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Seismic Retrofit of Pile Group Foundation with Thickened Caps

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Abstract: The case studied in the paper proves that thickening the pile cap is an effective seismic retrofit alternative to strengthen a pile group foundation. Unlike the typical seismic retrofitting of foundation, the proposed method eliminates the need to drive long piles into existing bridge substructures, substantially reducing cost, construction time and traffic interruption. The method thickens the pile cap of the bridge foundation to engage with a larger quantity of soil when under the influence of seismic excitations. The additional friction provided by the surface of the concrete encasement helps to resist the overturning moment of the earthquake forces, while the passive pressure provided by the soil helps to resist lateral forces during earthquakes. The method is recommended for implementation in the freeway bridge retrofit project in Taiwan due to construction constraints. A successful retrofit requires existing piles in at least moderate condition, detailed construction sequences and installation of the encasement.

Keywords: Bridge engineering, encasement method, pile group foundation, seismic retrofit, structural design.

INTRODUCTION

Taiwan is located in East Asia, bordered by the South and East China Sea, Philippine Sea, and Taiwan Strait. It lies in north of the Philippines, off the southeastern coast of China, and has a coastline of 1,566.3 km. The island is largely situated in a sensitive zone between the Philippine Sea Plate and Eurasian Plate. Owing to the accumulation of energy as the plates compress together, a major earthquake in every few decades is inevitable. [1] According to a recent report proposed by seismologists at National Taiwan University's (NTU) Department of Geological Sciences, a total of 50 active faults have been mapped and investigated around Taiwan. The research team suspects the total number of known faults that will approach to 70 once further mapping work is completed over the next few years [2].

Second only to typhoons, earthquakes are the most destructive natural disaster in Taiwan. Although the average number of casualties during each earthquake has been reduced over the years, the pecuniary losses have been increasing steadily. Particularly strong earthquakes that have resulted in significant losses have struck Taiwan almost every thirty years, for example in 1935, 1964 and 1999. Two major earthquakes that have occurred in the last ten years are the Rayli Earthquake on July 17, 1997 and the Chi-Chi Earthquake on September 21, 1999. The latter measured 7.3 on the Richter scale, making it the most powerful earthquake in Taiwan in the 20th century. It struck the central part of the island, causing many landslides in the mountainous regions of Nantou County. It is estimated that 12,000 buildings were destroyed, with 100,000 people left homeless. There were more than 8,000 aftershocks and six major tremors measuring 6 or greater on the Richter scale. The damaged roads, also blocked by debris, made the rescue extremely difficult [3].

These events have caught the attention of government agencies, regulatory bodies, insurance companies, the scientific community, and the general public with regard to safety hazards and potential losses associated with structures that perform poorly during earthquakes. As a result, there is growing national emphasis on improving seismic design requirements for new structures and the seismic retrofit of existing structures. Improvement of current earthquake design codes has been a top priority in recent years because previous codes only met a single performance level when the demand equals the ultimate capacity. Seismic requirements in bridge and building design codes have been extensively revised in recent years in Taiwan [4].

To mitigate the natural hazard and to prevent loss of life during earthquakes, Taiwan Area National Freeway Bureau (TANFB) initiated a seismic retrofit program for the No. 1 Sun Yat-sen Freeway. It is the oldest freeway in Taiwan and runs from Keelung City to Kaohsiung City, totaling 372.8 km in length. The construction of No. 1 Sun Yat-sen Freeway was completed, with the entire route open to traffic, on October 31, 1978. Many of its sections were elevated viaducts. They are deemed vulnerable according to research findings from investigations following the Chi-Chi earthquakes. Many bridges were designed following the same code standard as those damaged in the Chi-Chi Earthquake [5].

Many large-scale public facilities, such as the high-speed rail system, inter-city rapid transit systems, highways and coastal industrial parks, are under construction or have recently been completed in Taiwan. As a result of population increases, economic growth, and the concentration of population in potentially hazardous areas, casualties caused by natural disasters have increased significantly in the last ten

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Table 1. The scope of Taiwan freeway bridge seismic retrofit program.

