Building on soft ground: a case study in Tauranga, New Zealand

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ABSTRACT: Tauranga Crossing is a $NZ200m+ retail shopping centre under development in Tauranga, New Zealand. The site comprises highly variable ground conditions, including a 10 to 15m deep cut into a ridge exposing sensitive, fluvially reworked rhyolite volcanic soils; and a low lying area underlain by soft peat and estuarine paleochannel infilled deposits which was raised by 3 to 5m with engineered fill placed in 2006. Since 2006, settlements beneath the filled area of up to approximately 1m have occurred and creep settlements are ongoing.

The complex ground conditions and earthworks history presented geotechnical challenges for the development of shopping centre and parking buildings, due to settlement, liquefaction and cyclic softening of soils during an earthquake. To mitigate these geotechnical hazards, ground improvement was adopted to allow the buildings to be supported on shallow foundations as significant depth and variability of any end bearing layer precluded traditional piling. The ground improvement comprised Rammed Aggregate Piers® (RAP's, a patented technology of Geopier Foundation Company) designed and installed by Golder Associates, with design peer review provided by Aurecon. Critical RAP's beneath heavily loaded building foundations were grouted and this is the first known use of grouted RAP's in New Zealand. Surcharging was also undertaken in parts of the site, but RAP's were required for a two storey shopping mall and a two storey carpark building to accelerate the project programme.

This paper presents a unique site history and engineering ground model, which was subjected to multiple phases of ground investigation and construction staging. The geotechnical pathway for developing the site is discussed, along with design and construction of the RAP's and the results of a full-scale footing load test over an area of grouted RAP's.

1 INTRODUCTION

Tauranga Crossing is a large retail shopping centre under development in Tauranga, New Zealand. The total building footprint area is approximately 45,000m², with a further 20,000m² planned. The development consists of several warehouses, a state of the art cinema and a two-storey shopping mall building with an adjacent multi-level parking building (Figure 1). Ground levels are split into two platforms, which have a height difference of 5m and each with different ground conditions. The site lies in a seismically active area, and includes a range of geotechnical hazards such as liquefaction, soft ground and sensitive volcanic sediments. This paper outlines a unique site history, complex ground conditions, and the pathway to achieving the final solutions to mitigate the geotechnical hazards.

Figure 1: Architects impression of the project.

2 SITE HISTORY AND GROUND CONDITIONS

The site was farmland until earthworks were completed between September 2005 and December 2006, as part of development of the wider region into an industrial subdivision. The earthworks included cuts of up to 20m deep into an elevated terrace on the western portion of the site and fills up to 5m thick across a low-lying area situated in the eastern portion of the site (Figure 2).

The earthworks divided the site into two flat platforms separated by a 5m high batter extending approximately north-south between the historic terrace and low-lying areas. Following earthworks, the site ground conditions on the upper platform comprised 6 to 10m of volcanic ash and fluvial volcanic sediments (silts and sands), underlain by a 2m thick overconsolidated peat layer inferred to be >300 ka in age. This peat is underlain by more fluvial volcanics, and unwelded ignimbrite (dense sand) at depth.

On the lower platform, fine grained ash fill 3 to 5m thick is directly underlain by a 1 to 2m thick layer of Holocene age peat, fluvial volcanic sediments and a paleochannel infilled with soft estuarine deposits (S_u=15-30kPa based on Geonor vane testing) up to 6m thick or thicker (Figure 3). Beneath the estuarine deposits lies older fluvial volcanic sediments which extend below 40m depth (maximum investigation depth) and are variable vertically and laterally, ranging from dense sands to sensitive reworked tephras and a peat layer found at 35m depth. Groundwater deepens from west to east, with hydrostatic levels of approximately 3 to 6m depth on the upper platform, and 0.5 to 2m depth on the lower platform.

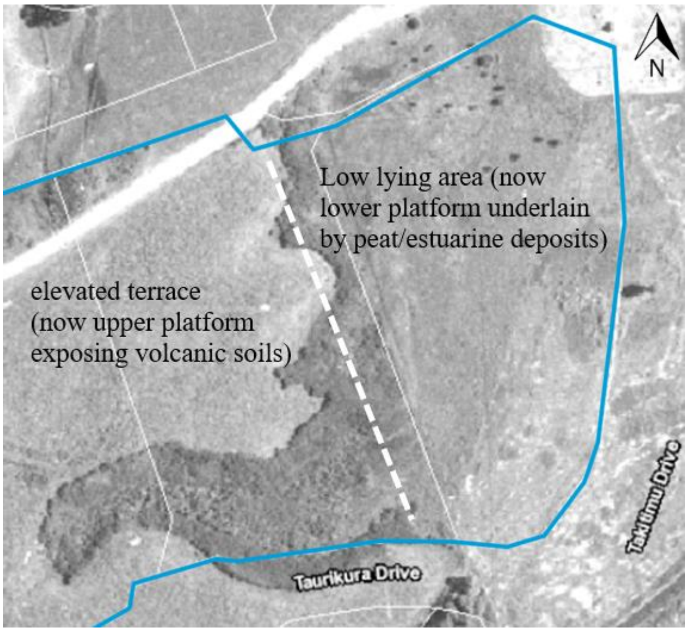

Figure 2: 1940 aerial of the site with property boundary shown by blue line and the current upper and lower platforms delineated approximately by the dashed white line.

