\cos\varphi_{dyn}}{\sqrt{\cos\delta - \sqrt{\sin(\varphi_{dyn}+\delta)\sin\varphi_{dyn}}}}$$

$$E_1 = \frac{[(N+\Delta P+W_1)-(T_2.\sin\alpha_2+T_1.\sin\alpha_1)+R_1\cos(\alpha_1-\varphi_{dyn})-U\cos\alpha_1]}{\cos(\alpha_2-\varphi)}$$

These above results can inherit some prior knowledge from Prakash and Sarma (1971) [12] as follow:

$$T_2 = c.\frac{B\sin\alpha_2}{\sin(\alpha_1+\alpha_2)}$$

$$T_1 = c_{mob}.\frac{B\sin\alpha_1}{\sin(\alpha_1+\alpha_2)}$$

and

$$R_1 = \frac{2.c_{mob}\sqrt{K_{dyn}}.\sin^2\alpha_3}{\cos\varphi_{mob}}.r_0[\exp 2(\pi-\alpha_2-\alpha_3)\tan\varphi_{mob}] + \frac{c_{mob}.r_o}{\sin\varphi_{mob}}.\{\exp[2(\pi-\alpha_2-\alpha_3)\tan\varphi_{mob}]-1\}$$

All symbols and parameters were explanatory as described in figure 2.

Mobilized cohesion c_{mob} and angle of internal friction φ_{mob} must be determined experimentally via lab test in modified shearbox apparatus developed by author. In conservative side, only φ_{mob} was taken into account instead of both cohesion and angle of internal friction, partly because this parameter is dimensionless [13].

- *Experimental studies to investigate the soil strength under vibration.*

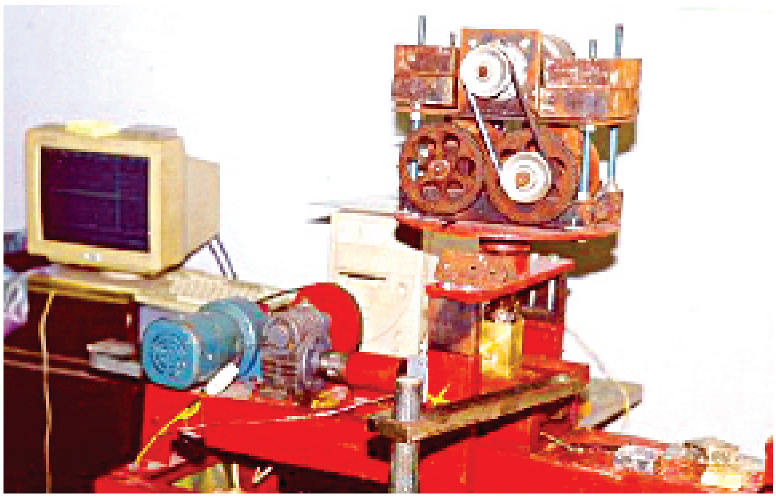
Unlike previous trend of experimental studies using lab tests in which undisturbed soil samples were sprung before shearing test, periodically varied normal stresses were applied over soil samples, whilst simultaneously subjected to shearing stress. This is like a soil element lying right below a footing of construction subjected to vibration effects, its foundation also vibrates. So unlike in earthquake that shear stress is cyclic.

Assumption to be verified is that under inconstant normal stress, there would be some changes in value of angle of internal friction and compare it to that of direct shear test.

Modified shearbox as in figure 3, vertical loading includes a static load, plus an additional amount due to vibrating eccentric masses, applying over soil square sample. As such, normal stress will not a fixed value. Force vertically applied to soil sample will be recorded electronically by piezo-electric ‘self-made’ loadcell. Perturbation as sum of multi frequencies vibration was eliminated by using an eccentric symmetrically locates in both sides of loading frame [13]. When a single exciting frequency was created and applied on soil sample, this apparatus was approved. Soil sample was 50x50 square so as to exactly calculate the reduced shear area when shearing. By using this square soil sample, mobilized shear stress was accurately calculated. Sliding friction of mechanism during shear testing was eliminated by running without soil sample. Data was recording via electronic RS232 gate to a computer. Over 600 undisturbed soil samples collected from many other soil stratums in Ho Chi Minh City were used in test with modified shearbox.