Project Phases	Project Scope	Number of bridge evaluated	Number of bridge retrofitted	Status
Phase I	Freeway No.1 and No.2 (including the widening projects of freeway No.1 Yuanlin-Kaohsiung section and freeway No.2)	490	412	Freeway No.1: completion in December 2009 Freeway No.2: completion in December 2011
Phase II	Freeway No.3 (northern section)	190	180	Under construction, scheduled completion in June 2016
Phase III	Freeway No.3 (central and southern sections) and freeway No.4, 5, 6, 8, 10	769	Note 1	In the feasibility study stage, scheduled for 2016~2025

Note 1: Actual number of bridges retrofitted is subjected to change based on seismic assessment results.

years, making seismic retrofit increasingly critical to public safety. Not only does the pace of new construction projects need to be maintained and safety ensured, but engineers are required to identify quick, economical solutions to maintain the extensive, well-established infrastructure system as well. Originally theorized by Japanese researchers, the pile foundation encasement method was assessed, found acceptable, and first tentatively implemented in Taiwan. This paper explains the design and analysis of the seismic retrofit strategy and addresses its potential modifications and future applications. There is very little literature available today that addresses it's modeling techniques and design issues. This paper reports the detail design. It is also the author's intent to share the project experience to promote the global application of this method.

OVERALL BRIDGE SEISMIC RETROFIT PROGRAM

The "National Freeway (Open-to-Traffic Section) Bridge Seismic Retrofit Program" was first instructed by Executive Yuan, Taiwan on January 30, 2004, following the conclusion recommended by the Council for Economic Planning and Development (CEPD) on January 9, 2004. The implementation period of Phase I project is from year 2004 to 2009. Phase II and Phase III of this program was then submitted to the Executive Yuan for approval after reviewed by the Ministry of Transportation and Communications (MOTC) to revise the engineering cost, benefit and financial plan again before the completion of Phase I. TANFB reviewed and revised Phase II and Phase III engineering cost, effectiveness and financial plan and reported to the MOTC on December 27, 2008, and submitted to Executive Yuan for approval. To speed up the program, the Executive Yuan demanded an immediate measure to merged Phase II and Phase III into "Phase II Project Planning of National Freeway Bridge seismic retrofit Project", and comprehensively considered the seismic capacity "seismic index" and social cost "traffic impact index" of seismic damage of bridge structures of different sections. TANFB considered the road net characteristics and made the priority of seismic retrofit, prioritize the following sections shown in Table **1**.

As the national freeway is the most important lifeline and disaster relief roadway network in Taiwan, the seismic performance criteria for bridges identified for this project are shown in Table **2**. The objective of retrofitting a bridge is to ensure that it will perform satisfactorily when subjected to the three levels of earthquake. More specifically, bridges after retrofit are required to meet the performance criteria. Selecting the preferred retrofit strategy is a complicated process. Not only is it often a challenge to find the right technical solution, it is also a challenge to satisfy a multitude demands from of socio-economic constraints. Constructability and environmental issue become a key constraint during retrofitting foundation in Taiwan as many viaducts allow limited clearance in height [6].

CONVENTIONAL SEISMIC RETROFIT METHODS

The failure mechanism of the pile foundation is typically the fracture of piles, punching failure at the pile cap, or pull-out failure of the pile. Researchers have conducted series of laboratory testing and computer modeling to analyze the problems [7, 8]. In the first case, the distortion or fracture of piles is caused either by the loss of lateral support from the liquefied sands or by soil layers of different stiffness. The relative movement of the piers induced by the fracture of underground pile causes the simple unconnected spans of the bridge to fall. The punching failure at the pile cap occurs when the pile cap is not sufficiently reinforced or has insufficient thickness. The third type of failure is due to a lack of adequate anchorage detailing between the pile top and the pile cap. The reinforcing steel in the concrete pile is pulled out of the pile cap or the pile shaft, causing displacements with devastating results [9].

The dramatic collapse of bridges is induced by failure of their foundations and/or supports and by the lack of integral action between the substructure and the superstructure. Foundation failure always lead to the need for extensive repair and extreme difficulties in reconstruction [10]. The retrofitting of existing foundation has no economical solution [11]. The conventional footing retrofit on the spread footing enlarges the existing footing in plan dimensions and depth. Dowel shear connectors are installed on the vertical (shear friction) and horizontal (shear flow) surfaces of the existing footing foundation. Projects enlarging the size of the existing footings usually require excavation under difficult circumstances and there are difficulties in pinning and attaching the existing footings to the new elements [12]. For a pile foundation retrofit, additional piles are driven around the perimeter as shown in Fig. (**1**), widening the plan dimension of the existing pile cap once the existing piles are examined for

Table 2. Bridge seismic retrofit performance criteria.