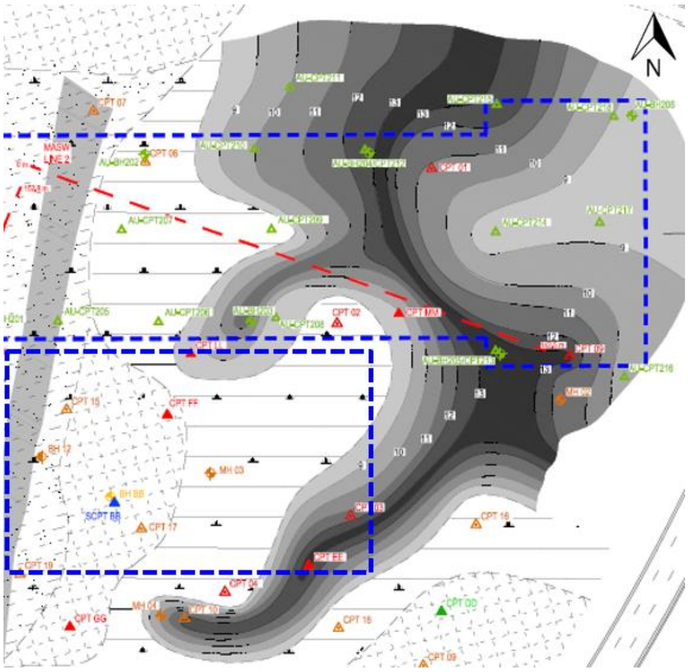

Figure 3: Isopach map derived by Aurecon showing estimated variation in depth of the estuarine infilled paleochannel on the lower platform in grey 1m contour bands. Approximate building footprints shown by dashed blue lines.

Settlement plates were used to monitor settlements induced by placement of fill over the peat and estuarine deposits in the low lying area. Since 2006, settlements of up to approximately 1m were recorded and further creep settlements of up to 100 to 200mm were inferred to occur by 2065 based on a 50 year design life, if left unmitigated (Figure 4).

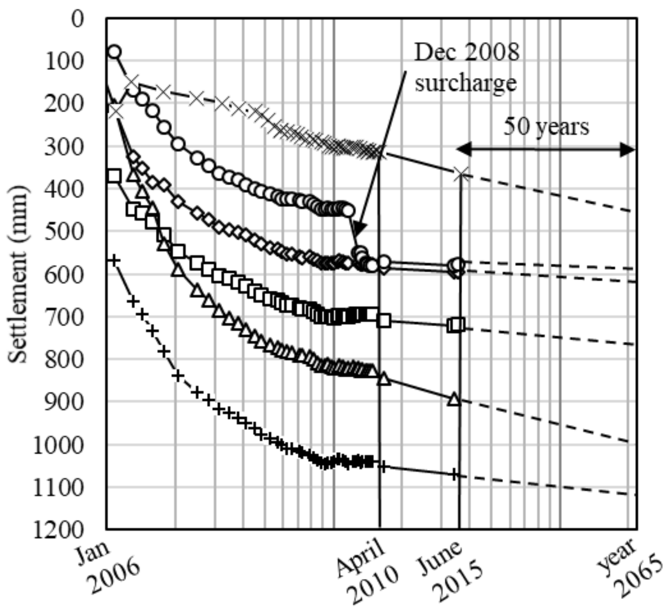

Figure 4: settlement monitoring data of the fill placed over the low lying area of the site (now the lower platform).

The site was sold in 2008 by the original developer who completed the 2005-2006 earthworks. A local consultant was commissioned shortly after by the new owner to undertake geotechnical assessments of the site for a proposed retail centre which was to comprise one to two storey concrete buildings with rooftop parking. Ground investigations comprised Cone Penetration Tests (CPT's), machine cored boreholes, and hand augered boreholes, from which shallow foundations were deemed feasible for the upper platform buildings and piling was recommended for the lower platform buildings, to mitigate settlement. The piling is thought to have been subsequently dismissed due to cost, so an alternative option of surcharging was implemented to allow shallow foundations after surcharge removal.