Results pointed out that under such varied conditions of stress like in lab tests, coefficient of internal friction was mobilized to a smaller value than that of conventional direct shear test. No result in mobilized cohesion was given. It was because the cohesion had dimension, that depended on scale, apparatus and condition of test device, unlike dimensionless coefficient 'tanφ' [13].

Fig 3. Modified shearbox apparatus implemented by Tham, D.H [13]

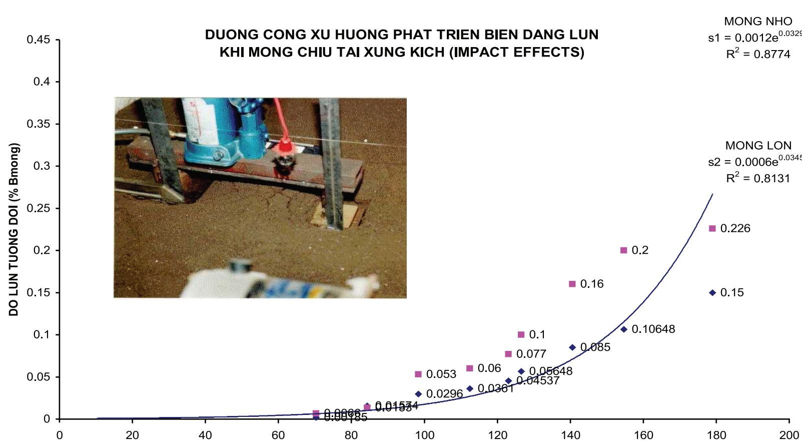


This modified shearbox developed by author won a fellowship to participate and introduce in the International Colloqium on Solid, fluid and Structure Interaction, held by University of Brussel (Belgium) and Vietnam National University in Ho Chi Minh City in Nhatrang Province 2000 [12].

- *Experimental studies on technical model using simulated soil.*

A small scale model using equivalent material [14] was conducted. As per similarity rule, but only partial similitude [15] was applied for studying qualitatively the additional settlement. To ensure a rigorous procedure, a repetitive research was carried out [16]. The result indicated that under some ways of dynamic effects, unlike the static load case, the length of sliding mass was shorter than that of static case of loading. Besides, under the same contact pressure, the smaller width of footings is, the bigger amount and speed of footing settlement is [17].

Fig 4. a) Lab test on small scale model using equivalent material; b) Plot diagram points out more rapid settlement of smaller width of model footing (75x75) as compared to bigger width (110x110)



- **Full scale site test**

Besides lab tests and small scale model using simulated soil [17], an in-situ test was conducted to validate theoretical findings. Plate bearing test was chosen. Target for the test is to investigate the change of pore water pressure as dynamic effects transferred to foundation of receiver footing; if an increase of pore water pressure due to dynamic effect (i.e. vibration) was detected (by measuring the water level in open standpipe installed around the plate), an additional settlement would have been occurred as the sequence of pressure detenuation. Four open standpipes (piezometer) were installed to different depths and located around the model footing. A 40 tons truck running on a rough road was chosen as source of vibration. The distance from the model footing and the edge of the road is about ten meters (this is the minimum distance with which, only the Rayleigh wave_ surface wave_ exists).

Fig 5. Site test for studying the additional settlement of model footing subjected to vibration

Some results were:

a. The additional settlement was significantly correlated in term of an exponential function of the contact pressure [18].

b. Under vibration, there was a trend of increase in pore water pressure to a depth of ten times of footing width. This resulted in an additional settlement of footing subjected to externally exciting vibration. Trend analysis allowed an extrapolation to have a predictable value of settlement for receiver footing [19,20,21].

