STUDY OF DIFFERENT APPLICATION EFFICIENCIES AND SIMULATION MODELS FOR MICROPILES ON SLOPES

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ABSTRACT

This paper discusses the application of micropiles on slopes along constructions and castle walls in historical site maintenance. Using the PLAXIS finite element method to perform simulations. The attainable results include that underpinning and strengthening with inverted L-shaped micropiles in coordination with low-pressure grouting reinforcement can increase the safety factor of slopes along the castle wall of historical sites, improve the foundations of the castle walls to substantially reduce the total amount of displacement, significantly inhibit the settlement, and alleviate the subsidence trend of the foundation structure of castle walls. Likewise, gantry-style micropile reinforcement methods can enhance the safety factor, reduce the total amount of displacement, as well as inhibit and alleviate the soil settlement. In summary, micropiles can indeed be used to provide useful stability to the foundation and inhibit the displacement in order to strengthen the slope state along the castle walls of historical sites, where the working space is relatively narrow. It is anticipated that the analytical results of this paper can be used as a reference for similar projects.

Keywords: micropiles, PLAXIS numerical analysis, application efficiencies, slope stability.

1. INTRODUCTION

In this paper, the finite element program of PLAXIS was used to conduct an in-depth analytical study on the effectiveness of micropiles when applied to slopes for the maintenance and strengthening of historical sites. PLAXIS, the finite element program, was adopted to conduct stability analysis on the retaining wall structure of micropiles.

The derivation method of the PLAXIS program for safety factors adopts the stress behavior of micropiles during the sliding displacement on stratum. When doing a safety analysis using the ϕ/c reduction method, that is conducting repeated reductions on the soil strength parameters (c values of soil cohesion and tanψ of

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friction angles within soil). The strength reduction factor (RF) during the moment of destruction is defined as the safety factor (Fan & Chien, 2004).

In this study, the analysis cases for maintenance applications of micropiles on slopes along constructions and castle walls of historical sites are discussed. Currently, there are many engineering disaster remediation methods commonly used, yet the micropile method has special applicability in situations where the relatively narrower areas along the boundary lines require the use of small equipment. In this paper, the effects of actual cases with and without a micropile retaining structure are discussed and the effect of rainfall on the analysis results.

2. DISCUSSIONS OF ACTUAL CASE STUDIES

2.1 Case (1): Basic data survey of Ershawan Fort (Haimen Tianxian)

The site of this case is located on the uphill area of Zhongzheng Road in Keelung City. The historical site of Ershawan Fort, also known as Haimen Tianxian, (Refer to Figure 1 for detail). The strata of this site consist of mainly sandstone and siltstone, intercalated with shales. The rock quality is generally good. The ground surface has a layer of weathered overburden; the partial platform area may contain backfill. The slope surface is generally stable and has no potential slippage going down to the bedrock, thus only the backfill and overburden may have problems of local subsidence deformation. Being judged by the terrain contour lines that are outwardly steep convex, the foundation of the castle walls may be partially located in the backfill. In addition, owing to rainwater infiltration within the plaza of the fort, cracks appeared in the cement-mortar pointing between the rock blocks at a corner of the fort walls. Furthermore, slightly differential settlement also occurred in the wall foundation at the same site.

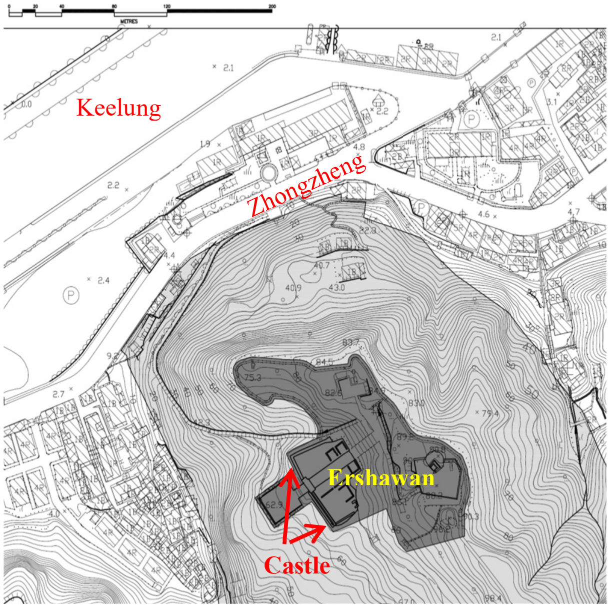

Figure 1: Map of historical site Ershawan Fort (Jeng & Yu, 2015)

Two holes, each with a depth of 15 meters, were drilled in the barrack area within the plaza of the fort; the positions of holes are shown in detail in Figure 2. In addition to the sampling test, an inclinometer is buried for subsequent monitoring purposes of slope displacement and groundwater level observation. According to the drilling results, the overburden layer beneath the ground surface of this site (3.6m ~ 4.1m depth) consists of yellow-brown and gray silty sand with rock fragments. The N-value of a standard penetration test ranges between about 7 to 12, which is classified as a loose to medium dense sandy soil layer. Whereby for the ground surface close to the BH-1 region (i.e. castle wall's corner), the overburden layer is about 2 ~ 2.5m and classified as backfill layer.

