Development of Combined Loading Apparatus for Physical Modeling

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Abstract

The new loading apparatus was designed and constructed to investigate the behavior of model foundation under combined loading conditions. Air cylinders were used to generate applied loads, the load and displacement were determined via load cells and linearly variable differential transducers (LVDTs) respectively. The key aspect of the new system is that the system can be highly applicable for any combination of vertical, horizontal and moment loadings and the displacement paths can be generated and applied to model foundations with precise force, position and direction. A number of combined loading tests of pile foundation and improved pile foundation were conducted on sand to evaluate the expected performance of the newly developed loading apparatus.

1. Introduction

In the design of foundation structures, bearing capacity is always a major concern, thus the issue of bearing capacity of foundations under combined vertical V, horizontal H and moment M loading has also attracted considerable research interest both experimental and numerical (Ticof, 1977; Tan, 1990; Gottardi and Butterfield, 1993; Butterfield and Gottardi, 1994; Martin, 1994; Allersma et al., 1997; Bransby and Randolph, 1998; Watson and Randolph, 1998; Gottardi et al., 1999; Byrne, 2000; Martin and Houlsby, 2000, 2001; Purattanasin, 2002). Full scaled field tests or laboratory experiments are considered as experimental works. Due to elimination of the scale effect, the full scaled field tests are the most favorable. However, it is difficult to make a comparison between observed and predicted behavior because a large number of variables involves when in-situ soil is tested with inadequate control. Thus, the laboratory tests become more and more popular because most of the parameters of the test are under controlled. Consequently, every test has the same initial conditions and the soil as well as the foundation behavior could be easily observed, monitored and compared. In addition, the laboratory experiments can be conducted both at unit gravity and enhanced gravity field (Purattanasin, 2002).

This paper presents a newly designed loading apparatus to develop and verify the elasto-plastic model of the foundation behavior under the combined load. The apparatus was first used to evaluate capacities of pile foundations. A number of initial tests were carried out with pile foundations on sand under combined loads to evaluate the performance of new loading system.

2. Design of combined loading apparatus

The loading apparatus was designed and constructed to study the performance of model foundations under combined loading conditions. The outstanding point of the new system is that it can be highly applicable for any combination of vertical, horizontal and moment loadings and displacement paths can be generated and applied to the model foundations with precise force, position and direction. The aim of the new apparatus are (1) to simulate the penetration process of model foundation; (2) to study the vertical capacity and pull out capacity of foundations; (3) to observe the elastic response during vertical loading; (4) to learn the model foundations' performance, behavior

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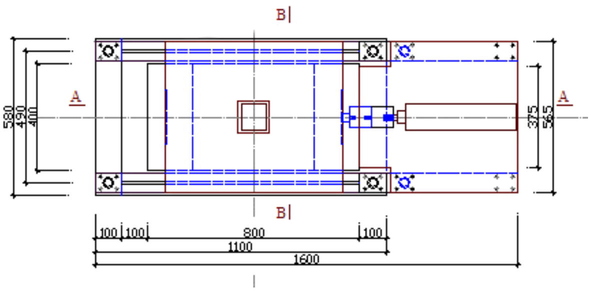
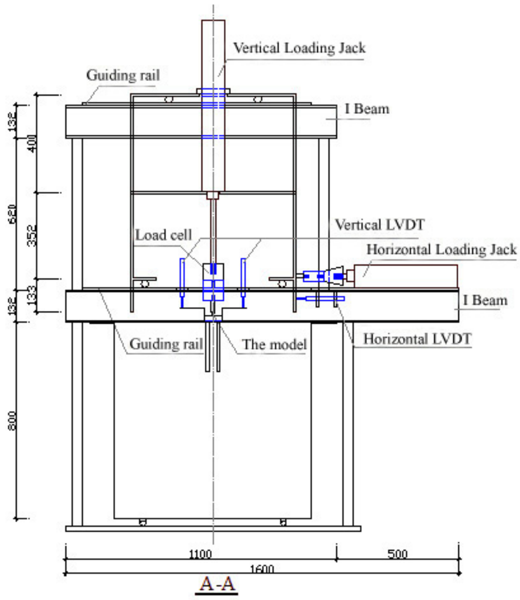
as well as the shape of yield surface under combined loading; (5) to identify the ultimate vertical, horizontal and moment capacity. This combined loading apparatus is expected to be appropriate for not only pile foundation but also many types of footings under the combined loading condition.