- **Theoretical postulation in far field**

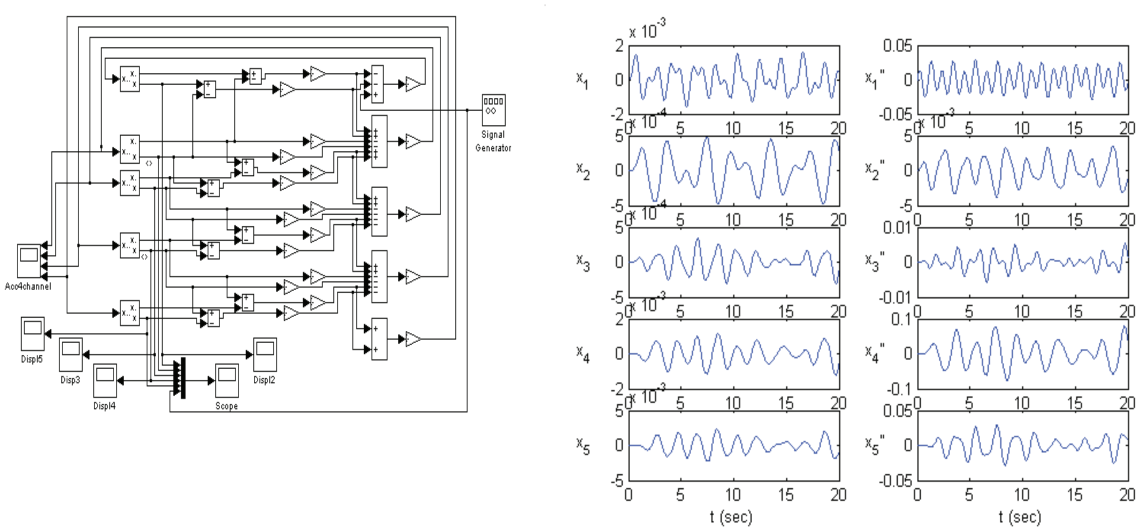
Far field study is to investigate the response of receiver footing due to vibration propagating from a source. It is necessary to establish a theoretical model for predicting the response of receiver footing according to vibration of the source. A mathematical model for taking over the response of Source – Medium – Receiver was created by considering each element of system as a mass participating in motion with the others altogether. Those were called "lumped masses", like what to be studied by Wolf [22]. Low frequencies were assumed because of great mass of inertia.

Masses were connected by springs and dashpots in which their values were complied with previous knowledge [23]. The sizes of masses were estimated in terms of pseudo-static approach (added mass participated in motion with mass was taken into account in pseudo-static approach).

Differential equation of motion for each mass was described as per D'Alembert principle. The system included 5 blocks: (1) Source M_1 ; (2) foundation of source (temporarily static dimension) M_2; (3) Soil medium M_3; (4) Foundation of Target or receiver foundation (temporarily static dimension) M4, and (5) Target mass (Receiver) M_5.

$$
\begin{aligned}
&F(t)-k_1(x_1-x_2)-c_1(\dot{x}_1-\dot{x}_2)=M_1\ddot{x}_1\\
&k_1(x_1-x_2)+c_1(\dot{x}_1-\dot{x}_2)-k_2x_2-c_2\dot{x}_2-k_X(x_2-x_3)-c_X(\dot{x}_2-\dot{x}_3)=M_2\ddot{x}_2\\
&k_X(x_2-x_3)-k_Y(x_3-x_4)+c_X(\dot{x}_2-\dot{x}_3)-k_3x_3-c_3\dot{x}_3-c_Y(\dot{x}_3-\dot{x}_4)=M_3\ddot{x}_3\\
&-k_5(x_4-x_5)-c_5(\dot{x}_4-\dot{x}_5)-k_4x_4-c_4\dot{x}_4+k_Y(x_3-x_4)+c_Y(\dot{x}_3-\dot{x}_4)=M_4\ddot{x}_4\\
&k_5(x_4-x_5)+c_5(\dot{x}_4-\dot{x}_5)=M_5\ddot{x}_5
\end{aligned}
\tag{2}
$$

Fig 6. Simulink modeling and the plotted response of motion of 5 elements: Source (x1) and its foundation (x2), Medium (x3), Receiver Foundation (x4) and Target or receiver (x5). x" is the acceleration [24]



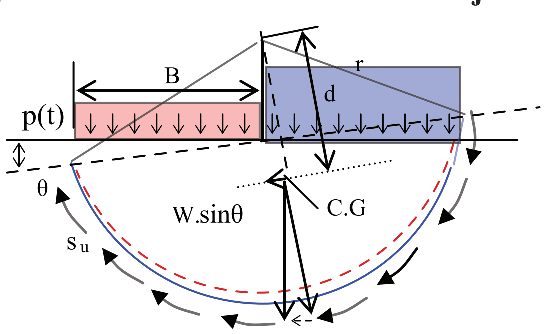
This system of governing equations (2) above-mentioned could be solved by using Simulink toolbox and programming in Matlab. After solving the system of equations a system of time dependent motion expression was given [24] as plotted in Fig. 6.