According to the test results, the unit weights of soil ranged between 19.0kN/m^3 ~ 19.3kN/m^3; the shear strength parameters C values ranged between 7.8kPa ~ 38.3kPa; ϕ angle ranged between 25.8° ~ 28.3°. Beneath the overburden layer is the rock formation. The rock formation mainly consists of sandstone to siltstone, where BH-1 showed more obvious weathering at first 1.7m thickness; its rock quality designation (RQD) index falls at about 16% to 33%, classified as poor to extremely poor. The indices of rock quality designation for the remaining soil layers can reach more than 75%, classified as good grades.

Inclinometers are also buried inside the drilled holes at this site in order to facilitate subsequent long-term observations on slope stability. After the drilling was completed and the initial values of inclinometers were observed, subsequent measurements were conducted on 27th November 2014. The results showed that there is downward slope surface displacement change at about 2 m depth below the ground surface of the BH-1 hole, the maximum displacement of the hole opening is about 2.7mm.

2.1.1 *Numerical analysis on the current state of the site*

The main slope stability analysis of the site focused on the cross-section stability of the slope in the backfill area at the northwest corner of the castle wall. Hereby in accordance with the drilling and test results, the slope stability analysis is conducted by analyzing the cross-sectional detail in Figure 3. The contents of analysis include the safety factor of the potential sliding surface, and settlement deformation analysis. The parameters obtained through the relevant tests are compiled in Table 1 and Table 2. The PLAXIS program is used to analyze the cross section of the current state (without remediation). The analysis results are shown in Figure 4 and Figure 5.

For the resulting safety factors under normal conditions and rainstorm conditions as well as the subsidence deformation analysis results, it is generally recommended that the safety factor of normal conditions is required to reach at least 1.5; whereas under rainstorm conditions, the safety factor is required reach 1.2. According to the results, regardless of slope conditions, both safety factors can reach above the generally recommended value, thus the slope stability is generally regarded as safe. Moreover, according to the subsidence deformation profile results, the PLAXIS program analysis shows that a larger amount of subsidence will be distributed in the body of castle wall itself and the soil layer beneath it, thus there is the possibility of tension crack occurrence. The maximum displacement under rainstorm conditions is evaluated to be about 22mm (Figure 4); the vertical subsidence deformation of the foundation surface is about 4.5mm (Figure 5). The areas enclosed by subsidence profile as shown in Figure 5 is defined as subsidence sink area. The analysis results above more or less coincide with the changes in depth from the second inclinometer observations.

2.1.2 Analysis and comparison of the reinforcement options for the foundations of the castle wall

According to the concepts of reinforcement design, the reinforcement of this Case (1) is divided into four options for analyses and comparisons. Option 1 is a proposal of underpinning and strengthening the retaining wall by first imposing the micropiles and then adding low-pressure grouting. Option 2 is underpinning and strengthening the retaining wall reinforcement with micropiles using different types of volumetric grouting. Option 3 is a single-row of micropiles. Option 4 is a single-row of micropiles with grouting.

(1) **Option 1: Underpinning and strengthening – Micropiles and low pressure grouting** (as shown in Figures 2-3)

The existing castle wall is at the northwest corner of the barracks area. Obvious cracks have appeared in the cement-mortar pointing between the rock blocks at a corner of the castle walls. According to the stratigraphic drilling data and the foundation test results, it is determined that the cracks and subsidence of the castle wall should be related to its partially located in the backfill area. Thus, micropiles are used to penetrate the rock around the peripheral platform of the castle wall as measures for underpinning and strengthening the foundations of the castle wall as well as confining the slope displacement. One row of micropiles is drilled vertically in connection with another row of inclined micropiles to be laid with a horizontal angle of depression of 15 degrees toward the inside plaza (Fig. 3). The diameters of the holes are about 11cm to 15 cm; the length of the vertical pile is about 10m and the length of the inclined pile is about 15m. Steel pipes with a diameter of 76mm and thickness of 4mm were placed into the holes; mortar with 1:1 proportion of cement and sand was poured into the pile holes. The tops of the two rows of micropiles are joined with a reinforced concrete (RC) collar beam, wherein the inclined micropiles with the depression angle of 15° is additionally locked into steel plate by threading the endpoint of the micropile; while one end of the 75° edge-bend rebar was inserted into the steel pipe of the inclined micropiles, the other end is hooked to the collar beam as a joint. To prevent the micropiles from staggered influences between each other during the process of construction, it is recommended that all the planar angles of construction of inclined micropiles are set to be parallel to the corner of castle wall at 45°(as shown in Fig. 2). Furthermore, to ensure that the contacting stress of the castle walls on the foundation is more balanced, an inclined grout hole is drilled inside the castle wall, local grouting reinforcement was carried out within the overburden layer of the castle wall's base bottom.

