Earthq Eng & Eng Vib (2013) 12: 1- DOI:

Field testing of stiffened deep cement mixing piles under lateral cyclic loading

Werasak Raongjant† and Meng Jing†

Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology, Thanyaburi 12110, Thailand

Abstract: Construction of seaside and underground wall bracing often uses stiffened deep cement mixed columns (SDCM). This research investigates methods used to improve the level of bearing capacity of these SDCM when subjected to cyclic lateral loading via various types of stiffer cores. Eight piles, two deep cement mixed piles and six stiffened deep cement mixing piles with three different types of cores, H shape cross section prestressed concrete, steel pipe, and H-beam steel, were embedded though soft clay into medium-hard clay on site in Thailand. Cyclic horizontal loading was gradually applied until pile failure and the hysteresis loops of lateral load vs. lateral deformation were recorded. The lateral carrying capacities of the SDCM piles with an H-beam steel core increased by 3–4 times that of the DCM piles. This field research clearly shows that using H-beam steel as a stiffer core for SDCM piles is the best method to improve its lateral carrying capacity, ductility and energy dissipation capacity.

Keywords: stiffened deep cement mixing pile; lateral capacity; cyclic lateral loading; energy dissipation capacity; field testing

1 Introduction

An important feature of pile foundations for offshore structures is the cyclic nature of the loading (both axial and lateral). Laboratory and field data show that cyclic loading may cause a reduction in load capacity and an increase in the settlement of piles. A deep cement mixing (DCM) pile is normally used to improve the engineering properties of the soft clay layer. However, although this kind of pile has many advantages in various applications, collapse caused by pile failure can occur, especially when subjected to lateral loads. Moreover, the unexpected lower strength than the design value commonly occurs due to lack of quality control during construction (Dong *et al.*, 2004). To mitigate these problems, a new kind of composite pile called a stiffened deep cement mixing (SDCM) pile, is introduced. A SDCM pile is a kind of composite pile and is shown in Fig. 1. Immediately after the construction of a wet mixing DCM pile, a precast concrete stiffer core with a higher strength and stiffness is inserted into the center of the DCM pile, or a hole is bored in the center of the DCM pile and fresh concrete is poured into the hole to act as a stiffer core. Thus, the stiffer core takes most of the load and gradually transmits it to the cement-soil via the interface between them. Furthermore, the cement-soil transfers the load to the surrounding soil through the pile-soil interface (Wu *et al.*, 2005).

Laboratory tests of six specimens were conducted to investigate the frictional resistance between the concrete core and the cement soil of SDCM piles. The test results show that the bearing capacity of the SDCM pile is approximately 2.66 to 3.57 times that of the DCM pile (Wu and Zhao, 2006). In 2008, the interface friction between the core concrete pile and the cement-admixed clay was studied by means of a direct shear box test and triaxal compressive test. The results revealed that the concrete core pile length should be more than 75% of the DCM pile length in order to have significant improvement (Tanchaisawat *et al.*, 2008). In 2010, a series of full-scale tests consisting of axial compression, lateral and pullout interface between the concrete core pile and surrounding DCM material were performed in Thailand. The SDCM piles consisted of DCM piles and precast reinforced concrete core piles inserted in the middle. Test results showed that the section area of the concrete core pile significantly affected both the lateral ultimate bearing capacity and the lateral displacements of SDCM piles (Jamsawang *et al.*, 2010). The full-scale test results were further simulated using 3D foundation software in order to study the parameters that affect the behavior of both the SDCM and DCM piles under axial compression and lateral pile load (Bergado and Suksawat, 2010).