Two areas of surcharging were undertaken under the supervision of the previous consultant during 2008 and 2009, by placing fill over the ground without installing wick drains. Settlements of 150 to 200mm were induced by a 25 to 35kPa load over a six to eight month period. Following surcharging, 50 year settlement magnitudes were predicted to have been reduced to 120 to 140mm or less. Construction of this previously proposed development never commenced, perhaps due to after effects of the Financial Crisis of 2007-2008, and the site was resold in 2012 to Tauranga Crossing Ltd.

In 2013-2014, eight years after the original site earthworks, another round of geotechnical investigations were initiated by a different consultant. This included a dynamic compaction (weight dropped from a crane) trial that was unsuccessful and achieved no ground improvement, probably because of the fine grained nature of the estuarine deposits and dampening effects of the peat and overlying a stiff crust of engineered ash fill.

The geotechnical consultant role was handed over to Aurecon in 2015 and due to further modification of the proposed building location, further ground investigations commenced. This included machine cored boreholes with Geonor vane testing, CPT's, multi-channel analysis of surface waves (MASW) and oedometer testing of the peat/estuarine deposits. The total number of combined ground investigations to date is approximately 110 CPT's, 19 machine cored boreholes, 750m of MASW, and numerous hand augered boreholes and Scala penetrometers.

The current Tauranga Crossing retail development comprises single storey retail and warehouse buildings on the upper platform, and a two storey shopping centre with an adjacent two storey parking building on the lower platform as shown previously in Figure 1. The development is split into three stages; Stage 1 on the upper platform which was constructed in 2015-2016 and opened in 2016, Stage 2 which spans the upper and lower platforms and is currently under construction and scheduled to open in April 2019, and a future Stage 3 which will extend the parking and retail buildings on the lower platform to maximise use of the property area.

3 GEOTECHNICAL DESIGN PROCESS

3.1 *Upper platform*

The upper platform buildings were able to be supported by shallow foundations with an earthquake life safety based design rather than low damage or damage avoidance. The key geotechnical considerations were liquefaction potential and bearing capacity of sensitive fine grained volcanic soils. Liquefaction induced settlement was predicted to be 100 to 200mm in the ultimate design level earthquake, and relatively low shallow foundation ultimate bearing capacities of 100 to 200kPa were adopted (governed by punching failure in the seismic case). Much care was required when digging the foundations, to minimise disturbance to the fine grained volcanic soils which had a tendency to become 'spongy' and liberate water when trafficked by machinery. These characteristics are thought to be caused by halloysite dominated clay mineralogy, and overconsolidation (some of the founding soils had been exposed by cuts of up to 15m).

3.2 *Lower platform*

Liquefaction and cyclic softening induced settlements following the design level earthquake were estimated to be in the order of 200mm. However, the thickness of non-liquefiable crust provided by the original site filling was considered able to support a shallow foundation system.

The building footprints extended outside the previous 2008-2009 surcharge zones so settlement was a key hazard. A settlement model of the lower platform area integrating the estuarine paleochannel and peat extents was developed using Settle3D and soil compressibility parameters based on back analysis of historical settlement data and the ground investigation data. Primary consolidation of 100 to 200mm and 50 to 100mm of creep over a 50 year period was predicted, indicating total settlements of 150 to 300mm which was not tolerable for the proposed buildings. This confirmed that some form of settlement mitigation would be required.

Piling to mitigate settlement was not recommended due to the significant depth and lateral variability of end bearing layers to pile into, and the expected significant cost of construction. Instead, surcharging was adopted for which filling began late in 2015. The surcharge was 50 to 60kPa without wick drains and induced settlements of 250 to 400mm over 12 months. However, the surcharging exercise was never completed because part of the building had not yet been surcharged as it was awaiting fill material, the building footprints shifted several times to extend outside the surcharge area, and then ultimately the project programme was accelerated to a point that precluded further surcharging options. At this time alternative settlement mitigation methods were explored, and ground improvement was considered to be the most practical, cost and time efficient option for the lower platform.

The purpose of installing ground improvement was to mitigate consolidation and creep settlement and it also had the added benefit of reducing seismic effects such as liquefaction, cyclic softening and ground damage. Differential settlement risk due to variable ground conditions was critical to mitigate (e.g. if the buildings were entirely underlain by peat and estuarine deposits, the foundation behaviour might be more uniform). Installing ground improvement adds resistance against soil compressibility and seismic effects across the proposed building footprints, and also facilitates staged building construction.

Several ground improvement options were assessed at the preliminary design stage; deep soil mixed columns, driven timber poles, Rammed Aggregate Piers® and stone columns. RAP's are a patented technology of Geopier Foundation Company and are similar to stone columns, with the key difference being that the RAP's are built using downward pressure on the mandril that stone flows down, rather than a vibrating probe (Figures 5 and 6).

