Lessons learnt on stability of a piled retaining wall in weak soils

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ABSTRACT

This paper presents a case study on a distressed piled retaining structure of 7.5m hight over soft soils. Due to the underlying weak materials, the retaining structure was designed to be supported by five rows of vertical driven precast concrete square piles. During backfilling of the constructed retaining wall, excessive lateral movement was observed. Investigation was conducted to reveal the probable causes of the wall distress. It was noticed that the normal stability assessment using slide method had over-estimated the safety margin of the piled wall. The vertical effective stresses for computing the sliding resistance at the bottom of the wall were over-estimated without considering the vertical support from the pile. An unrealistic safety factor was produced to justify the design. The lateral resistance of the vertical piles was not adequate to provide the lateral stability of the wall under the actual lateral earth pressure.

1 INTRODUCTION

A reinforced concrete (RC) retaining wall, with retaining height ranging from about 1.6m to 7m, was built at close proximity to an existing stream to retain a building platform at reduced level of RL48.00m. The project site is underlain by Kenny Hill Formation consisting of Carboniferous to Triassic meta-sediment interbedded between meta-arenite and meta-argillite with some quartzite and phyllite. Due to intense weathering processes in a tropical climate, the upper meta-sediments have been transformed into residual and completely weathered soils (Grades V and VI). The upmost overburden materials are soft compressible alluvial deposits from the stream. Sudden movements and vertical flexural cracking of the 7m high retaining wall were observed when the backfill behind the wall reached the height of about 1m below the wall top. The backfill material was partially removed to reduce the earth pressure on the retaining wall after the wall movement.

2 FORENSIC INVESTIGATION

2.1 Site Observation

Site inspection was carried out immediately after the wall displacement and tilting were reported. During the site inspection, vertical flexural cracks were observed at the front and back of the displaced wall, particularly over the portion in close proximity to the return of the wall. Three (3) levels of weepholes had been installed in the retaining wall at RL42.5m, RL45.0m and RL47.50m. There was water staining from the weephole drains located at the mid height and bottom rows, revealing that groundwater level behind the retaining wall had previously risen above RL45m. The incident occurred after an intensive prolonged antecedent rainfall event. Figure 1 shows the overall site condition after the distress and the water staining at the weephole drains.

2.2 Subsurface Information

The layout of two previous subsurface investigation (SI) works carried out for the project is shown in Figure 2. The first one consisted of seven boreholes for the entire project site. The second SI works consisted of three boreholes and 25 Mackintosh Probes carried out along the retaining wall alignment. Only basic laboratory tests, such as soil classification had been performed in both SI works. There was no strength testing carried out in either SI.

The particle size distribution tests from boreholes BH-8, BH-9 and BH-10, which are closest to the RC retaining wall, indicate significant percentages of silt and clay materials within the first 3m depth. From interpretation, the overburden materials above RL38m are likely to be alluvial deposits, which are primarily soft compressible fine soils.

Additional SI work, consisting of two boreholes, vane shear tests, ten Mackintosh Probes and laboratory testing, was proposed to investigate the shear strength parameters and to reconfirm the subsoil profile. The SI layout plan and borehole profiles are shown in Figure 3. Borehole ABH-1 was carried out about 14m behind the RC retaining wall indicating higher percentage of silt and clay while borehole ABH-2 was carried out near the toe of the RC retaining wall showing high percentage of sand and gravel. Both boreholes ABH-1 and ABH-2 encountered hard material at RL34m and RL32m respectively. The borelog profile of ABH-1 shows the top 5m of fill above RL42m with low SPT-N values. From RL42m down to RL35m for borehole ABH-1 and RL32m for borehole ABH-2, the subsoil materials are considered likely to be alluvial deposits.

Penetrating vane shear tests were carried out next to ABH-2 to determine both the peak and remoulded undrained shear strength profiles of the soil. The interpreted undrained shear strength profile is presented in Figure 4. The vane shear tests indicated a sudden drop in the measurement of peak undrained shear strength ($S_{u,peak}$) at the depth of about 4m below ground, where the measured strength is close to the remoulded strength ($S_{u,remolded}$), potentially suggesting the existence of a disturbed shearing zone associated with a slip surface at this depth.