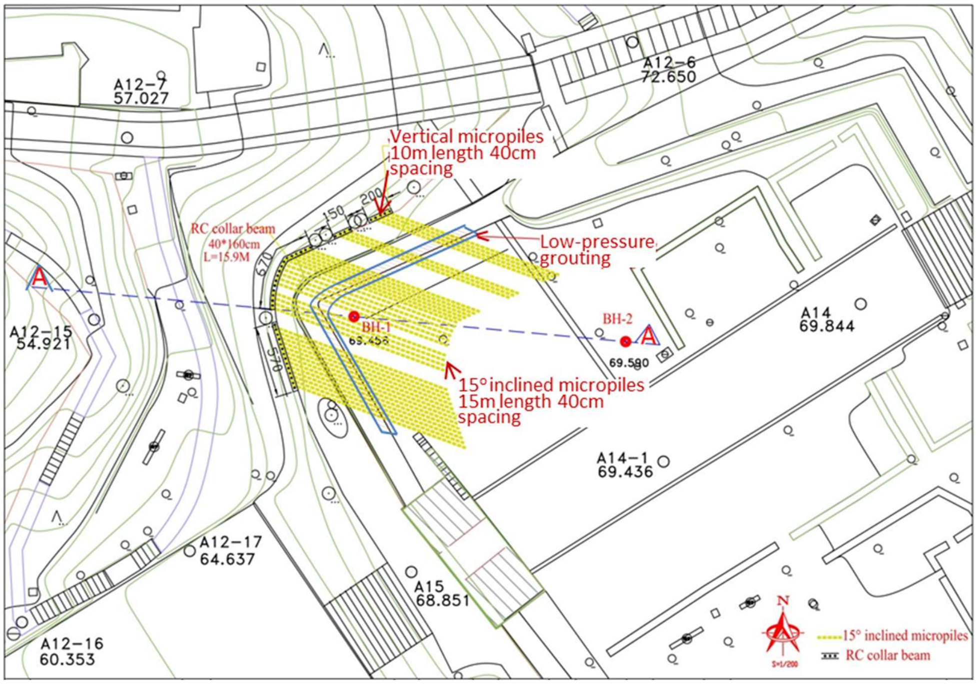

Figure 2: Plane diagram of the micropile configuration scenario for the underpinning strengthening and reinforcement of castle walls

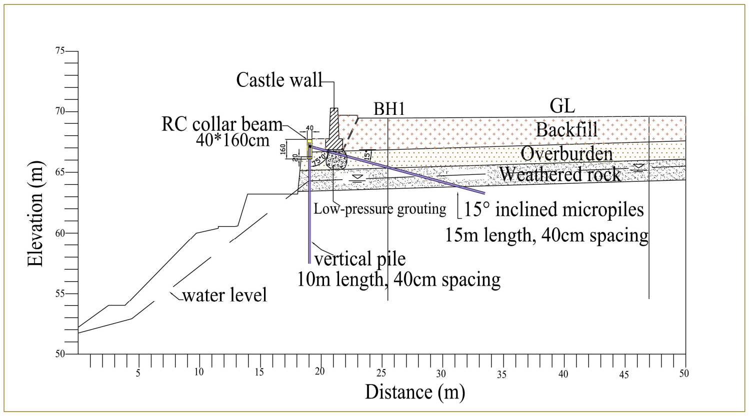

Figure **3**: Details of Cross-Section A where underpinning strengthening and reinforcement are imposed for Castle Wall

Table 1: Parameters of soil, rock formation, and grouting

Parameter Soil layer	Cohesion **C**	**ø**	**E**	γ_t	Poisson's ratio ν
	KPa	(degree)	KPa	KN/m³	
Backfill	5	25	$2x10^3$	19.5	0.3
Rock formations	45	30	$9x10^6$	23	0.3
Weathered rock	40	30	$4x10^6$	22	0.3
Overburden	6	25	$4x10^3$	21	0.3
Castle wall	30	25	$2x10^6$	23	0.3
Grouting	40	30	$6x10^6$	23	0.3

Table 2: Parameters of micropile

Axial stiffness	EA	1.42×10^6	kN/m
Flexural rigidity	EI	$1.65x10^3$	kN˙m²/m
Equivalent thickness	d	0.4	M
Bulk Density	w	2	kN/m³/m
Poisson's ratio	ν	0.15	

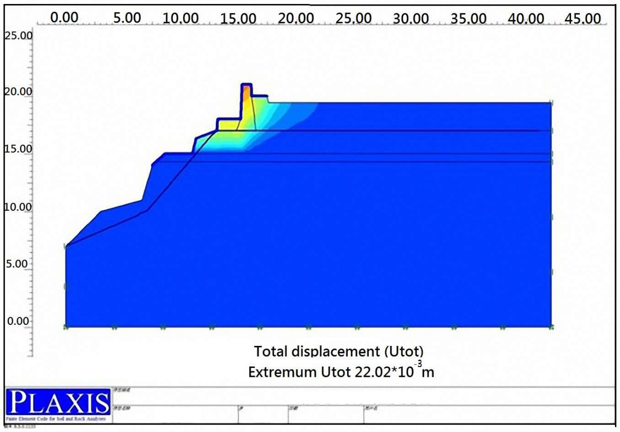

Figure 4: Current state - Rainstorm - Total displacement distribution(Maximum value of 22.02mm)

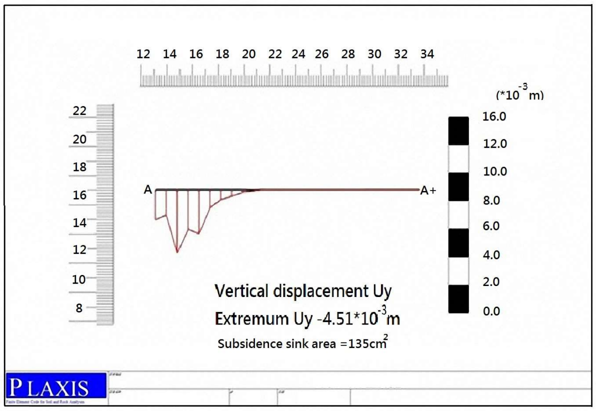

Figure 5: Current state - Rainstorm - Foundation subsidence profile (Maximum value of 4.5mm)

The results of the foundation reinforcement analysis by underpinning and strengthening the retaining walls of castle are shown in detail in Figure 6.