All the reported research work about SDCM piles focus on the bearing capacity or interface reactions

Correspondence to: Werasak Raongjant, Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology, Thanyaburi, 39 Moo 1, Rangsit-Nakhonnayok Road, Klong 6, Thanyaburi 12110, Thailand

Tel: +0066-25494692; Fax: +0066-25493412

E-mail: werasaky@yahoo.com

†Lecturer

Received August 7, 2012; **Accepted** March 18, 2013

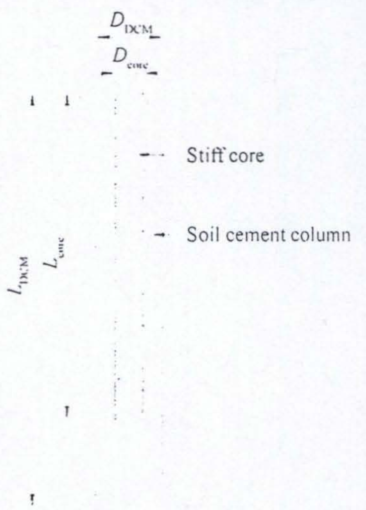


Fig.1 Stiffened deep cement mixing pile (SDCM)

of piles with concrete or reinforced concrete cores. Larger section, longer length or a greater number of piles may be required for the construction of offshore and underground wall bracing to resist the cyclical horizontal loading pursuant to the design requirements (Jamsawang, 2008; Shinwuttiwong, 2007; Suksawat, 2008). Hence, consideration was given in this research to increasing the strength of the stiffened deep cement mixed piles to protect against cyclical horizontal loading via various types of high strength materials installed as the core of the piles.

A field investigation of eight full-scale SDCM piles with different forms of stiffer cores under lateral cyclic loading was carried out on site in the Nongchok area of Thailand. The test results are presented and analyzed in this paper.

2 Project site and subsoil profile

The full-scale tests were performed in the Nongchok area of Thailand. The site is situated in the central plains of Thailand, famous for its thick layer deposit of soft Bangkok clay. The uppermost 2.5 m thick layer is composed of organic matter, which is underlain by a soft to medium stiff clay layer of 11.5 m thick. A stiff clay layer is found at a depth of approximately 14.0 m below the surface. The undrained shear strength of the soft clay obtained from a field vane test was 25 kPa and the strength of the stiff clay layer is more than 200 kPa. Piles were embedded though soft clay into medium-hard clay on site.

The full-scale cyclic loading test in the field consisted of two DCM piles and six SDCM piles, which were constructed in a row, with center to center spacing of 1.50 m. The field layout is shown in Fig. 2.

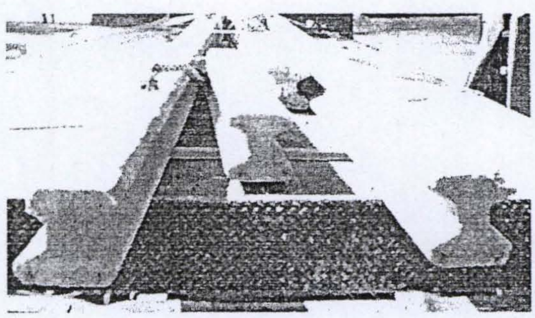
3 Design and construction of SDCM piles

The test piles were designed to consider the soil

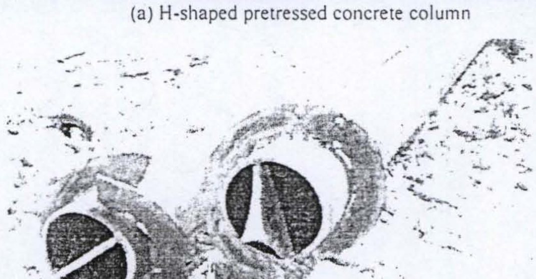
Fig. 2 Pile layout on site

survey results. The strength of the concrete piles was found by compression test to be 60 kPa. A wet process was employed to construct the soil cement piles in this research. They were constructed by jet grouting with a cement content of about 200 kg/m^3 to soil with a water to cement ratio of 1:1 by weight.

