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Micropiles: an effective foundation for seismic strengthening. Design recommendations

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ABSTRACT

Seismic strengthening of existing buildings regularly includes the addition of bracing elements requiring additional foundation tension and compression resistance. Micropiles, comprising a single steel bar grouted into a bored hole (ground anchor), are the normal means of achieving this additional foundation resistance. Micropiles are preferred because they can be constructed in confined spaces and offer both tension and compression resistance. Design of these micropiles is normally based on the results of static tension tests. This static tension test is a poor resemblance of the dynamic reverse cyclic (compression/tension) loading applied in an earthquake. The damaging effect of the reverse cyclic loading on the micropile's bond is poorly understood and allowance for this in design is inconsistent in the industry and may be non-conservative.

This paper presents the results of two reverse cyclic load tests and provides recommendations for the design of micropiles.

1 INTRODUCTION

Seismic strengthening of existing buildings regularly includes the addition of bracing elements requiring additional foundation tension and compression resistance. Micropiles, comprising a single steel bar grouted into a bored hole (ground anchor), are the normal means of achieving this additional foundation resistance. Micropiles are preferred because they can be constructed in confined spaces and offer both tension and compression resistance.

There are a number of issues that need to be considered in the design and construction verification of these micropiles. These include the degrading effect on grout to country bond by dynamic reverse cyclic (compression/tension) loading. This paper considers this issue and others affecting the performance of micropiles. Design guidance is provided to respond to these issues.

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The discussions and guidance have been prepared with micropiles bonded into dense Wellington alluvium in mind. This information could be applied to other geology with caution.

2 ISSUES TO BE CONSIDERED IN DESIGN

The authors have identified the issues listed below as essential to be considered in the design of micropiles to resist seismic foundation loads. In the subsequent sections each issue is described in turn and design recommendations are provided to address these issues.

- **Stiffness compatibility of new micropiles and the building's existing foundations:** Differential settlement potential between the micropiles and the building's existing foundations need to be considered. Relative stiffness of foundations also needs to be considered; are the micropiles relatively stiff such they attract unintended high loads?
- **Reverse cyclic loading and degradation of grout to country bond:** Seismic loading is likely to apply cycles of compression and tension loading to the micropile. This reverse cyclic loading is damaging to the available grout to country bond.
- **Bond length and strain degradation of bond:** Long bond lengths can be subject to large strains under tension loading. These large strains can reduce the micropile's available grout to country bond.
- **Ground conditions and drill method:** Ground conditions and method of construction of the micropile can substantially effect the grout to country bond capacity achieved.
- **Test micropile details:** In the design and construction of test micropiles care needs to be taken to ensure the length of bond transferring load from micropile to ground is known.
- **Strength reduction factor**: In evaluating the strength reduction factor to be applied to the grout to country bond the uncertainties and consequences of failure need to be understood.

2.1 Stiffness compatibility of new micropiles and the building's existing foundations

In the design of new buildings the use of mixed (more than one type) of foundations is generally avoided. This is to limit differential settlement potential or varying load response. Adding micropiles to an existing building may be an effective means of resisting additional loads from seismic strengthening elements, but as part of the decision to use micropiles their behaviour in conjunction with the existing foundations needs to be considered along with the effect of this on the behaviour of the building. Potential differential settlement between existing and new foundations needs to be assessed. If the micropiles are stiff relative to the existing foundations the micropiles could attract unintended high loads. This needs to be assessed and allowed for in design. Specific examples to be aware of and avoid/allow for in design include:

- Adding micropiles to a building on shallow foundations bearing on soils prone to settlement from earthquake shaking or other effects (e.g. shrink, swell, creep): The micropiles and strengthening may improve life safety in a large seismic event, but this could be at the cost of increased differential settlement damage under serviceability or smaller more frequent seismic events. The building owner needs to be made aware of and accept this increased risk of damage, or an alternative solution developed.
- Supplementing an existing shallow foundation with micropiles to increase compression and uplift resistance: Relative stiffness of the two foundation types needs to be considered in assessing the load distribution and micropile design. It may be necessary to design the micropiles to resist 100% of the transient compression loads.

2.2 Reverse cyclic loading and degradation of grout to country bond

Seismic loading is likely to apply cycles of compression and tension loading to the micropile. This reverse cyclic loading is likely to be damaging to the available grout to country bond. Undertaking reverse cyclic load testing of a micropile is considerably more complex and expensive than undertaking static tension or cyclic tension testing. In the absence of available reverse cyclic load test data the authors have previously applied the following design approach:

- Assess the ultimate geotechnical capacity in static tension by load testing a sacrificial micropile to failure in accordance with AS2159; Piling Design and Installation.
- Reduce the assessed ultimate geotechnical capacity in static tension by a factor of 0.7 to make an allowance for degradation of bond during reverse cyclic loading.
- Further reduce the capacity by a strength reduction factor of 0.7 to allow for uncertainties. The selection of this strength reduction factor and associated micropile testing is discussed in Section 2.6 of this paper.