- Response of receiver Foundation in near field.

In order to answer the question that:

- "What is the unstable condition under vibration ?"
- When is vibrating foundation collapsed ?".
- What happens to soil foundation under a vibrating receiver construction ?

Fig 7. Sliding mass on cohesive foundation subjected to vibration



From the conventional definition of safety factor for moments :

$$\eta = \frac{antirotatingMoment}{rotatingMoment}$$

the
$$\eta = \frac{M_I + M_G + M_{SCC} + M_{DD} + M_{CF}}{M_{qq'}} = \frac{M_{\sum chTruot}}{M_{GTruot}}$$

where :

M_I Moment due to vibrating rotary Inertia mass;

M_G Moment due to eccentric centre of mass;

M_{SCC} Moment of resist due to mobilized soil strength s_{mob};

$M_{ĐĐ}$ Moment of vibrating mass due to depth of footing;

M_{CF} Moment of resisting due to Coulomb's viscous friction, with respect to $\dot{\theta}$;

$M_{qq'}$ Moment of resisting due to dynamically sliding mass, including p(t) and q_b;

the expression above was rewritten:

$$\eta = \frac{\frac{W}{g}.\overline{r}^{2}.\ddot{\theta} \pm W.d.\sin\theta + \kappa\pi B.s_{mob} + \frac{1}{2}[q_0 + q(t)].(B)^2 + \mu_{dyn}(N.\dot{\theta}) - U}{1/2(q_b + p(t))B^2} = 1$$

(3)

W is sliding mass together with added mass

r = radii of rotation

d = distance from the center of rotation to the center of sliding mass

B = width of footing

s_{mob} = mobilized shear strength

q_o = contact pressure; q(t) = additional cyclic loading, developing over vibrating mass

m = Coulomb's viscous friction

N = pseudo-static reaction of sliding mass against the underlying foundation

U = Excess pore water pressure raised when the mass vibrates

$\dot{\theta}$ = angular acceleration

Change and regroup the expression (3), it is indicated a traditional non-linear second order differential equation of a pendulum swinging around a decayed pivot.

By programming the equation is solved analytically, and plotting it, we plot the diagram of rotary angle in time domain as described in figure 8.

It is noted that a stable value after a while results in the additional settlement of the vibrating foundation in reality [25].

CONCLUSION

Unlike studies on earthquakes, construction works subjected to dynamic effects (i.e. vibration, impacts or perturbation) propagating from a source in far field could be studied *tentatively* from theoretical aspects (mathematical models), from near field to far field, from test over undisturbed soil samples using modified shearbox in laboratory to small scale technical model using simulated soil (because the state of the art apparatus as centrifuge to study reduced physical model), from small scale model to full scale in-situ test.

In some definite conditions, models for studies mentioned above can be used to evaluate qualitatively responses (i.e. acceleration, velocity and displacement) of a structure or construction works (for example, a pile is hardening right after casting in earth) under vibration, running from a source propagating through soil medium and coming to attack their foundation (construction activities such as excavating to build the basement of high rising buildings, or vehicle mobility). It definitely still needs to further it in both theoretical research, lab test and in-situ test together with finite element modeling to calibrate and create several practicable models to use efficiently in reality.

ACKNOWLEDGMENT

Author would like to thank Assoc. Prof. Yeung Wai Hung, NanYang Technological University, (NTU) Singapore for his invaluable assistance in solving the governing differential equations of motion with Matlab during the course Train the Trainee at NTU (2004). Supports from Dr. Son, T.N.H by 2003 and Dr. Huynh P.D by 2011 are also acknowledged.