2.1 System description and geometry of the apparatus

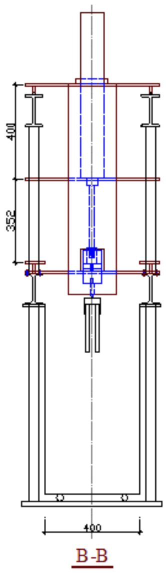
There are four main parts in the loading apparatus: loading system, measuring system, control system and data acquisition system. Figures 1, 2 show the schematic drawings and general view of the combined loading system.



(a) Top View



(b) Cross –section A-A



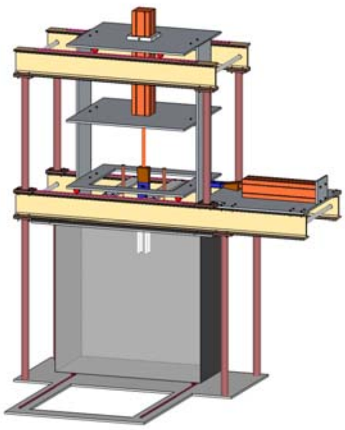
(c) Cross-section B-B

Figure1 Schematic drawing of combined loading system

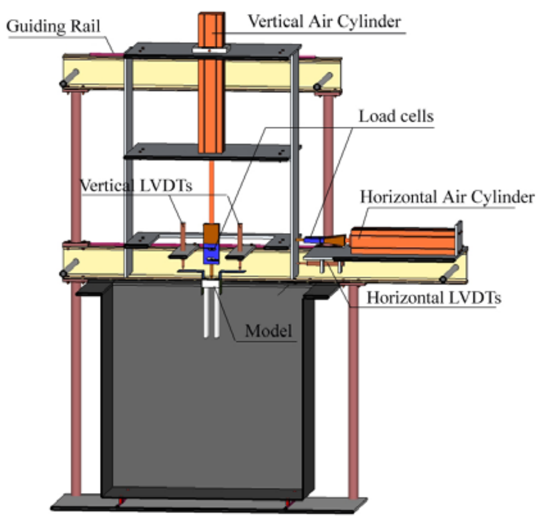
Besides, the loading apparatus includes a soil container. The container is a steel box having inner dimensions of 80cm in length, 40cm in width, and 80cm in depth. These dimensions were chosen large enough so that there will be no interference between the wall of soil container and the failure zone around the model foundation. An interesting point of the loading apparatus is that the container is linearly and smoothly movable out of the loading system by means of its four wheels moving on two rails in order to easily prepare the soil before testing.

2.2 Loading system

Two air cylinders whose models are MDB1B80-400 and MDB1B80-300 (SMC Co., Ltd., Japan) were respectively used for applying the vertical and horizontal loads on the foundation. The configuration of the vertical air cylinder allows a piston to move up and down so that any designed vertical load and pull out force could be applied while the horizontal air cylinder was used to generate horizontal load. They were mounted on a gantry system which is clearly shown in Figure 2. The gantry system includes a fixed part and unfixed part moving along four rails on four I section beams by means of its eight wheels. The horizontal and vertical air cylinders were mounted respectively on the fixed and unfixed parts. Hence, in terms of eccentric loading cases, the vertical loading system was horizontally moved to a position in order that it can apply the desired eccentric point on the footing. In other words, moment loading could be generated by this way.