The factor of 0.7 to allow for reverse cyclic loading is based on review of static load test data and engineering judgement. Static load testing indicated that strains at a load of 70% of the micropile capacity were relatively small. It was judged that with relatively small strains bond degradation with reverse cyclic loading was not likely. On a recent project this approach was challenged. It was suggested that the approach may be unduly conservative. To test this a sacrificial micropile was constructed and tested by reverse cyclic load testing. The results of that test are presented in Figure 1.

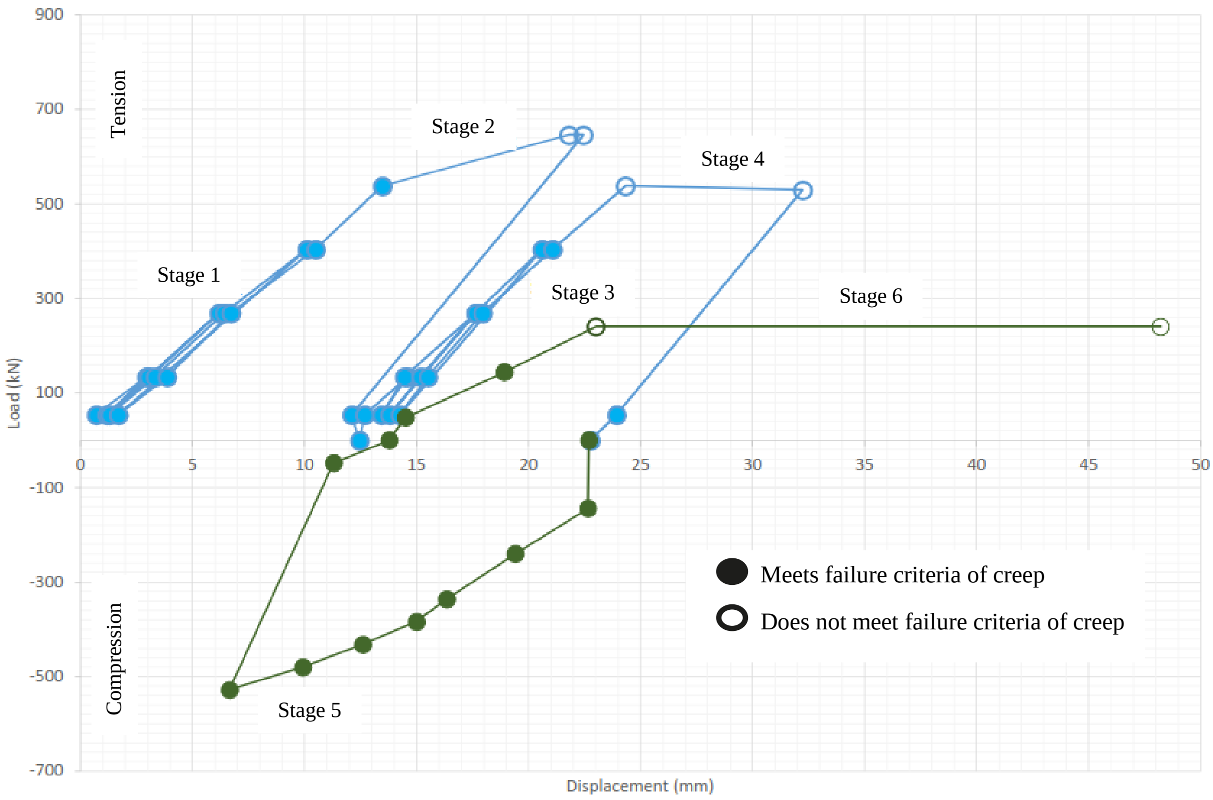

Figure 1: Reverse cyclic load test to failure

The test pile was constructed in dense alluvium and included an 8m free length, 8m bond length and 220mm diameter. Each increment of loading was tested against the AS2159 failure criteria of creep of 0.5mm/15min. The stages of the test are numbered on Figure 1 and comprised of the following:

- Stage 1: 3 cycles of loading from 50kN to 400kN in tension. 400kN represented 70% of the assessed ultimate geotechnical capacity in tension. This tension cyclic loading resulted in no permanent displacement of the micropile.
- Stage 2: Increase static tension loading to find the static tension capacity. The micropile resisted 550kN without creep. At 650kN more than 0.5mm/15min creep was recorded. It was concluded that the static tension capacity was approximately 600kN.
- Stage 3: A further 3 cycles of 50kN to 400kN in tension was applied. This was resisted without further creep.
- Stage 4: Static loading again increased to investigate the static tension capacity. The capacity was found to have reduced. It was more than 400kN but less than 550kN.
- Stage 5: Compression load was applied incrementally up to 550kN. This load was resisted without creep.
- Stage 6: Tension load was applied incrementally. A load of 250kN could not be sustained without creep.

It was concluded from this test that if strain was allowed to occur cyclic loading is likely to degrade the bond. Reverse (up and down) cyclic strains are likely to be more damaging than up (tension) only. This test indicated that the proposed 0.7 factor to protect against reverse cyclic loading degradation is likely of the right order. Further testing would be required to verify this.

On the basis of this test production anchors were designed and constructed with the originally proposed design approach of a cyclic reduction factor of 0.7 and a strength reduction factor of 0.7, overall reduction factor of 0.49. All production micropiles were proof tested in static tension to 120% of the ultimate limit state seismic design load. One production pile was tested as described in Figure 2.

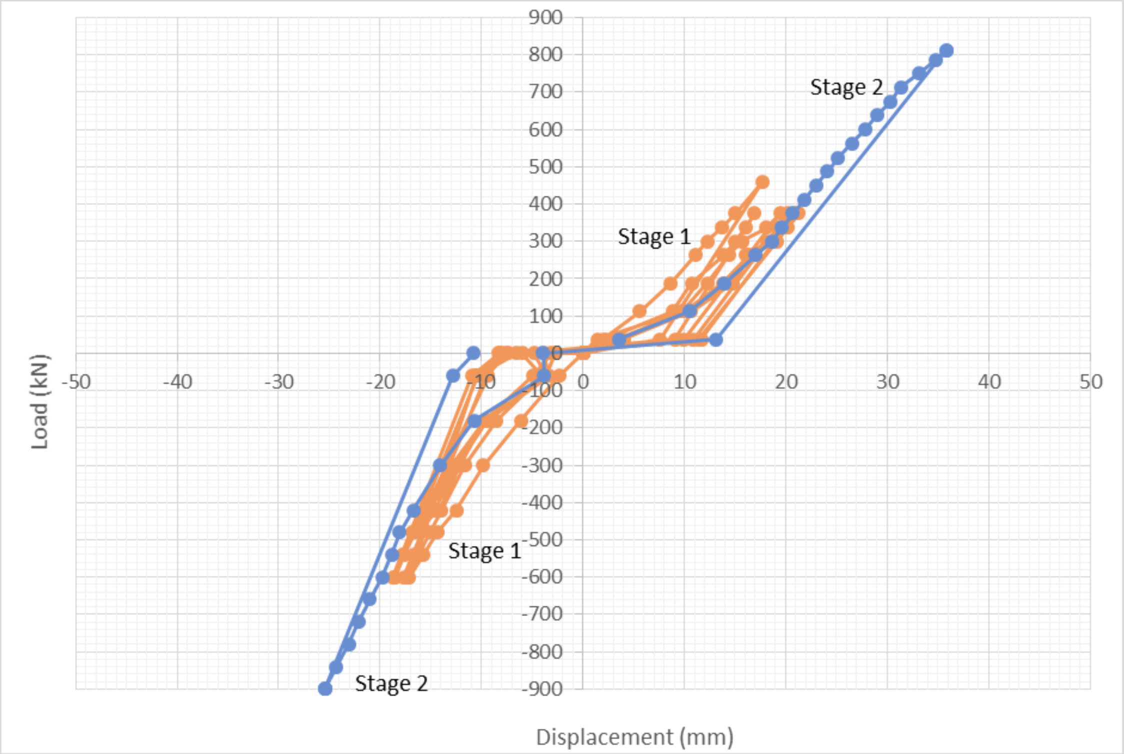

Figure 2: Reverse cyclic proof testing

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The production pile was required to resist reverse cyclic loading of 400kN in tension and 600kN in compression. The design comprised an 8m free length, 16m bond length and 220mm diameter in dense alluvium. For the tension design only the top 10m of bond was considered so as to limit strain and associated bond degradation (refer section 2.3 of this paper). The stages of the proof test are numbered in Figure 2 and comprised:

- Stage 1: 6 cycles reverse cyclic loading to the ULS load in tension and the ULS load in compression. This loading was sustained while meeting the creep criteria of <0.5mm creep/15min. Permanent displacement of 10mm accumulated.
- Stage 2: The load was incrementally increased in tension and then in compression to the limits of the loading reaction system, i.e. 800kN in tension and 900kN in compression. These loads were resisted without creep.