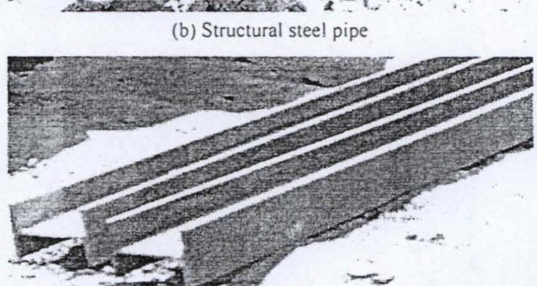
All eight test piles were 0.6 m in diameter and 7 m in length, with three different forms of stiffer cores 6 m long (Fig. 1). Two piles, C1 and C2, were DCM piles without stiffer cores used as reference samples. Two piles, C3 and C4, were SDCM piles with a stiffer core of H-shaped cross section prestressed concrete columns with a size of 180 mm×180 mm (Fig. 3(a)). Two piles,



(a) H-shaped pretressed concrete column



(b) Structural steel pipe



(c) Structural steel H-beam

Fig. 3 Different stiffer cores for SDCM piles

C5 and C6, were SDCM piles with a stiffer core of structural steel pipe, with an outer diameter of 168 mm and a wall thickness of 4.5 mm (Fig. 3(b)). The other piles, C7 and C8, were also SDCM piles with a stiffer core of structural steel H-beam with a size of 175 mm × 175 mm × 7.5 mm × 11 mm and weight of 40.2 kg/m (Fig. 3(c)).

4 Test program

A hydraulic jack (operated via a baud pump) was used to apply horizontal load to the piles at 0.3 m below the top of the piles, as shown in Fig. 4. One end of the jack was fastened to the test pile, while the other end was fastened to a prestressed concrete reaction wall, which was constructed 2.0 m away from the test pile. Load was generally measured using a 1000 kN load cell. Horizontal deflections were measured at 0.3 m below the top of pile using an LVDT, reading to an accuracy of 0.01% of the nominal deflection.

A pseudo-static cyclic loading system was used to provide indicative behavior typical of a large earthquake or wind loading. Load control was used at first with increments of 5 kN until the pile yielded. Then, displacement control was used with three cycles at each stage until failure occurred.

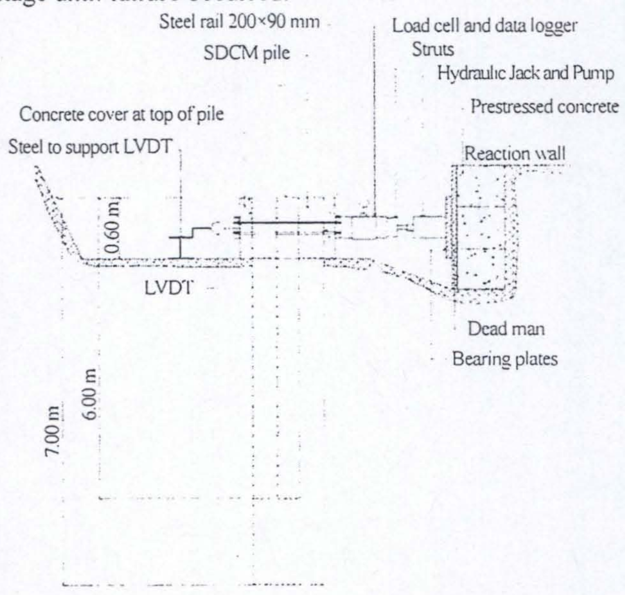


Fig. 4 Field test set-up

5 Test results and analysis

Considering that similar results were obtained from the same type of piles, only the behavior of piles C1, C3, C5, C7 are discussed here.

5.1 Failure mode

The failure of all piles occurred below the ground level, at a distance of about two times the diameter of the pile. The failure loading was about 10% greater

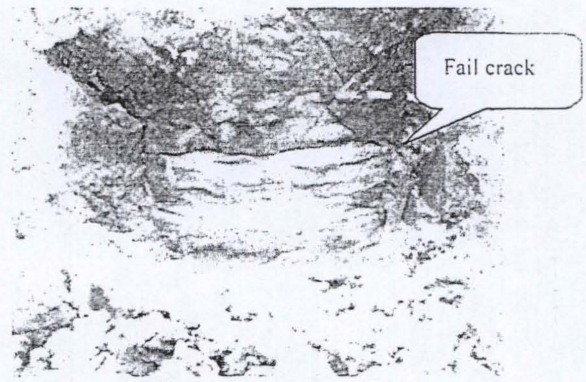


Fig. 5 Failure mode of pile

than the theoretical value, due to the homogeneous and stronger pile construction by wet low pressure used in the study (Tanbuntem, 1980). The failure modes of all the piles were long pile failures that occurred by bending moments, as shown in Fig. 5 (Bergado and Suksawat, 2010).