Consolidated Isotropically Undrained (CIU) triaxial tests, with pore pressure measurement, were also carried out to confirm the drained shear strength parameters. The interpreted effective shear strength parameters in the material below the wall were c'=5kPa, ϕ'=33°.

Figure 1: Overall Site Conditions and Water Staining at Weephole Drains

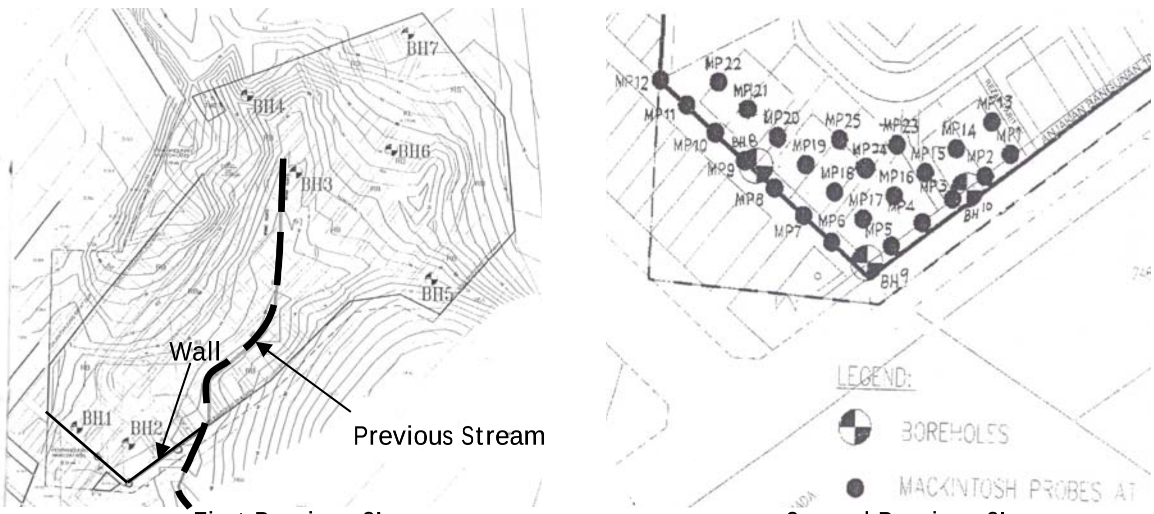
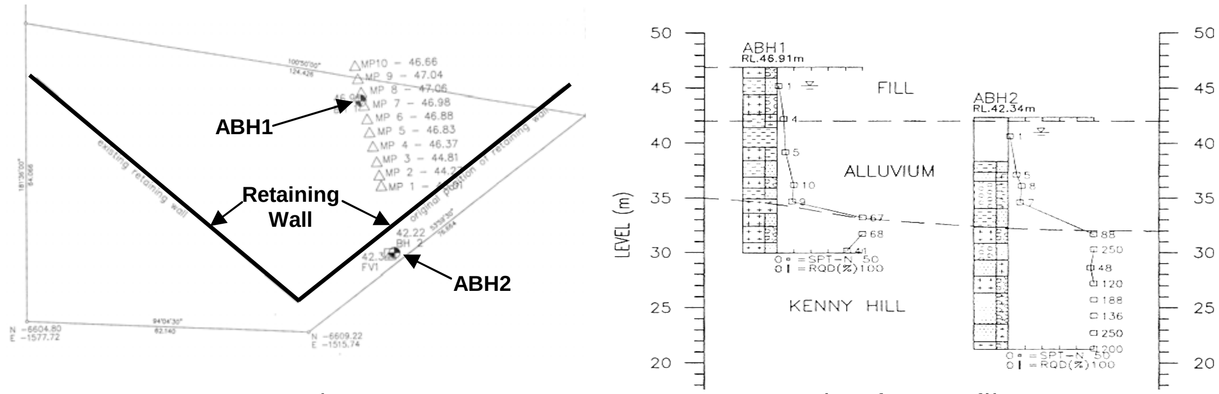