This second cyclic test indicated that the pile met the performance requirements. The results provide some support to the design approach, i.e. of the reduction factors of 0.7 and 0.7. Further testing would be required to verify the design approach.

2.3 Bond length and strain degradation of bond

(BS-8081, 2015) and other guidance documents recommend that bond length to resist tension loads be no more than 10m. This is because for longer bond lengths the stretch of the steel centre bar on loading can be relatively large and consequently the outer grout to country bond over the upper portions of the micropile experience large strains. These large strains of the grout to country bond can result in the bond reducing to a residual, i.e. the bond starts to “unzip”. To mitigate this effect the following is suggested:

- Limit bond length in tension to 10m maximum
- Construct test micropiles as long as is practical so that they are representative of the production micropiles. The limit of test jack capacity often limits the length of test microplie constructed.
- In interpretation of test micropile results compare the strains (elongation of bar along bond length) developed during testing with the strains that could be experienced by the production micropiles under design loads. If the production micropile strain is significantly larger some reduction in the assumed bond may be required.
- If the test micropile is short compared to the production micropile in extrapolating the capacity from the test to the production micropile consider assuming a residual grout to country bond over the additional length of the production micropile compared to the test micropile. This residual value can be established by re-testing the test micropile after displacing it say 50mm.

In compression loading the structural element of the combination of the grout and the steel bar will be relatively stiff and thus strain degradation of bond is not such a big issue, but excessive bond lengths should not be used.

2.4 Ground conditions and drill method

Ground conditions, drilling method and workmanship are all likely to influence the grout to country bond achieved for a micropile. The authors discussed drill methods used with contractors, and reviewed available test data for micropiles constructed in Wellington alluvium. The objective was to identify a relationship between drill methods and capacities achieved. The alluvium typically comprises dense sand with occasional beds of stiff silt. Test data was available from (Christie, 2015), (Wightman, 2017) and Tonkin & Taylor Ltd files and is summarised in Figure 3. Drilling methods used include rotary grout injection, rotary water wash, auger and percussion air flush.

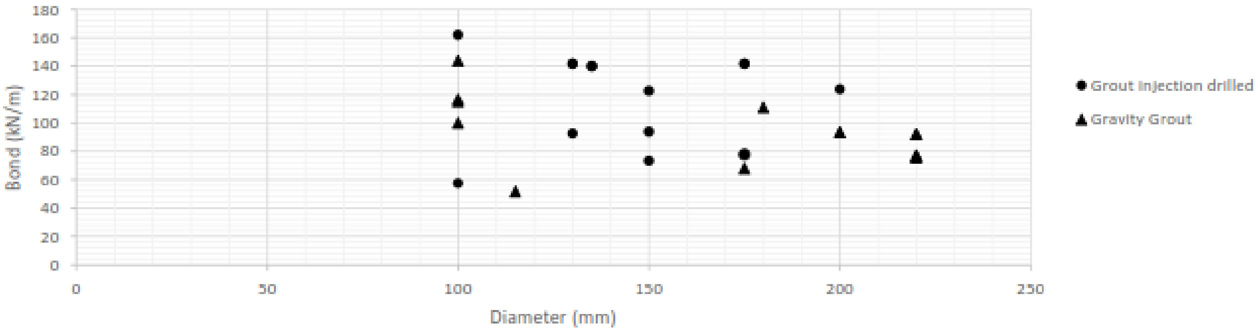

Figure 3: Micropile test results testing in Wellington alluvium

From the discussion with contractors and review of the data the following was concluded:

- The data did not indicate any consistent relationship between drill method and capacity achieved.
- Details of how one drill method was applied by one contractor varied from that by another. For example, in one application of grout injection drilling the contractor's objective may be to minimise grout consumption and maximise drill length production, while another's objective may be to maximise grout to country bond with associated larger volumes of grout being injected. All grout injection drilled anchors are not alike. It depends on the details of the work methods applied. The same is likely to apply for other drill methods.
- Individual contractors have their own preferred methods of drilling.

Noting the above the following is recommended when specifying micropiles:

- Allow the contractor to select the drill method.
- Require the contractor to construct a test micropile(s) using the same drilling and grouting details as they propose for all production micropiles. Test the micropile(s) to failure to determine the grout to country bond to be applied in design of the production micropiles.