Under cyclic horizontal loading, the piles C1, C3 and C5 failed at the critical section of 1.02 m , 0.90 m and 1.04 m from the head of the pile, respectively. However, pile C7, with an H-Beam steel stiffer core, broke in two positions at 0.82 m and 1.22 m from the head of the pile, due to the better loading distribution capacity of the H-beam steel.

5.2 Load vs. horizontal deflection curves

Figures 6 to 9 show the measured hysteresis loops of lateral load versus horizontal deflection at 0.3 m below the top of the piles. The stiffened core was found to have a significant effect on the pile's behavior. SDCM piles C3, C5 and C7 showed more satisfactory ductility performance under lateral cyclic load than DCM pile C1. The lateral strength drop of the SDCM pile was more gradual than the DCM pile.

The hysteresis curves of all four piles experienced a significant pinching caused by the shear stresses due to lateral cyclic load. However, the hysteresis loops of SDCM pile C7 exhibited a more rounded shape than the hysteresis loop of the other piles, which indicates that an H-beam steel stiffer core is more effective at improving the energy dissipation capacity of the pile.

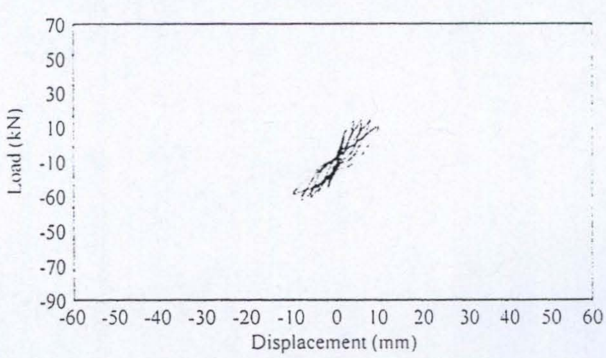


Fig. 6 Measured hysteresis loops for DCM Pile C1

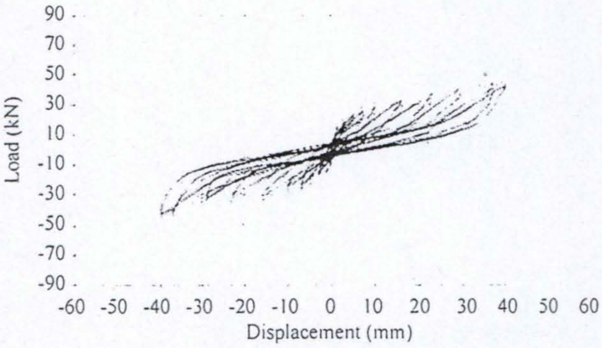


Fig. 7 Measured hysteresis loops for SDCM Pile C3

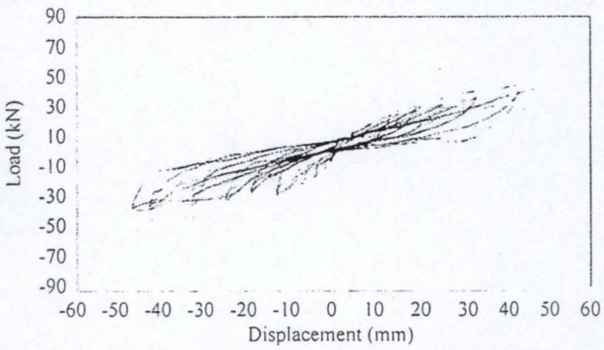


Fig. 8 Measured hysteresis loops for SDCM Pile C5

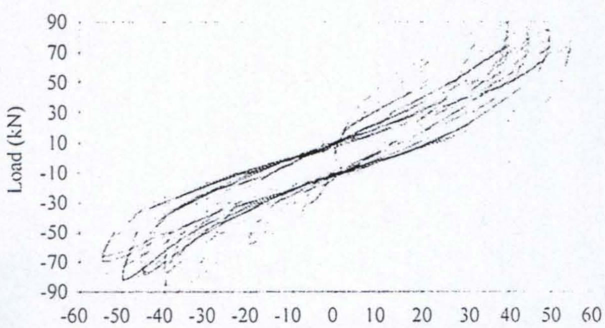


Fig. 9 Measured hysteresis loops for SDCM Pile C7

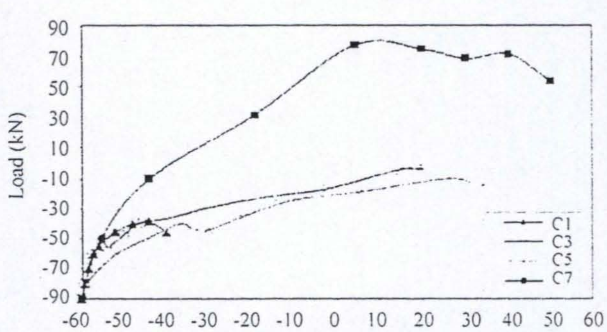


Fig. 10 Skeleton curves of hysteresis loops

5.3 Skeleton line

The skeleton curves of the hysteresis loops for all four piles are shown in Fig. 10. For pile C1, the ultimate lateral capacity was 24 kN with a deflection of 8 mm. For the three SDCM piles, the ultimate lateral capacity and the corresponding lateral displacement were much higher. The ultimate lateral capacity of pile C3 and C7 was 49 kN with a deflection