As indicated, after conducting reinforcement with micropiles and grouting (Volume of 2.0m x 1.6m/m length), the maximum displacement under rainstorm conditions can be reduced from 22mm to 7mm; while the vertical subsidence of the foundation of the castle walls can be reduced from 4.5mm to 1.25mm, that is to one-quarter that of the current state.

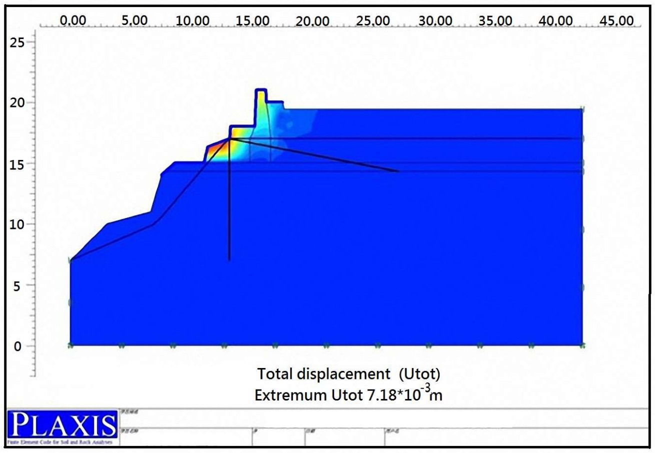

Figure 6: Total displacement after micropiling and grouting (Maximum value of 7.18mm)

(2) **Option 2: Underpinning reinforcement with Micro piles and different type/volumetric grouting**

Using micropiles as the underpinning reinforcement for the foundation of this confined space has advantages due to the particular applicability of the method in narrow spaces. The micropile with its horizontal angle of depression provides underpinning action to the foundation of the castle wall, but due to its small cross-section, there is a possibility of insufficient EI rigidity, thus low-pressure grouting is added to the foundation of the castle wall.

2.1.3 Comprehensive comparisons of the effectiveness of four options for Case (1)

After compiling the four options, the comparisons between each type of reinforcement are shown in Table 3. The comprehensive descriptions are as follows:

From Table 3, installing single-row vertical micropiles in the initial slope of the castle wall in its current state forms the retaining wall in the ground that directly enhances the safety factor by 5.6%. The maximum displacement is significantly decreased by 53.1%; the single-row vertical micropiles have improved the displacement resistance significantly. The amount of vertical subsidence of castle wall's foundation has reduced by 37.6%. If further reduction of the soil deformation behind the retaining wall in the ground is required, it is necessary to add additional reinforcement measures. Below are the comparative discussions on the effectiveness of each reinforcement type as shown in Table 3.

Comparing Type 1 with Type 2, inserting single-row vertical micropiles with additional grouting will enhance the safety factor from 5.6% to 6.3%; controlling the maximum displacement amount, causes a progressive decrease from -53.1% to -58.4%; while the amount of vertical subsidence of the foundation of the castle wall decreases by 82.6% progressively from the initial slope condition. Thus, the single-row micropiles with grouting reinforcement can significantly improve the soil subsidence trend around the piles as well as reduce the amount of soil deformation after forming the retaining wall in the ground. Comparing the vertical subsidence sink areas of Type 1 and Type 2, Type 1 is 98cm^2; Type 2 is 15.6cm^2, thus a difference of 84% between the two is found.

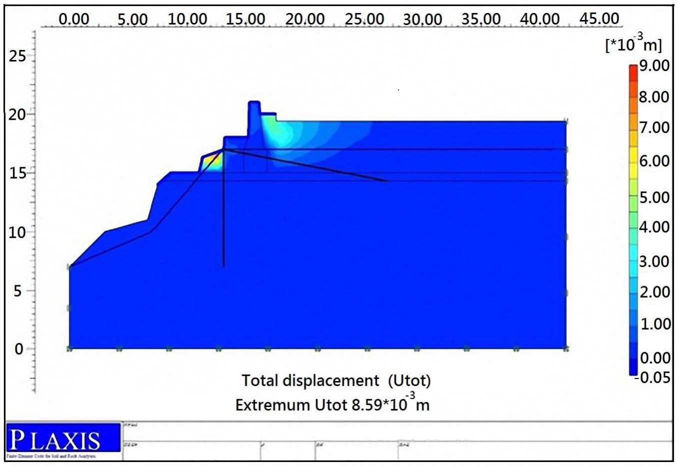

Figure 7: Micropiles + 1 times volume of grout – Rainstorm – (Total maximum displacement of 8.59mm)

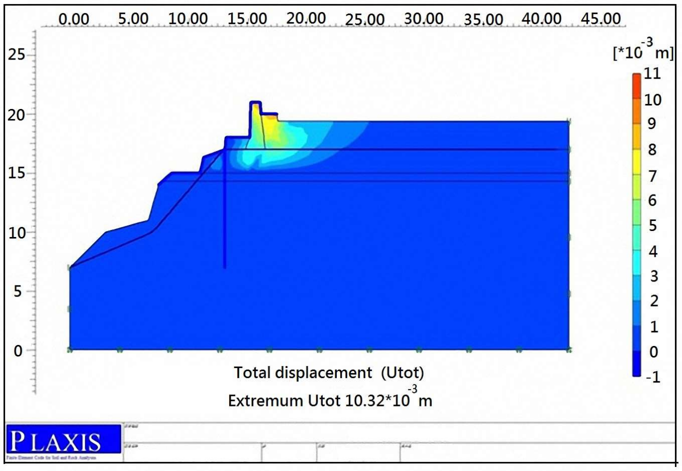

Figure 8: Single-row micropiles - Rainstorm – (Total Maximum displacement of 10.32mm)