Earthquake ground motion	Design earthquake response spectral acceleration coefficient		Seismic principles: Expected element behaviors	Post earthquake service level	Post earthquake damage level
Moderate Level Earthquake (MLE) DLE/3.25	Site Specific		Structures remain linear or nonlinear elastic	Immediate: Normal traffic after earthquake	Minimal
	1/3.25 of Design Level Earthquake (475 years return period)				
Design Level Earthquake (DLE) Return period: 475 years 10% probability of exceedance in 50 years	Site Specific		Members form plastic hinge and reach their allowable ductility capacity	Limited: Limited traffic after earthquake	Repairable
	S_S^D	0.80、0.70、0.60、0.50			
	S_1^D	0.45、0.40、0.35、0.30			
Maximum Credible Earthquake (MCE) Return period: 2500 years 2% probability of exceedance in 50 years	Site Specific		Members form plastic hinge and reach their ultimate ductility capacity; No Collapse	Emergent: Emergent traffic after earthquake	No Collapse
	S_S^M	1.00、0.90、0.80、0.70			
	S_1^M	0.55、0.50、0.45、0.40			

lack of tension and compression capacity. The newly installed piles are tied together in the pile cap to work in tension and compression so that the foundation can act as a unit. The conventional method becomes problematic when the construction site has limited clearance and working space. Insufficient width on the right-of-way during construction often makes the retrofit extremely challenging. Inadequate vertical clearance underneath the existing bridge also complicates the retrofit.

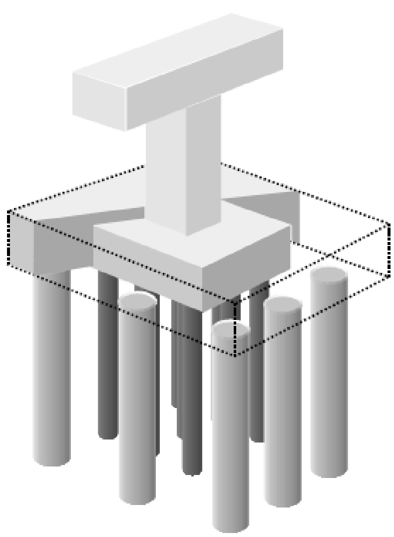

Fig. (1). Conventional foundation retrofit.

To minimize the work involved in foundation retrofit, the U. S. Federal Highway Administration FHWA contracted a research study to develop improved seismic design methods for micropile systems used in the seismic retrofitting of bridge foundations in 1995 [13]. Laboratory centrifugal model tests were conducted to correlate with numerical model studies on various micropile systems (isolated piles, groups, and networks of piles) to evaluate their behavior under axial, lateral, and combined loadings in selected engineering applications. Shaking table tests were also conducted at University of Canterbury - Christchurch, New Zealand as part of the overall study to improve seismic design methods. Drilled micropiles offer the same high bearing capacity as driven steel piles, with the added advantage of allowing installation in areas presenting difficult access and low headroom. Micropile drilling methods generate minimal disturbance or vibration to adjacent structures, making micropiles an excellent underpinning alternative. However, the relatively high cost compared to other piling systems limits its future applications. Other researchers had tried other options with some success [14-17].

PROPOSED METHOD

The "In-Cap Method" was invented in 2003 and modified in October 2004 by Japanese engineers. The name is an abbreviation of the pile foundation "Incremental Capacity Method." It is mostly used as a hybrid method for the seismic strengthening of existing pile foundations in conjunction with the modification of existing substrate [18]. According to the original design document, steel sheet piles are first installed around the existing pile foundation to a targeted design depth. Then, the soil underneath the pile cap is replaced by engineered grout through High Pressure Jet Grouting, or Jumbo Special Grout, JSG. Once the substrate is solidified, the sheet pile and injected grout act as a monolithic unit [19]. A partial view of the In-Cap Method can be seen in Fig. (**2**). Not only does the system help reduce the unsupported length of piles; it also provides lateral stability to the pile group foundation by involving passive soil pressure during the seismic excitations. The perimeter of the steel sheet piling also offers surface friction for resisting the overturning moment in the event of an earthquake [20].