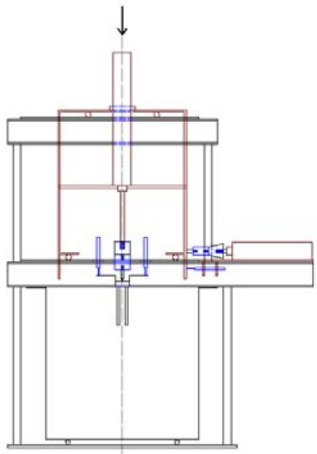
(a) 3D general view



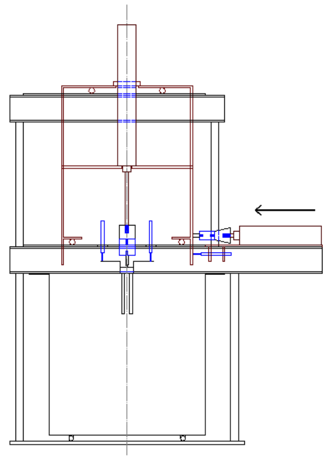
(b) 3D cross section

Figure 2 The schematic 3D drawing of loading apparatus

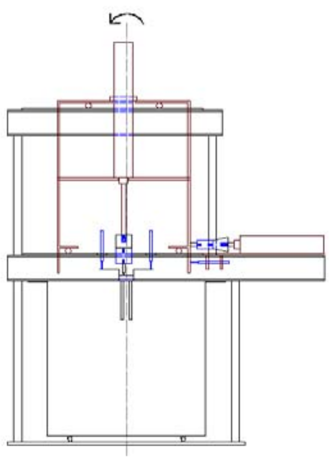
The loading mechanisms of the system are graphically demonstrated in Figure 3. The loads were transmitted to the model through a rigid pointed steel rod (in case of vertical load) or rigid connector (in case of horizontal load), which were both connected with load cells. A key feature of this loading system is that any combined loads can be generated and applied to the model with high precise force and position.



(a) Vertical loading



(b) Horizontal loading



(c) Moment loading

Figure 3 Loading mechanism

2.3 Measuring system

The loads and the displacements of the model of foundation were measured via load cells and linearly variable differential transducers (LVDTs) whose data could be recorded by Portable Data Logger program through a computer. Two load cells (L-05002 and L-05003, Geo-Intergration Co., Ltd., Thailand) whose capacities are 5KN were screwed to the pitons to quantify the applied loads. The linearly variable differential transducers (LVDTs) were fixed on very stiff reference plates and their spindles contacted with measuring plates all the time during testing. Due to the small size of the model, two steel arms or measuring plates used to measure the vertical settlement of the foundation were attached to the surface of pile cap via screws. The arms were rigid enough to ignore their own bending. In each arm, there was a small fixed hole where LVDT's spindle is on. This helps to calculate rotation angle of model foundation.

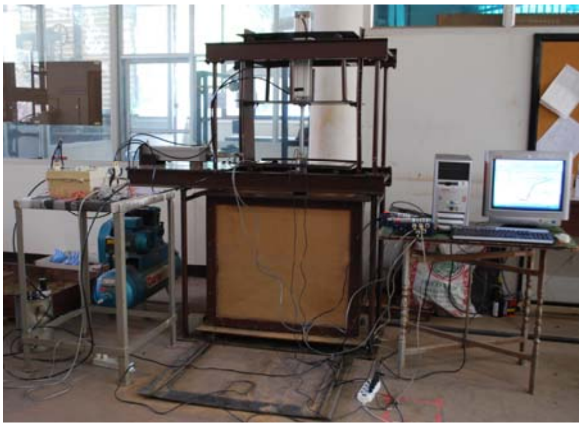


Figure 4 Combined loading apparatus

2.4 Control and data acquisition system

The air cylinders were operated due to air bump through filter regulator, solenoid valves and electric controlling box. The first one was used to filter air and control the air pressure of cylinders as well; the others were used to control the cylinder's pistons movement. All sensors and transducers (load cells and LVDTs) were connected in turn with transducer connection boxes, data logger and computer. The output signal from sensors and transducers could be accepted and captured every second in the computer by using Portable data logger program.