Table 3: Comprehensive comparisons on the effectiveness of each option for Case (1)

Reinforcement Type / Comparative Item	(0). Initial condition	(1). Single-row vertical piles	(2). Single-row vertical piles with grouting	(3). Vertical and inclined piles with grouting	(4). Type (3) with 1.5 times the grouting in convex shape	(5). Type (4) with grouting in L-shape	(6). Type (3) with 2 times of the grouting
Factor of safety (FS)	1.723	1.820(+5.6%)	1.831(+6.3%)	1.919(+11.4%)	1.926(+11.8%)	1.902(+10.4%)	1.924(+11.7%)
Total displacement (mm)	22.02	10.32(-53.1%)	9.16(-58.4%)	8.59(-61.0%)	8.44(-61.7%)	8.70(-60.5%)	8.55(-61.2%)
Foundation Subsidence (mm)	4.49	2.80(-37.7%)	0.78(-82.6%)	0.77(-82.8%)	0.76(-83.1%)	0.33(-92.6%)	0.19(-95.8%)
Subsidence sink area (cm^2)	135	98(-27.4%)	15.6(-88.4%)	15.4(-88.6%)	15.9(-88.2%)	10.9(-91.9%)	6.2(-95.4%)

Note: the percentage in brackets means the effectiveness percentage compare to initial condition.

Comparing Type 3 with Type 1 and Type 2, the addition of inclined micropiles significantly improves the safety factor by 11.4%; the maximum displacement decreases significantly by 61% compared with the maximum value at the initial condition. Compared with Type 1 and Type 2, the displacement amount is decreased from 53.1% to 61%, with respect to Type 0; the value of declining magnitude has increased. Comparing Type 2 and Type 3 with Type 1, after using micropiles to form the retaining wall in the ground beneath the castle wall's foundation, the only differences are with or without grouting. The subsidence amount is directly affected so that it decreases significantly 82.9%. This proves that grouting can significantly improve the subsidence.

Comparing Type 3 with Type 6, when the volume of low-pressure grouting injected beneath the castle wall's foundation is increased by 2, the safety factor is increased from 11.4% to 11.7%; the maximum displacement can be decreased from the - 61% trend to - 61.2%; the magnitude has been slightly enhanced by 0.2%. While the maximum benefit is that the vertical subsidence amount of castle wall's foundation can be reduced from - 82.9% to - 95.8%, a decrease of 13%. Considering the vertical subsidence sink area, Type 3 has an area of 15.4 cm^2 and Type 6 has an area of 6.2 cm^2; the difference in the vertical subsidence sink area between the two decreases by 60%. Therefore, a larger grouting volume reduces vertical subsidence and also has the benefit of directly inhibiting the soil's vertical subsidence behind the retaining wall in the ground.

Comparing Type 4 with Type 5 that use different volumetric shapes of low-pressure grouting under the foundation of the castle wall, a comparison of the convex shape and the L shape at 1.5 times of the volume, shows that the benefits to the safety factor and the maximum displacement are only slightly different. While for the vertical subsidence amount of castle wall, the L shape can reduce the -83% trend to -92.7%; for the vertical subsidence sink area, Type 4 has an area of 15.9 cm^2 and Type 5 has an area of 10.9 cm^2. The difference in the sink area of vertical subsidence for the two decreases by 31%. Thus, comparisons of the configuration type and the position show that the vertical subsidence sink position of the L shape closer to the castle wall's foundation has a more significant improvement on controlling the amount of soil vertical subsidence behind the retaining wall in the ground.

2.2 Case (2): Samantabhadra Temple (pu-shian shih) in Sanxia District

The site of this case is located along the slope of Samantabhadra Temple (pu-shian shih) on Touliaokeng Road, Sanxia District, New Taipei City. Due to erosion by typhoons and heavy rains in recent years, many places near the hall appear differential settlement, affecting the safety of access and surrounding buildings. The location of the site is shown in Figure 9.

2.2.1 Determination on the Cause of Destruction

The position of the disaster is located in the plaza next to the hall. Cracks and deformations have appeared on the square floor and boundary walls. According to the contour map and the field survey results, it has been determined that the main causes are because the plaza occupies a larger flat space, part of the boundary walls' foundation could be in the backfill zone, and the adjacent private land is in the steeper sloping surface. The current state is supported by a simple retaining wall and a short intersegment buttress, the disaster caused by differential settlement was triggered by heavy rains.

2.2.2 Planning Concept of Reinforcement Options

Adopting the gantry reinforcement option, micropiles are installed between the inside of the retaining wall and the square floor to penetrate into the rock. With a double-row pile configuration with an interval of 1.5 m between rows, a spacing of 40 cm in between piles, hole diameter of about 20 cm, and vertical pile length of 10m, the 37kg rail piles are inserted into the holes and mortar with 1:1 proportion of cement and sand poured into the holes. In between the double-row micropiles, the tops of the piles are connected with RC collar beam to form the gantry model to strengthen the micropiles and confine the slope displacement. The planar and cross-sectional details are illustrated in Figure 9 and Figure 10.