The In-Cap Method, as proven by experiments and computer modeling, can increase the overall pile foundation capacity in resisting seismic loads. Many bridge seismic retrofit projects in Japan have been executed using this method with successful results [21]. It increases the stiffness of the pile foundation such that the plastic hinge will have a better chance to occur at the bridge column instead of at the piles. In other words, the retrofit leads to easy repair at a later stage, suggesting a cost-effective solution for seismic retrofitting [22]. This method is particularly advantageous when the construction space is tight and the vertical clearance under the bridge is strictly limited. Like the micropile construction, the In-Cap Method causes minimal disturbance or vibration to adjacent structures. However, the cost of In-Cap construction in Taiwan is amplified due to a lack of availability of proper equipment to perform such work.

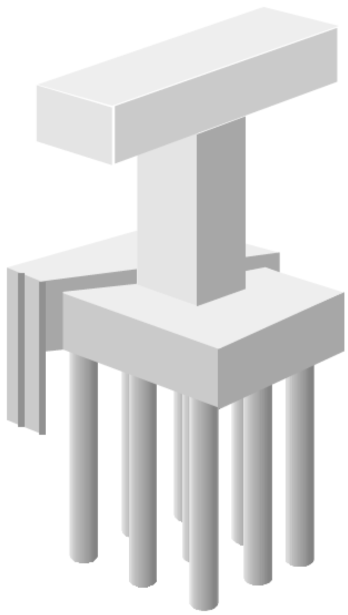

Fig. (2). Foundation retrofit using in-cap method.

Instead of steel sheet piles, 45-cm diameter precast reinforced concrete piles are installed around the existing boundary of the pile cap, making the "encasement method" particularly suitable in a congested area. The soil at the circumferences of the existing pile cap is first modified using the JSG method. Then 45-cm diameter precast reinforced concrete piles are installed at 90-cm spacing and encased with the existing pile cap. The enlarged pile cap engages a larger quantity of soil in resisting earthquake forces than the original pile cap. The additional friction provided by the surface of the precast concrete piles help to resist the overturning moment, while the passive pressure provided by the soil helps to resist lateral forces during earthquake events. Once proven effective, this method is recommended for implementation in Taiwan's freeway bridge retrofit project in response to construction constraints. The concept is illustrated in Fig. (**3**).

MODELING

The encasement method can be validated from a theoretical standpoint. The free body diagram of an existing pile foundation prior to the encasement retrofit is shown in Fig. (**4a**) where the piles are assumed to be pinned and connected to the bedrock at the bottom of the piles. The lateral pressure diagram from the surrounding soil is a triangular distribution. The free body diagram of a pile group foundation after retrofitting using the encasement method is shown in Fig. (**4b**). The lateral load-resisting capacity provided by the monolithic unit underneath the pile cap could greatly improve the overall rigidity of the pile foundation.

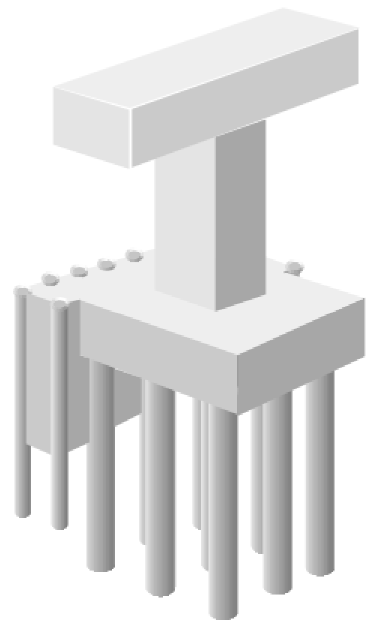

Fig. (3). Foundation retrofit using thickened pile cap.

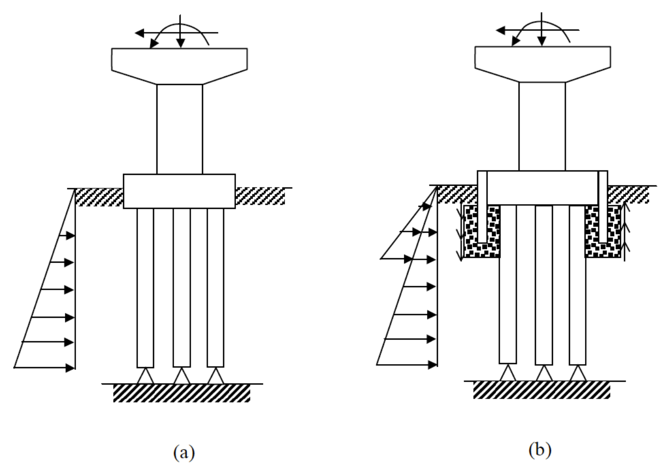

Fig. (4). Free Body Diagram of Existing Foundation and Retrofit.