of 45.03 mm and 40 kN with deflection of 43 mm, respectively. For the SDCM pile with a stiffer core of H-beam steel, the ultimate lateral capacity was 81.25 kN with a corresponding displacement of 45 mm. The results demonstrated that the ultimate lateral capacity of the SDCM with an H-Beam steel core increased by 3–4 times that of the DCM pile, with a corresponding increase in lateral deflection of 6–7 times. The stiffer core, especially the H-beam steel stiffer core, significantly increased the lateral ultimate bearing capacity, because it improved the stiffness and ductility of the SDCM pile and also resisted most of the bending moment due to the lateral cyclic load.

5.4 Rigidity attenuation

Dividing the summation of absolute values of positive and negative ultimate lateral loads in each loading cycle by the summation of the corresponding absolute values of positive and negative lateral displacements, the result can be defined as the lateral rigidity in each cycle G_i, where i is the number of the loading cycle. G_0 denotes the initial lateral rigidity of the pile. The G_i/G_0 Versus lateral displacement curves for the four piles in this test are shown in Fig. 11.

It can be seen that the lateral rigidity reduced rapidly at first and then slowed down prior to complete failure. The rigidity attenuation was mainly induced by the accumulated damage, such as soil cement cracks and yield of steel core, and the loosening of the soil around the pile. The rigidity of DCM pile C1 decreased very quickly. The rigidity attenuation of SDCM pile C3 shows consistent behavior with DCM pile C1, whereas it had much larger lateral displacement at failure. The SDCM piles that had a steel stiffer core, C5 and C7, had much slower rigidity attenuation as the lateral deflection increased, due to the higher elastic modulus and homogenous materials of the steel cores. In particular, the H-beam steel stiffer core showed significant improvement in the lateral cyclic loading resistance capacity of the piles.