Figure 2: Previous SI Layout Plan



Layout Plan

Subsurface Profile

Figure 3: Additional SI Layout Plan and Profile

2.3 Retaining Wall and Foundation

A section through the distressed RC retaining wall is shown in Figure 4. The RC retaining wall was supported on 5 rows of driven precast 200mm RC piles at 2m longitudinal spacing. The vertical compressive working load of the 200mm RC square piles is 450kN. High strain dynamic pile test was previously carried out on seven of the piles. The pile driving records of the test piles indicated that the piles were driven to end-bearing condition and the installed lengths ranged from about 4.5m to 11.7m. The mobilised pile capacity in the six tested piles had achieved a minimum factor of safety of 2.0 and one pile with a marginally lower factor of safety of 1.8. The test cube results for the wall construction show that the concrete cubes had achieved the designed strength of 30MPa.

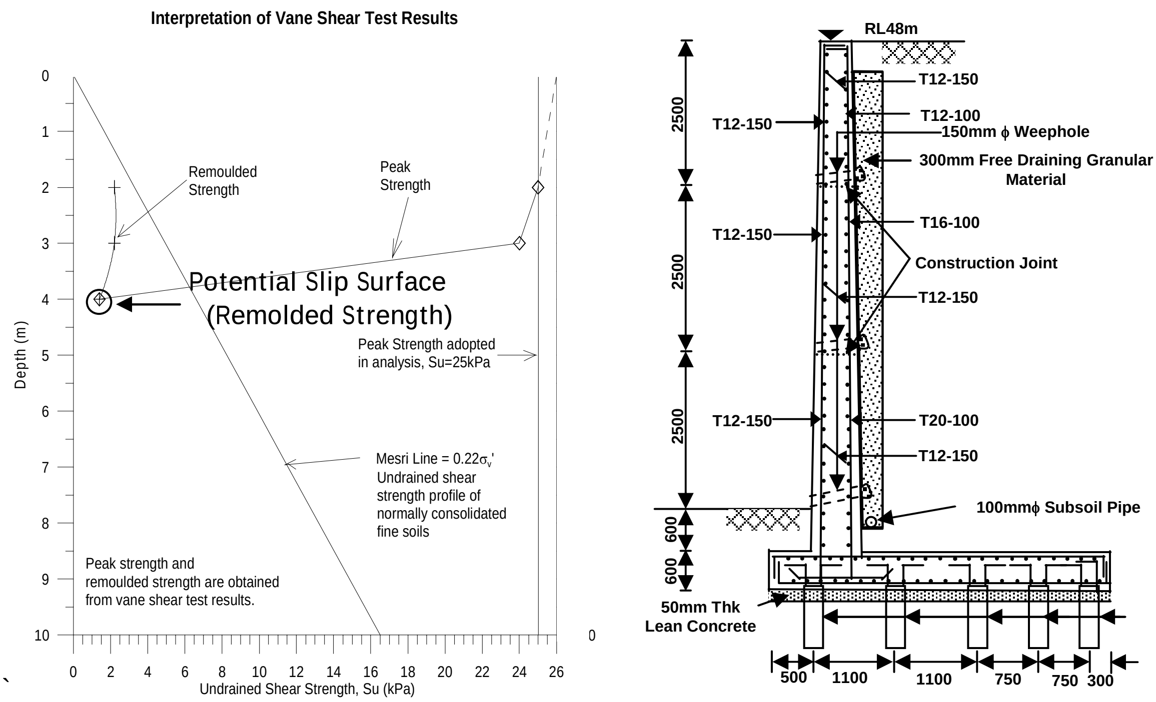


Figure 4: In-situ Undrained Shear Strength Profile Below the Wall and Typical Wall Section

2.4 Geotechnical Assessments

For the geotechnical wall stability assessment, three cases of groundwater levels at RL40.4m, RL42.5m and RL45m were modelled. The observed water staining at the second row of weephole drains suggested the most probable groundwater level was above RL45m at the time of wall distress. The following stability aspects have been performed with the achieved factor of safety (FOS) summarised in Table 1.