Similar to the In-Cap Method, the encasement method also provides protection to the underground piles by reducing the lateral displacement at the top of the piles during an earthquake. The result obtained from small-scale equivalent static loading tests conducted by the scholars who invented the In-Cap Method showed that the relative displacement at the pile top after retrofitting is substantially smaller than without the retrofit. It is apparent from Fig. (**5**) that the lateral displacements of the pile top can be greatly reduced by the encasement method, since the pile cap involves the passive pressure of the surrounding foundation soil. In other words, the vulnerability of the pile can be reduced significantly through the method.

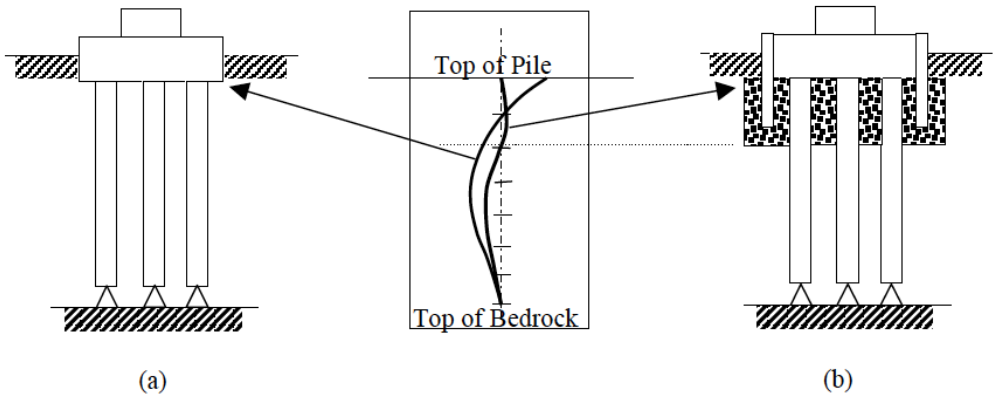

Fig. (5). Lateral displacements of foundation with and without the retrofit.

The engineers invented the In-Cap Method also conducted a series of 1:50 small-scale experiments considering three cases. The first case simulates the as-built condition of an existing pile group foundation; the second case reflects the retrofit strategy using In-Cap Method with grouting; the third case uses steel sheet piling without grouting. The P-Delta effect of each case when subjected to a point load is analyzed. The capacity of an existing pile foundation retrofitted using the In-Cap Method with grout is 1.5 times stronger than the original pile foundation without retrofit.

The design team built Finite Element Model, FEM computer models to verify the soil structural interaction of pile foundation with and without the retrofit. The load and displacement curves of each case obtained from the computer models match extremely well with the result obtained from the experimental conclusion. The design team is, therefore, confident that the proposed method functions under rigorous conditions and detailed analysis.

CASE STUDIED

To demonstrate the implementation of the proposed method, one of the piers (PD10D@16K+682.00) of the Sun Yat-sen Freeway is studied. The pier is located near the northern part of the freeway system that connects Keelung and Taipei, serving southbound traffic. The steel box girder bridge was constructed and completed in the 1970s and has remained the vital transportation line for commuters ever since. The total length of the viaduct from center to center of the pier is 22,000 m (4@5,500 m). The traffic volume grew tremendously as soon as construction was completed. The highway has been widened once as of today and the right-of-way does not allow for a full-scale foundation retrofit. Since the viaduct was based on an early design specification, the seismic resistance capacity is inadequate when assessed with today's standard. The TANFB decided to analyze the problem and hired a private consultant to investigate potential long-term solutions.

The seismic demands is generated from an elastic spectral analysis (Single-Mode Spectral Analysis, Procedure 2 in AASHTO Div. IA Sec.4.4) performed using the design ground acceleration. Seismic capacities are calculated at their nominal ultimate values without the capacity reduction factor, φ. For limited space, the calculation of single mode spectral method is briefly described as Figs. (**6** and **7**). Each column stiffness and shear forces of individual column at bents caused by the transverse earthquake load are calculated based on the information obtained from as-built plans.