2.2.3 Stratigraphic Parameters of the Base

According to the on-site construction drilling survey results for the site of this case, the parameters of stratigraphic soil are compiled in Table 4; the micropile parameters are listed in Table 5.

2.2.4 Analysis and comparisons of reinforcement options

For the analysis using the PLAXIS program, the result is shown in Figure 11. The following analytical method is a progressive step-by-step option analysis: Option1 is single-row piles; Option 2 is double-row piles; and Option 3 is double-row piles with RC collar beam. After the analysis, the results and the current state were compared.

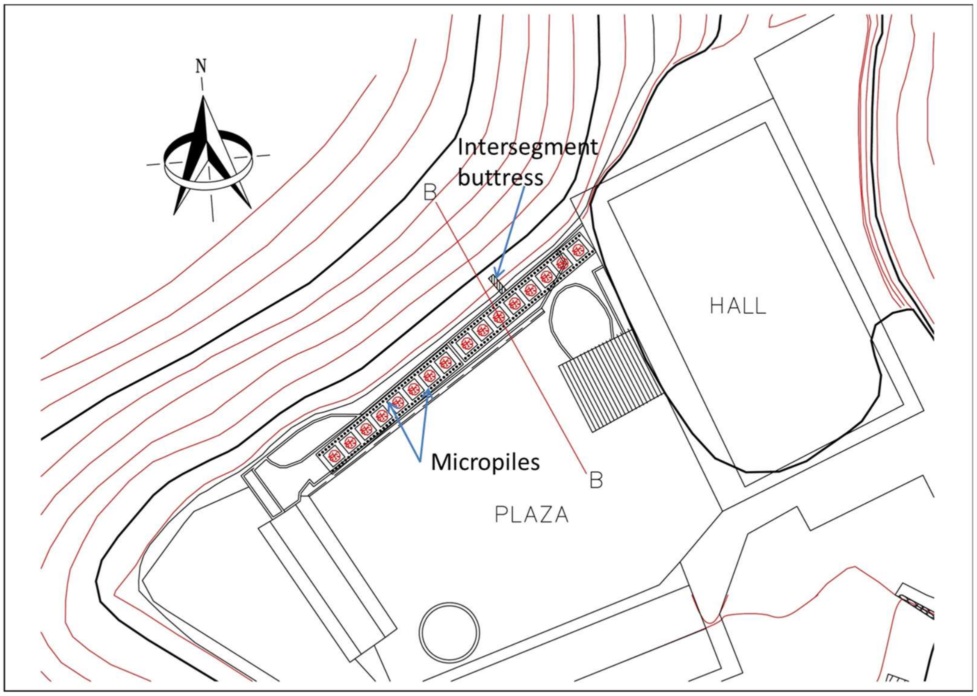

Figure 9: Micropile configuration state for gantry reinforcement option in Case (2)

Table 4: Parameters of soils in Case (2)

Parameter / Soil	Cohesion **C**	**ø**	**E**	γ_t	Poisson's ratio ν
	KPa	(Degree)	KPa	KN/m³	
Backfill	5	30	$2x10^3$	19.5	0.3
Rock formation layer	50	32	$9x10^6$	23	0.3
Weathered rock	40	30	$4x10^6$	22	0.3
Overburden	10	30	$4x10^3$	21	0.3

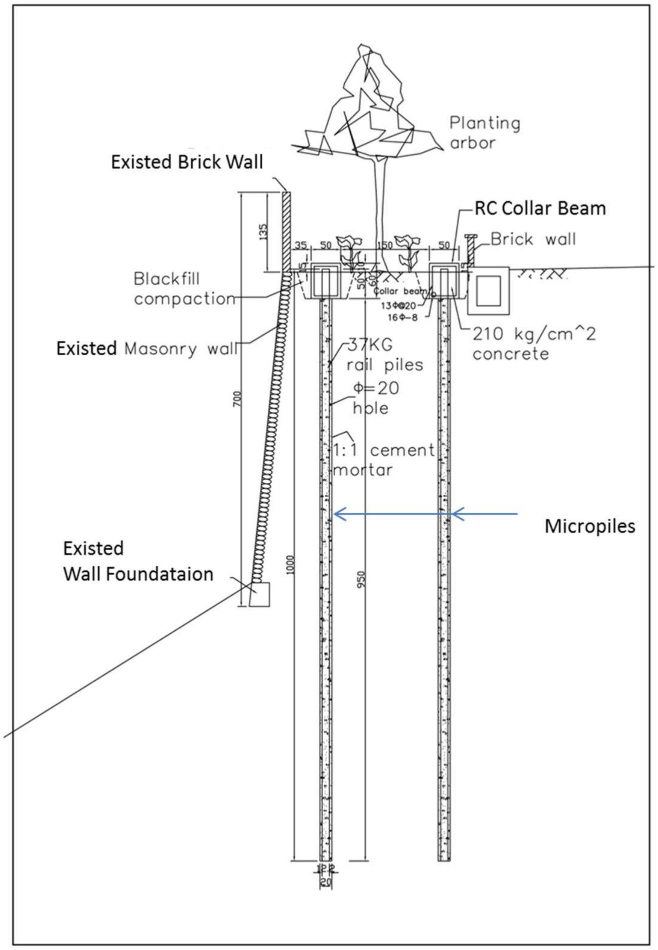

Figure 10: Cross-section B-B view of micropiles in Case (2)