2.4.1 Overturning Stability

The minimum FOS required for retaining wall overturning stability is 2.0. Based on the analysis, the retaining wall can achieve the minimum FOS for most cases of different groundwater conditions.

2.4.2 Sliding Stability

The minimum FOS required for retaining wall sliding stability is 1.5. The sliding stability of the retaining wall is assessed by taking account into the passive resistance in front of the wall embedment, sliding resistance underneath the RC wall base and lateral resistance contributed by the pile foundation.

Based on analysis, the sliding stability of the retaining wall is less than 1.5 when the groundwater level behind the wall rises above RL42.5m. Wall sliding failure is predicted when groundwater level rises to RL45m.

2.4.3 Bearing Capacity

Bearing capacity is not a concern for the retaining wall as it is supported by piled foundation. This is because the vertical load of the retaining wall system will be transferred to the lower more competent bearing stratum through the end-bearing piles.

The analysis reveals that the compression bearing capacity requirement in terms of supporting the vertical load for the retaining wall is adequate.

2.4.4 Global Stability (External Stability)

Limit equilibrium slope stability analysis software was used to assess the global stability of the retaining wall system.

Global stability analyses with both short-term (undrained) and long-term (drained) shear strength parameters have been carried out. The short term shear strength parameters are adopted from the aforementioned interpreted vane shear tests results. The undrained shear strength of 25kPa was used for alluvial subsoils.

As the wall is vertically supported by the end-bearing piled foundation, the stability analysis assuming zero self weight for the soil above the wall base and the wall itself was performed to avoid unrealistic increase of vertical effective stress in the stability slide forces, which will improve the FOS against instability. Comparison of FOS between this stability model and the one with soil weight and wall self weight is also tabulated in Table 1 to reveal potential errors. For short-term FOS (total stress analysis), the error ranges from 4% to 7%, whereas for long-term FOS (effective stress analysis), the error ranges from 41% to 105%.

Table 1: Factor of Safety for Geotechnical Assessment

Ground Water Level	**Overturning (>2.0)**	**Sliding (>1.5)**	**Bearing Capacity (>2.0)**	**Global Circular Stability (>1.4)**			
				Without Self Weight		**With Self Weight**	
				Short Term (>1.2)	**Long Term (>1.4)**	**Short Term (>1.2)**	**Long Term (>1.4)**
RL40.4m	3.8	1.50	2.5	1.16	1.70	1.24	2.39
RL42.5m	3.7	<u>1.34*</u>	2.5	1.19	<u>1.25*</u>	1.25	1.92
RL45.0m	2.9	<u>0.97*</u>	2.5	1.13	<u>0.80*</u>	<u>1.17*</u>	1.64

* Note : The underlined FOS means design inadequate. Ultimate limit condition prevails if FOS < 1.0.

2.5 Structural Assessments

2.5.1 Steel Reinforcements for RC Wall

Structural checks have been conducted for the wall stem and base. It was found that the upper reinforcement provided for the wall base is marginally inadequate when the groundwater level rises to about RL45m. The structural checks of the retaining wall for different cases are summarised in Table 2. However, the geotechnical failure predominates over the structural failure for the corresponding groundwater conditions.

2.5.2 Structural Capacity of RC Pile

As the retaining wall system is subjected to vertical forces, lateral forces and bending moments, these externally imposed forces and moments will be transmitted to the RC pile foundation. Thus, the induced bending moments along the RC pile must be checked to ensure that the bending moment capacity of the pile is not exceeded.

The ultimate lateral resistance of a pile will only be achieved when the ultimate bending moment capacity of the pile is reached and one or more plastic hinges are formed. Based on Brom's approach (Elson 1984), the estimated ultimate lateral pile resistance is 32kN for fixed pile head condition and 20kN for free pile head condition. From the pile anchorage connection to wall base, the pile is expected to behave with a fixed pile head condition under lateral loading condition. The lateral stability analysis results reveal that the ultimate lateral resistance of the pile will be reached when groundwater level rises to between RL42.5m and RL45m. With the above reasoning, flexural cracks are expected to occur in the piles supporting the RC retaining wall.