3. The performance evaluation of new combined loading apparatus

A number of tests were conducted to evaluate the system capacity as well as to investigate the pile foundations on sand under combined loading condition. Takemura (2009), Nguyen and Punrattanasin (2010) used sheet piles around pile foundation, called improved pile foundation, to increase moment resistance and bearing capacity respectively. Accordingly, three types of model foundation used to evaluate the system performance are shown in Figure 5 namely pile foundation (PF), pile foundation with sheet piles at two sides of the pile cap (PFTS) and pile foundation with sheet piles at the four sides of the pile cap (PFFS).

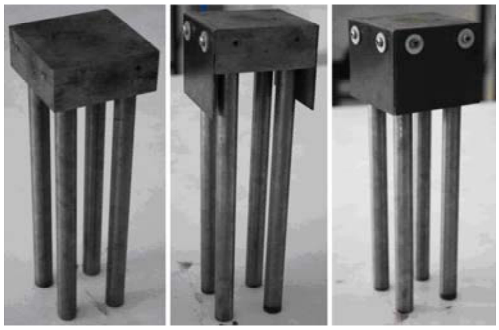


Figure 5 Three types of model foundations: PF, PFTS and PFFS

Figure 6 Pile cap with grooves

The model foundation includes four identical steel piles (200mm in length and 14mm in diameter), a steel pile cap (70mm x 70mm x 30mm) and steel sheet piles (1mm in thickness and 30mm in length). The distance from the center to center of piles in the group is 3d or 42mm (d is the pile diameter). The four piles are screwed into the pile cap; the sheet piles (30mm long from the bottom of pile cap) are connected to the pile cap by screws. Also, the top of the pile cap has many grooves, shown in Figure 6, in order that the load can be applied with different eccentricities.

The soil used for all tests was dry Puttaisong sand which is easily found in the Northeast of Thailand. Besides, the sand is uniformly graded sand, sorted by particle sizes. The sand was poured from the hopper into the model container whose size is large enough with no apparent influences of boundary effects. In order to create the same initial condition for all the tests, the height of the hopper above the deposited sand surface was chosen to be 50 mm and periodically adjusted to the rise of the sand surface to maintain the constant height. In other words, uniform sand, of which relative density is constant, could be achieved by this way. The sand was fully poured into the container. It means that there was no apparent influence from effects caused by the bottom of the container (Al-Mhaidib, 2006). Table 1 summarizes the properties of the sand.

Table 1 Physical properties of experimental sand

Type	Sand
Unit weight (kN/m3)	14.39
D60 (mm)	0.395
D30 (mm)	0.360
D10 (mm)	0.240
Uniformity coefficient, C_u	1.646
Coefficient of graduation, C_c	1.367

In order to evaluate the combined loading apparatus and to investigate the foundation behavior under combined loading condition, a series of 10 loading tests was conducted and reported in this paper. They are grouped and detailed according to the type of loading showed in Table 2.

Table 2 Test condition

Test group	Sub-group	Test No.
Vertical Loading Test	PF	1
	PFTS	2
	PFFS	3
Vertical Horizontal Loading Test	PF	4. (V_{start}=60% V_{max}) 5. (V_{start}=75% V_{max}) 6. (V_{start}=90% V_{max})
Vertical Moment Loading Test	PF	7. (E=e/B=0.1) 8. (E=e/B=0.167) 9. (E=e/B=0.25) 10. (E=e/B=0.333)

4. Experimental Results

4.1 Vertical Capacity

All three kinds of model foundations (PF, PFTS and PFFS) were carried out under vertical loading for comparison purpose. The ultimate bearing capacity of the foundation is defined at the peak values in the vertical load–vertical settlement curve. In case, the peak load occurs at very large settlement, according to Punrattanasin (2009), the loading corresponding to the settlement of 0.1B is considered as the ultimate bearing capacity. Since the loading system is displacement-controlled, the load and displacement can be continued and measured after the ultimate load or at very high settlement. The vertical load – vertical settlement relationships of all kinds of models were plotted in Figure