To allow for variability of ground conditions the following is suggested:

- Construct the test micropile(s) alongside a borehole so that the ground conditions along the tested bond length are known.
- Select a location and depth range for the test bond length which is generally unfavourable compared to the ground conditions encountered at other locations and depths across the site within the founding layer, i.e. the objective is to determine a moderately conservative value of the grout to country bond with respect to ground conditions.

2.5 Test micropile details

It is crucial in the interpretation of micropile tests to know actual bond length tested. If not detailed and constructed with care what is assumed to be free length can actually be providing additional grout to country bond and additional resistance. The test micropile detail presented in Figure 4 is proposed to provide confidence in the tested bond length. This detail can be used for either a gravity grouted micropile or one grout injection drilled. Stage 1 is to drill a hole to the top of the proposed bond length, install a PVC casing in that hole and a plug of grout in the base. Stage 2 is constructed once the plug of grout has set. The test micropile is constructed by drilling and grouting through the Stage 1 PVC tube.

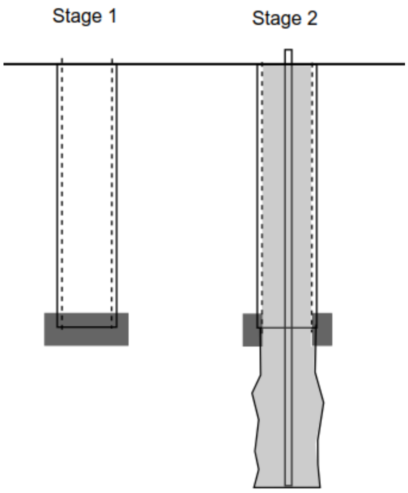

Figure 4: Test micropile detail

2.6 Strength reduction factors and load testing regime

It is common for the design of seismic strengthening to be based on load combinations with overstrength factors (capacity design). AS2159; Piling Design and Installation, provides a risk based method for selection of strength reduction factor (SRF) for ULS design. Clause B1/VM4 of the New Zealand Building Code allows higher SRF to be considered for load combinations including overstrength factors. (Palmer 2013) cautions against use of these higher SRF and provides some guidance.

For ULS design and load combinations including overstrength factors it is suggested that:

- The ultimate geotechnical strength be determined by static load testing prototype micropiles to failure in accordance with AS2159, and reducing the static load test value to allow for reverse cyclic loading, longer bond lengths and other effects discussed in this paper.
- The design ultimate geotechnical resistance be determined by reducing the ultimate geotechnical strength by a SRF as determined by AS2159, but not greater than 0.7.
- All production micropiles be verification static load tested in accordance with AS2159 to not less than 110% of the ULS load.
- A micropile could be expected to fail with extreme loading in a non-ductile manner, i.e. peak resistance drop off to a residual. The above rigorous testing regime and limited value of the SRF is proposed to reduce the likelihood of this undesirable failure scenario.

3 CONCLUSION

Design of micropiles to resist building seismic loads needs to consider the issues listed below. Possible mitigation of these issues is also described:

- Adding micropiles to a building on shallow foundations may improve life safety in a large seismic event, but this could be at the cost of increased differential settlement damage under serviceability or smaller more frequent seismic events. If the micropiles are stiff relative to the shallow foundations they may attract unintended high loads. These factors need to be considered and allowed for in selecting and designing micropiles to support seismic strengthening.

- Seismic loading is likely to apply cycles of compression and tension loading to the micropiles. This reverse cyclic loading may be damaging to the available grout to country bond. It is proposed that design load application be limited to avoid large strains and mitigate this effect.
- Long bond lengths can be subject to large strains under tension loading, resulting in bond degradation. To mitigate this bond lengths in tension should be limited to 10m maximum and design load application limited to avoid excessive strain.
- Drilling method used and workmanship can effect grout to country bond achieved. Design should be based on tested anchors constructed by the same drill and grouting method as the production micropiles.
- To make allowance for variability in ground conditions the test micropiles on which design is to be based should have a bond length spanning relatively unfavourable ground. This requires a borehole alongside the test micropile(s) and sufficient investigations across the site to inform the variability of ground conditions.
- Test micropiles must be detailed and their construction monitored so that their bond length is known with confidence.
- A micropile could be expected to fail with extreme loading in a non-ductile manner. A rigorous testing regime and limited value of the strength reduction factor (SRF) is proposed to reduce the likelihood of this undesirable failure scenario. A SRF as determined by AS2159, but not greater than 0.7 is proposed.

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