To confirm the occurrence of flexural cracking at the RC piles, Pile Integrity Tests (PIT) were carried out on six selected piles. The test results indicated that discontinuities were detected at a depth of about 1.0m to 4.0m below the top of the piles.

Analyses of the shear force capacity for RC piles are also summarised in Table 2. It was observed that the shear resistance of the RC piles was not critical under the corresponding loading conditions in which the flexural failure of pile is expected occur first.

Table 2: Adequacy of Wall Structural Assessment

Ground Water Level	Bending Reinforcement required (mm^2/m)			Bending Reinforcement provided (mm^2/m)			Induced Shear Stress (N/mm^2)	
	Wall	Base (Upper)	Base (Lower)	Wall	Base (Upper)	Base (Lower)	Required	Provided
RL 40.4m	2036	1989	780	3143 (T20-100)	2514 (T20-125)	2514 (T20-125)	0.19	1.23
RL 42.5m	2066	2058	780	3143 (T20-100)	2514 (T20-125)	2514 (T20-125)	0.32	1.23
RL 45.0m	2613	2736	780	3143 (T20-100)	2514* (T20-125)	2514 (T20-125)	0.82	1.23

* Note : The underlined value indicates design inadequacy.

3 PROBABLE CAUSE OF WALL MOVEMENT & REMEDIAL SOLUTIONS

Based on site observations and the analysis results, the assessed cause of the wall movement is primarily due to inadequate lateral resistance of the piled retaining wall when groundwater rises above RL45m after prolonged antecedent rainfall. The lateral resistance of the retaining wall from the wall base friction is insignificant as the stiff pile foundation attracts most vertical wall loading. As a result, the soil beneath the wall base did not experience much increase of vertical effective pressure and hence lowering the effective resistance of the stability slides in the global stability. The assessment shows that the total lateral resistance provided by the retaining wall and foundation system is inadequate to resist the lateral forces when the groundwater level rises above

RL45m. Therefore, the increased lateral forces have caused structural failure to the piles, thus leading to excessive wall movement.

Based on the findings from the investigation, the following preliminary suggestions were made when considering the remedial works of the new retaining wall:

- The vane shear results show evidence that the slip surface could have been formed at about 4m below the ground at the RC wall toe. The strength profile indicates that the available strength at the shearing zone has reduced to residual strength. Therefore, it is important that the disturbed material at the shearing zone be removed and replaced with material of higher strength. Otherwise, ground treatment methods such as stone columns can be considered.
- The analyses results reveal that the sliding resistance for the retaining wall is inadequate when groundwater level rises above RL42.5m. Therefore, adequate sliding resistance shall be provided for the new retaining wall system. In addition to this, the global stability with slip surface passing underneath the wall shall be analysed to ensure adequate FOS.
- It is also important to have adequate surface and subsurface drainage for the new retaining wall system during and after construction. This is to minimise the infiltration of surface runoff into the wall backfill as the FOS against instability of the retaining wall system reduces significantly with the rise of groundwater level within the wall backfill.

4 CONCLUSIONS

From this simple forensic investigation, the following conclusions and lesson learnt can be summarised:

- The water level within the wall backfill and the active soil wedge behind the wall have remarkable influence on the factor of safety against instability. Weepholes on the wall do not necessarily warrant the wall stability. Subsoil drainage system can be incorporated to control the water level within these soil zones to effectively improve the factor of safety.
- When pile foundations are used to support retaining walls, caution must be taken to properly model the vertical effective stress in the soil beneath the wall, which can be model with zero self weight of backfill above the wall base and the wall itself. If this aspect is not properly addressed, errors in factor of safety on the optimistic side can be as high as 105% depending on type of analysis and groundwater condition. If the in-situ soil sliding resistance under the wall self weight is adequate to resist lateral earth pressure and ground water pressure, designing the wall without pile foundation could be safer than the one with all vertical piles, except for necessary assessment on wall settlement to ensure adequate serviceability limit.
- Slender vertical piles are generally not suitable for supporting retaining wall on weak and compressible soils as they offer insignificant lateral resistance to the wall. Raked piles in combination of vertical piles can be a more effective foundation system to support the wall if wall settlement is a concern.

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