7 to evaluate the improvement capacity received from the sheet piles. From Figure 7, it is clearly shown that there is no peak load of the curves, so the ultimate capacities of foundations were chosen as the load at settlement of 0.1B= 7mm. Figure 7 also presents that the vertical ultimate capacity of pile foundation (PF) is 288.17N and those of pile foundation with two sheet piles (PFTS) and pile foundation with four sheet piles (PFFS) are 326.31N and 364.27N respectively. In addition, it should be noted that the settlements start at around the load of 130N. It means that 130N is driving capacity of foundations before touchdown. In summary, the sheet piles can enhance the bearing capacity of pile foundation. In fact, with 3cm length sheet piles, the bearing capacity of pile foundation with sheet piles (PFTS and PFFS) increase by 13.24% and 26.41% respectively compared with that of pile foundation (PF).

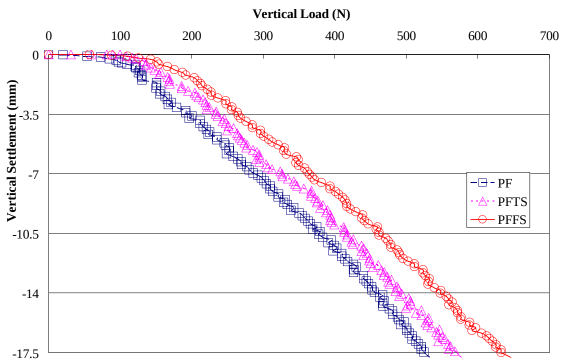
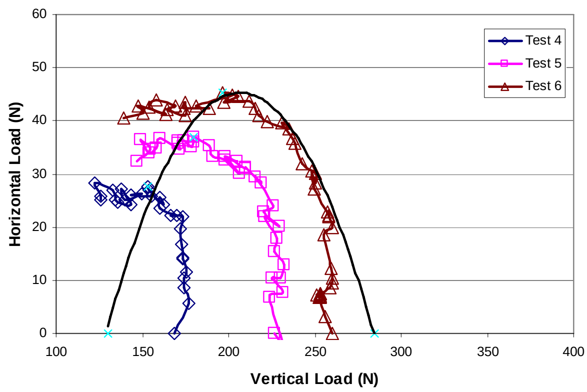


Figure 7 Vertical load- settlement relationship of three kinds of model foundation

4.2 Horizontal Capacity

A concept of swipe test was first introduced by Tan (1990) to investigate the horizontal capacity and the shape of yield surface in V-H load space for conical footing on sand. The concept was then adopted and modified to identify the horizontal capacity of many types of footings (Gottardi and Butterfield, 1993; Punrattanasin et al., 2004, 2008).

In addition, Punrattanasin et al. (2004) indicated that failure surface of horizontal capacity of square shallow foundation is parabolic shape. Three horizontal swipe tests (detailed in Table 2) were performed to evaluate the horizontal capacity of the pile foundation in V-H load spaces. Besides, it is noticed that, in this research, the driving capacity of pile foundation (130N) was considered as a new zero value for generating the failure surface. Figure 8 presents the results of the horizontal swipe tests for the pile foundation



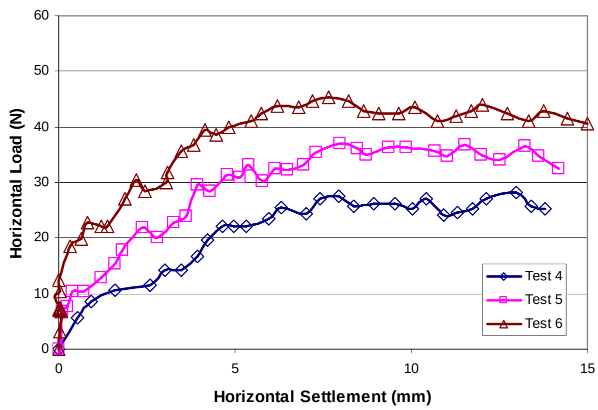


Figure 8 Horizontal swipe tests of pile foundation (PF)

Figures 8 clearly illustrates that the horizontal loads increase moderately until reaching the peak at horizontal settlement of about 7mm and then slightly decrease. Conversely, the vertical loads fall slightly until the peak then rapidly drop down to failure. From Figure 8, it is clearly shown that the maximum horizontal load of the pile foundation is 45N.