REFERENCES

1. ИВАНОВ, П.Л.,(1991) “ГРУНТЫ И ОСНОВАНИЯ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ”, ВЫШАЯ ШКОЛА,МОСКВА.
2. Kokusho T., (1980) “Tests of dynamic soil properties”, journal JSSMFE, Vol 20, No 2.
3. Hierli, W. , “One dimensional wave propagation in soil, Experimental theoretical Investigations”, IUTAM symposium providence 1963.
4. Madabhushi S.P.G and Schofield A.N., (1996) “ Centrifuge modeling of tower structures on saturated sands subjected to earthquake perturbations”, *Geotechnique* 43, No 4.
5. Nguyễn Ngọc Quỳnh (1979) “ Failures and damages when piling in urban construction”, Institute of Mechanics – Center of Natural Sciences and Technologies.
6. Dalmatov,B.I.,Ershov,V.A., Kovalevsky,E.D., “Some cases of foundation settlement in driving sheetings and piles.”, Proceedings of 7th International Conference on Vibration International Conference on Vibration.
7. D’Appolonia, D.J., “Effects of foundation construction on nearby structures”, Proceedings of 4th Pan-American International Conference on structural dynamics
8. Lo, K.Y and Stermac, A.G., “ Induced pore pressures during pile-driving operations.”, trích Proceedings of 6th Intl conference on soil Mechanics. & Foundation Engineering., Vol 2.1965.
9. Tham, D.H (2002) “Studying the effects of vibration due to pile driving and heavy truck mobility on soil foundation in the vicinity”, Doctoral Thesis, VNU-HCM.
10. Tham, D.H (2001) “ An survey on the coefficient of lateral pressure of foundation under vibration” internal journal of the Institute of Applied Mechanics.
11. Tham, D.H (2007) “A more detailed investigation in estimating the soil bearing capacity of foundation subjected to vibration ”, Proceedings of 8th national Congress on Mechanics, Hanoi.

12. Tham, D.H (2000), "The experimental studies of the shear strength of sub base soil under receiving footings affected by construction vibration sources", Symposium of Intl Colloqium in Mechanics of Solids, Fluids, structures & Interactions, Nhatrang.
13. Tham, D.H (2000), "Studying the effect of dynamic loadings on shear strength of soil underlying the vibro-induced construction by using a modified shearbox ", Journal of Science and technology development, Vietnam National University in HCM.
14. Glushikhin (1996) " Modeling in Geotechnics" , Balkema, Netherlands.
15. Luong, M. P. (1981) "Dynamic, cyclic, and transient aspects in soil engineering.", Proceedings of the NATO advanced study, Portugal.
16. Tham, D.H (2002), "Some results of tests in reduced model about settlement of footing on cohesionless soil subjected to vibration" presentation and paper in Proceedings of the 7th national congress on Engineering mechanics, Hanoi.
17. Tham, D.H (2004), "Some results of experimental studies on small scale model about the model footing on non-cohesive soil under vibration", Journal of Agriculture and Rural development, ISSN 0866-7020.
18. Tham, D.H (2005), "Analyzing the damage of Van Thanh tunnel and construction works in its vicinity" Journal of sciences, Open University in HCMC.
19. Tham, D.H (2001) "Plate bearing test under vibration", Journal of science and technologies development, Vietnam National University in HCM.
20. Tham, D.H (2001) "An investigation about the increase of pore water pressure in foundation due to truck mobility over soft soil", Journal of science and technologies development, Vietnam National University in HCM.
21. Thẩm, D.H (2001) "Analyzing the response of in-site bearing plate subjected to dynamic effects", Journal of science and technologies development, Vietnam National University in HCM.
22. John P. *Wolf* (1994), "Foundation Vibration Analysis Using Simple *Physical Models*, Swiss Federal Inst. of Technology, Lausanne, ISBN-10: 0130107115, Prentice Hall
23. Nguyen Truong Tien (1987) "Dynamic and static behavior of driven piles", Report No 33, Swedish Geotechnical Institute, ISSN 0348-0755.
24. Tham, D.H (2007), " Mathematical model for studying the effects of vibration emitted from a source, propagating thru soil medium and stirring the receiver foundation", Proceedings of the 8th National congress on Mechanics, Hanoi.
25. Tham, D.H (2010) "Studying the dynamic equilibrium of a foundation lying under a footing subjected to vibration" (Case of cohesive foundation, research in near field)", journal of sciences Open University in HCM, ISSN 1859-3453.