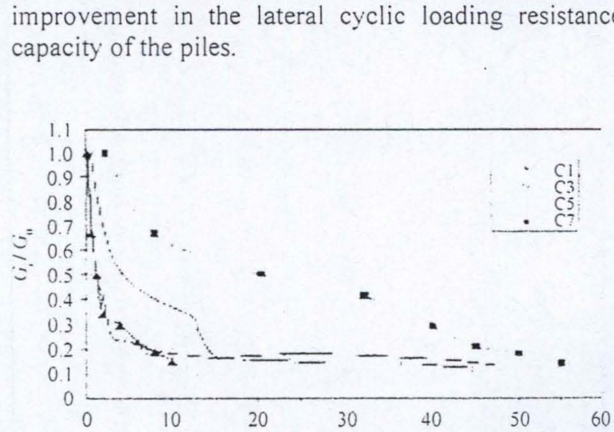


Fig. 11 Rigidity attenuationsof four piles

5.5 Energy dissipation capacity

In order to conduct a more precise analysis of the energy dissipation capacity of piles, normalized parameters were used in this study. The accumulated ductility factor was defined as the ductility factor for a given cycle plus the sum of the ductility factors in all previous cycles. The corresponding accumulated energy dissipation was calculated as the sum of the areas enclosed by all previous hysteresis loops. The relationships between them for the four piles are plotted in Fig. 12.

The stiffer core obviously contributed to improving the energy dissipation capacity of the piles. SDCM piles C3 and C5 show similar capacity as the DCM pile C1 at the initial load stages, whereas they had much better energy dissipation capacity with larger ductility ratios. At a given level of accumulated ductility factor, pile C7 with a steel H-beam core experienced a significantly higher energy dissipation capacity. This confirms the qualitative observations based on the shape of the hysteresis curves.

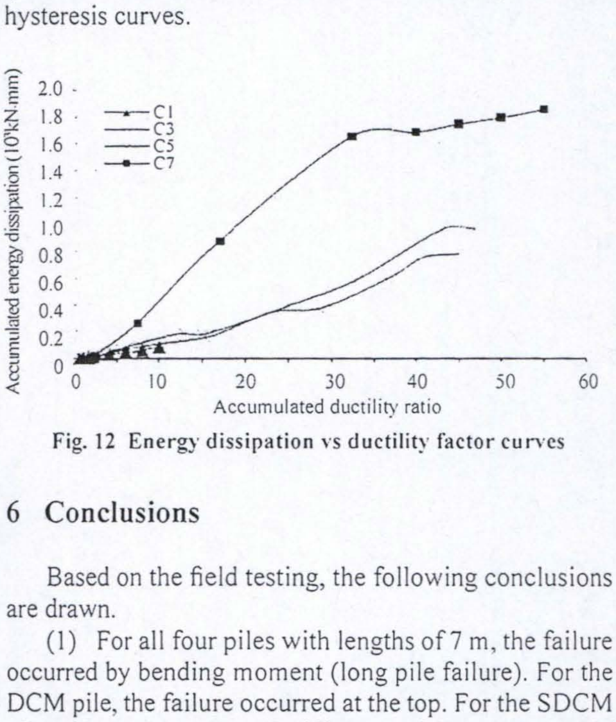


Fig. 12 Energy dissipation vs ductility factor curves

6 Conclusions

Based on the field testing, the following conclusions are drawn.

(1) For all four piles with lengths of 7 m, the failure occurred by bending moment (long pile failure). For the DCM pile, the failure occurred at the top. For the SDCM pile with an H-beam steel stiffer core, failure occurred in two sections due to the more effective load distribution of the stiffer core.

(2) Increasing the strength and flexural rigidity of the stiffer core for the SDCM piles can obviously improve their lateral carrying capacity and ductility. For the same flexural rigidity of stiffer cores, an H-beam is more efficient than steel pipe in increasing the lateral resistance of the SDCM piles.

(3) Under cyclic lateral loading, the SDCM beam with an H-beam steel core had a more rounded shape than the hysteresis loop of the other piles, which indicates that the H-beam steel stiffer core was best able to resist lateral deformation and improve the energy dissipation capacity of the piles.

Acknowledgement

The authors gratefully acknowledge the Thailand Research Fund (TRF) for their financial support to this study.

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