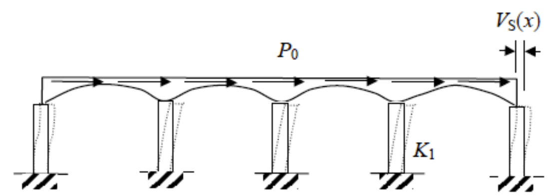

Fig. (6). Assumed uniform loading for longitudinal mode of vibration.

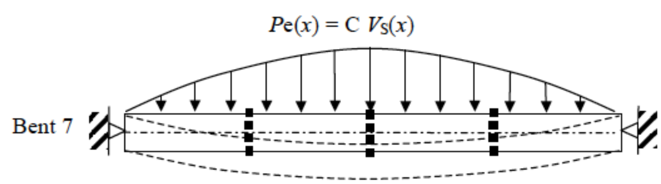

Fig. (7). Plan view of four span bridge subjected to equivalent static loading.

Based on the push-over analysis performed using SAP2000, the six existing 2,000-mm diameter concrete pile group is adequate in compression. The estimated maximum axial load in compression is 1,005.50 tons where the pile capacity is 2,519.48 tons. But the pile foundation is insufficient in tensile strength under the new seismic design criteria. The estimated maximum axial load in tension is 344.09 tons where the pile tensile capacity is 272.14 tons. The capacity-to-demand ratio in tension is 0.79 and the goal is to reach 1.0 after the retrofit. The total reinforcing steel required by the design code in the cross sectional area is 235.62 cm^2 and the actual reinforcing steel is 302.10 cm^2. On the steel detailing, the pitch of the steel spiral reinforcement is under 75 cm and the 135-degree hook was used. There was no splice near the pile caps.

As for the pile cap, the shear capacity is checked and the punching shear for the column to pile cap and the concrete piles to the cap are also found adequate. The flexural reinforcements at the top of the pile cap are sufficient both in the transverse and the longitudinal directions required by the design specifications: they are 182.52 cm^2 and 131.82 cm^2, respectively. The flexural reinforcements at the bottom of the pile cap are also adequate both in the transverse and the longitudinal directions. The estimated maximum negative bending moment of the pile cap in transverse and longitudinal directions is 1412.61 t-m and 1,361.21 t-m, respectively. The C/D ratios are 2.50 and 2.90. The estimated maximum positive moment of the pile cap in transverse direction is 2,288.72 t-m and C/D ratio is 2.22. However, the estimated maximum positive moment of the pile cap in longitudinal direction is 4,893.18 t-m and C/D ratio is only 0.64. The risk of pile failure under the older seismic design criteria has been noticeable and proactive measures must be taken to protect the public.

The compressive strength of the new pile cap addition is 280 kg/cm^2 and the yielding strength of the reinforcement is 4,200 kg/cm^2. A total of 56 evenly spaced 45-cm diameter micropiles are installed at the periphery of the existing pile cap. The length of the piles is 6 m and the plastic moment capacity of the piles is 17.79 t-m.

CONCLUSION

The proposed method is a seismic retrofit strategy that engineers can consider in a foundation retrofit project, especially when the construction site is very limited. Once the grouting is applied in conjunction with the CCP piling technique, the lateral displacements of the pile cap can be reduced up to 50% when compared to that of the existing foundation. The pile foundation after retrofit is roughly 1.5 times stronger than it was prior to the retrofit. Since the method may be applied for the first time, government authorities require solid analytical results to justify its use. The computer modeling technique is quite unique in this application because the spring constants are obtained through several iterations. The proposed encasement method reduces the existing pile lengths so that the pile capacity becomes higher. However, the benefits have not yet been recognized and must be quantified at a later stage. In light of the lessons learned from the implementation of this method of pile foundation retrofit, the authors of this paper hope that the structural engineering community will take full advantage of this innovative method.

LIST OF NOTATION

C/D = Capacity Demand Ratio

CEPD = Council for Economic Planning and Development

DLE = Design Level Earthquake

FEM = Finite Element Model

FHWA = U. S. Federal Highway Administration

MCE = Maximum Credible Earthquake

MLE = Moderate Level Earthquake

MOTC = Ministry of Transportation and Communications

TANFB = Taiwan Area National Freeway Bureau

S_S^D = Design earthquake response spectral acceleration coefficient

S_1^D = 1.0 Second Design earthquake response spectral acceleration

S_S^M = Maximum design earthquake response spectral acceleration

S_1^M = 1.0 Second maximum design earthquake response spectral acceleration

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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Declared none.

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