Table 5: Parameters of micropile

EA	kN/m	4.11×10^6
EI	kN·m^2/m	9.1×10^3
d	m	0.4
w	kN/m^2/m	2
ν	0.15	

Option 2: Double-row micropiles are installed to penetrate the rock. The interval between the two rows of piles is 1.5m, the spacing between each pile is 40 cm. The analysis result of the PLAXIS program shows that under rainstorm conditions, the maximum displacement in the condition of double-row micropiles can be reduced from 24mm to 7.58mm; while the amount of vertical subsidence of the retaining wall and floor can be reduced approximately from 6mm to 0.78mm (one-seventh). These results show that the double-row micropiles have a significant improvement on both the displacement and amount of vertical subsidence of the original retaining wall, flower bed, and plaza.

Option 3: In between the two rows of micropiles, the tops of the piles are connected with a RC collar beam to a gantry to strengthen between the rows of piles and confine the slope displacement. The analysis results is shown in Figure 12. Under the rainstorm conditions, the maximum displacement can be reduced from 24mm to 6.4mm; while the amount of vertical subsidence of the retaining wall and floor can be approximately reduced from 6mm to 0.9mm (one-sixth). Thus, the option of double-row micropiles with RC collar beams is the most effective for improving the safety factor and maximum displacement.

2.2.5 Case (2): Comprehensive comparisons of the effectiveness of reinforcement next to the Samantabhadra Temple

From Table 6, as the direct benefit of installing single-row micropiles to form the retaining wall in the ground is an increase in the safety factor by 40.9%; the maximum displacement decreases significantly by 67.4%; while the amount of vertical subsidence decreases significantly by 66.6%. Thus, the single-row vertical micropiles can alleviate and improve the subsiding soil surrounding the piles; and after the retaining wall in the ground is formed, the soil deformation has decreased. Its direct contribution is its significant improvement in resisting the displacement and inhibiting the amount of vertical subsidence. A comparison of the total displacement sink area (i.e. areas enclosed by retaining wall displacement) shows that it can be reduced from 840cm^2 to 273cm^2; the improvement to the total displacement sink area is a reduction of 67%. The subsidence sink area can be reduced from 218.6 cm^2 to 45 cm^2, that is, the improvement of the vertical subsidence sink area is a reduction of 79%. Thus, the contributions of single-row vertical micropiles have significantly enhanced the resistance of the displacement sink area; and the improvement of inhibiting the vertical subsidence sink area has also been enhanced. Overall, the direct benefit of single-row vertical micropiles is an increase in the safety factor from 1.1 to 1.55, which is more than the generally recommended safety factor of 1.5. In terms of security, Option 1 has met the stability requirements.

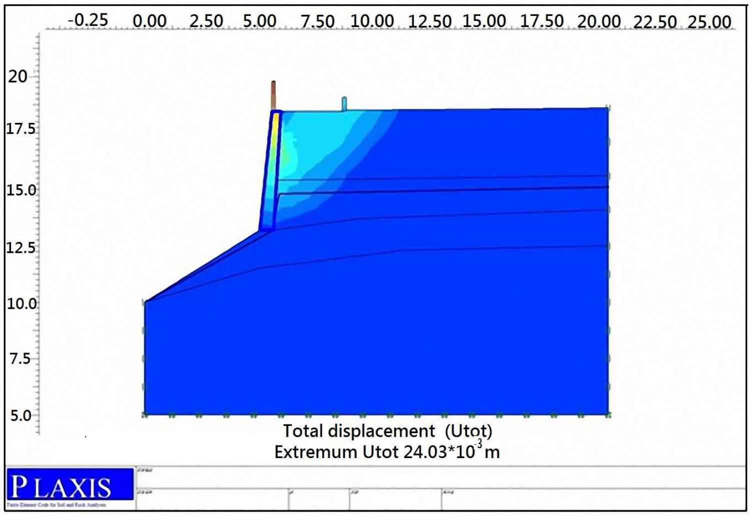

Figure 11: (B-B current - rainstorm) total displacement (Maximum value of 24.03mm)

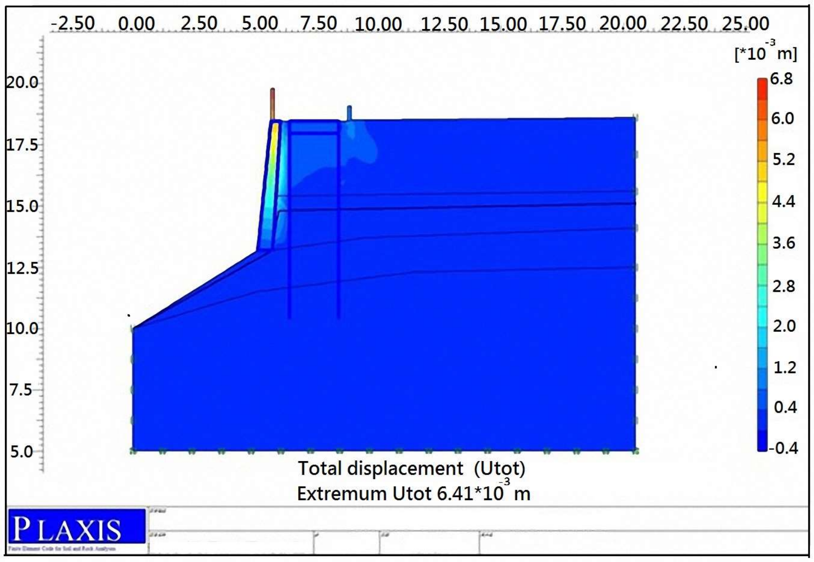

Figure 12: Double-row micropiles with collar beam under rainstorm conditions – (Maximum total displacement of 6.41mm)