4.3 Moment Capacity

A series of eccentric loading tests of pile foundation was implemented to illustrate the application of loading apparatus in terms of moment loading. The effect of load eccentricity was studied by applying a vertical force at different distances from the pile cap centerline. Besides the centre of pile cap, four other points with eccentricities E= e/B = 0.1, 0.167, 0.25 and 0.333 were made (e: eccentricity, B: width of pile cap). The results of the series are graphically presented in Figure 9. Similar with above case, the load at a settlement of 0.1B (7mm) was chosen as the ultimate bearing capacity of the foundation.

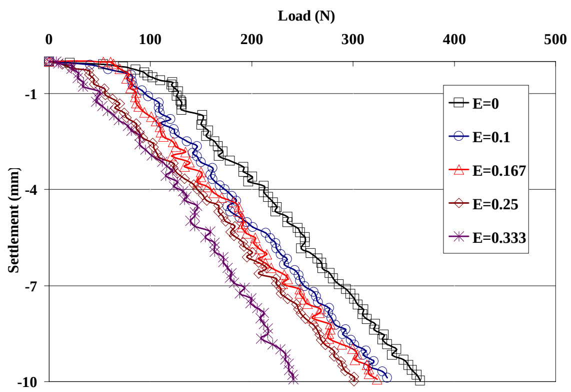


Figure 9 vertical load- settlement relationships of pile foundations under various eccentricities

From Figure 9, it is easy to point out the eccentric vertical ultimate bearing capacities of pile foundation in cases of E= 0.1, 0.167m 0.25 and 0.333 are 251N, 236N, 226N and 189N, respectively. Besides, it also obviously indicates that the more eccentricity increases, the less the bearing capacity gets. The horizontal displacements of pile foundations were neglected in all experiments until the failure conditions were approached.

The pile foundation under a vertical eccentric load V may be considered as subjected to a vertical load V and a moment M, which is equal to the load V times its distance from the centre. The effect of the moment acting on a pile foundation on sand is plotted in Figure 10 in terms of a normalized diagram on M-V plane with respect to Vmax (centric ultimate bearing capacity of a pile foundation) (Punrattanasin, 2002). Figure 10 indicates that the maximum moment (M_{max}) can be approximated by $M_{max}/B = 0.25V_{max}$, for pile foundation (PF).

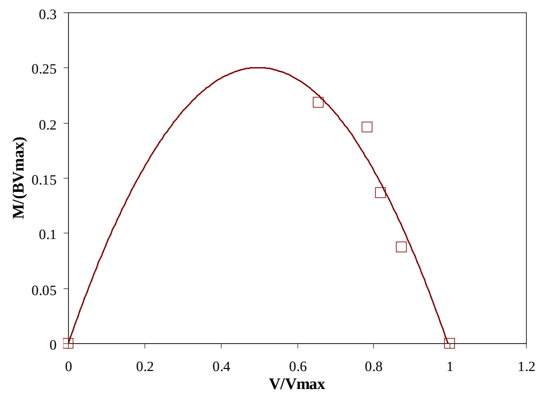


Figure 10 Normalized load-moment relationships

5. Conclusion

The combined loading apparatus was newly developed to study the performance of model foundation under the combined vertical, horizontal and moment loadings. The air cylinders were used to generate the applied load, load cells and linearly variable differential transducers (LVDTs) were used to determine the loads and displacements respectively. The system can be highly applicable for any combination of vertical, horizontal and moment loadings and the displacement paths can be generated and applied to the model foundations with precise force, position and direction. Besides, the system is appropriate with not only pile foundations but also the other footings. With the new apparatus, a number of combined loading tests of pile foundation and improved pile foundation were carried out on sand to evaluate the new loading system and determine their vertical, horizontal and moment capacities. In terms of vertical loading, the result reveals that using sheet piles can enhance the capacity of pile foundation.

6. Acknowledgments

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