Table 6: Comprehensive comparison of reinforcement effectiveness under rainstorm conditions for Samantabhadra Temple in Case (2)

Reinforcement type Comparative item	(0). Initial condition	(1). Single-row micropiles	(2). Double-row micropiles	(3). Option (2) + Collar beam
Safety factor	1.10	1.55	1.61	1.75
Displacement (mm)	24.03	7.84	7.58	6.41
Subsidence (mm)	5.99	2.00	0.78	0.95
Displacement sink (cm^2)	840	273	262.5	224
Subsidence sink (cm^2)	218.6	45	13.1	9.0

By comparing Type 2 with Type 3, the difference in the benefit of double-row micropiles and gantry-style micropiles is that the safety factor is further enhanced from 46.4% to 59.1%; the safety factor has been slightly increased by about 12.7%; the maximum displacement can be reduced from -68.5% to -73.3%, a decline in magnitude of about -4.8%, while subsidence amount in the retaining wall and plaza floor increases by about 2.9%. The total displacement sink area can be reduced from 262.5cm^2 to 224cm^2, an improvement of about 14.6 %. The vertical subsidence sink area can be reduced from 13.1cm^2 to 9.0cm^2 (31%). Thus, when the effectiveness of Type 3 gantry-style micropiles is compared with that of Type 2 double-row micropiles, a direct improvement is achieved in the safety factor, total displacement, and vertical subsidence. Taking the loss of earth of the soil body of the plaza due to the total displacement sink and the vertical subsidence sink into consideration, it is recommended to adopt the Type 3 gantry-style micropile reinforcement for improvement. This option forms a frame-type structure on the planar architecture. Within the frame, the space can still provide gridiron for planting in configuration with grafting, which can give the functional benefits of taking both the ecological environment and protecting the soil from erosion loss into consideration.

3. CONCLUSIONS AND RECOMMENDATIONS

According to the analysis results, micropile application can provide several benefits; these benefits are summarized below as a reference for similar projects.

(1) In both cases, the direct benefit of installing single-row vertical micropiles to form a retaining wall in the ground is an enhanced safety factor of about 6% to 40%; and the maximum displacement is significantly reduced from about 53% to 67%. Moreover, if the single-row vertical micropiles are coupled with grouting, the soil subsidence trend near the pile bodies can be improved significantly, so that after forming the retaining wall in the ground, the amount of soil deformation can be further reduced; the amount of reduction is about 82%.

(2) In Case (1), the micropiles are underpinned in an inverted L-shaped manner in order to increase strength. Additionally installing an inclined pile can further enhance the safety factor by about 11%; and after forming the retaining wall in the ground, the total displacement and amount of soil subsidence are further reduced by 8% and 45% (comparing the percentage difference between Type 3 and Type 1 list in Table 3) respectively.

(3) For micropiles coupled with low pressure grouting of different volumes and configurations, only slight differences were apparent in the safety factor and the maximum displacement. The major contribution is to reduce the subsidence amount and this has direct relationship with the position of the grouting. As the improvement position is closer to the vertical subsidence sink, its improvement on the amount of vertical subsidence of soil after installing the retaining wall in the ground is more significant.

(4) Among the reinforcement methods for the vertical subsidence of the foundation of a castle wall at a historical site in this paper, taking consideration of the narrow and confined space of construction, equipment, manpower, and other conditions from the perspectives of engineering design, it is recommended to use the method of installing the micropiles in inverted L-shaped manner with low-pressure grouting for strength and reinforcement. The effectiveness of Option 1 in the improvement of safety factor, total displacement, and amount of vertical subsidence is the best. After reinforcement, under rainstorm conditions, the maximum displacement can be reduced from 22mm to 7mm; while the vertical subsidence of the castle wall's foundation can be reduced approximately from 4.5mm to 1.25mm (one-quarter).

(5) In Case (2), the micropiles with gantry configuration can enhance the safety factor with a maximum enhancement of up to about 59%; the total displacement and soil subsidence amount can be drastically reduced by about 73% and 84%.

Furthermore, this construction method provides alternative function by forming a frame-type structure on the planar architecture to provide scope for planting in the frame, which can take consideration of both the ecological environment and protection of the soil from erosion loss.

REFERENCES

Fan Chia-Cheng, Chien Chin-Lung, (2004), Study on the Mechanical Behavior and Restoration Technology of Embankment Construction Ecology Method for Collapsed Road in Mountain Area, *2004 Cross-Straits Proceedings for Sino-Geotechnics/Geotechnical Engineering Seminar*, Taipei, Thesis No. 69.

Jeng, Ching-Jiang, Yu, Yu-Yu (2015), *Report on the Damage Cause Investigation and Restoration Planning Design for the Historical Sites of Urshawan Fort* (*Geotechnical Division*), Keelung City Cultural Affairs Bureau.