Preliminary ground improvement designs for cost estimation and programming purposes were undertaken using the software packages PLAXIS 2D and Settle3D. RAP's or stone columns were found to be the most efficient solution, with an estimated cost of approximately $NZ7M for the 16,000m² of building area requiring ground improvement. Timber poles and deep soil mixing came in around 30% more expensive, and the timber pole option was also likely to have a much longer installation programme.

A performance based specification for the RAP/stone column ground improvement was developed with input from Tauranga Crossing and the project structural engineer, and released for tender. Three tender submissions were received, two for stone columns and one for RAP's, with the RAP tender being successful. The RAP tenderer was Golder Associates, who were engaged on a design-build contract with Aurecon undertaking design peer review and also construction observations. The specified ground improvement performance criteria are shown in Table 1.

3.2.1 *Shopping centre building*

The foundation systems for both the shopping centre and parking buildings comprised shallow pads tied together with strips and ground beams. Working loads acting on the shopping centre building pads ranged between 500 to 900kN, with pad sizes of 2.5 to 3.5m. Strips are generally 0.5 to 3m wide, and the ground level is covered by an on-grade floor slab.

Table 1. Ground improvement performance criteria

Parameter	Design value
Design life	50 years
Shallow foundation bearing capacity	400kPa geotechnical ultimate rupture bearing capacity
Long term (50 year) settlement (e.g. primary + creep with consideration of immediate)	Differential settlements no greater than 25mm over 6m (angular distortions of <=1/240)
	Total settlement no greater than 50mm
Serviceability level earthquake liquefaction/cyclic softening mitigation	Differential settlements no greater than 25mm over 6m (angular distortions of <=1/240)
Ultimate level earthquake liquefaction/cyclic softening mitigation	Differential settlements no greater than 100mm over 6m (angular distortions of <=1/60)

Figure 5: RAP installation rig at Tauranga Crossing.

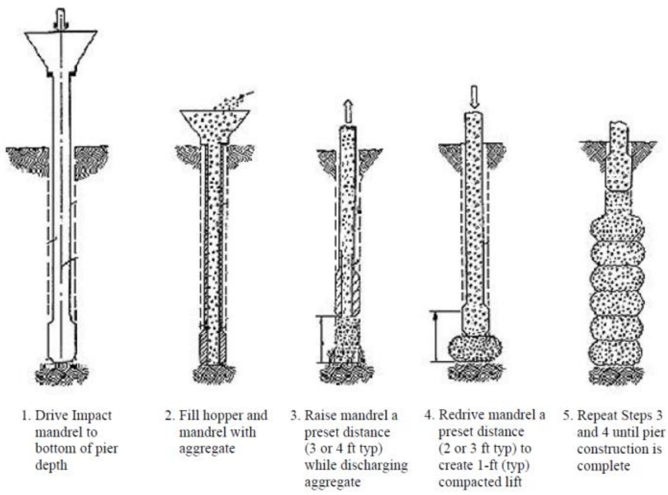

Figure 6: Stone column installation process (Geopier 2017)

Golder's design solution for the shopping centre building incorporated between three and five RAP's under every pad footing with a regular grid of RAP's beneath the on-grade floor slab. RAP lengths ranged between 6 and 11m, depending on the thickness of the soil layers requiring improvement. The RAP's underlying footings on the eastern side of the shopping centre building were grouted because they penetrated peat which may have provided limited confinement to the RAP's and hence reduce their effectiveness. Approximately 2450 RAP's in total were installed for the shopping centre building.

3.2.2 *Parking building*

The parking building pad footings were up to 3m x 4m in size with working loads up to 2800kN. The design for the carpark building comprised between nine and twelve RAP's beneath each footing, ranging in length from 10 to 17m. All carpark building RAP's were grouted. RAP's were not designed between footings, due to the ground level carpark surface comprising a flexible asphalt pavement which can accommodate some settlement. Approximately 420 RAP's were installed in total for the parking building.

3.2.3 *RAP design methods and philosophy*

The adopted RAP design methods were as follows:

- Composite soil-RAP parameters based on Priebe (1995) for bearing capacity assessment, and in-house Geopier Foundation Company methods.
- Settlement mitigation design based on both composite modulus (theoretical) and measured stiffness (load-deflection test and empirical) approaches. Settlements were estimated using 1D and equivalent raft spreadsheets and the software's Settle3D, RS2, RS3 (also used for bearing capacity assessment) and PLAXIS 3D. Mitigation of creep settlement in the non-grouted RAP areas beneath the shopping centre floor slab was assessed by back calculating soil parameters from the previous fill and surcharge settlement data, then predicting creep magnitudes in the improved ground using the Soft Soil Creep constitutive model in PLAXIS 3D. Efficiencies were also made in the areas that had been subject to previous preloading where soils had undergone strength and stiffness gain through consolidation.
- Liquefaction mitigation using an experience based approach from RAP-soil densification testing in Christchurch (Vautherin et. al. 2015)

3.2.4 *RAP construction and testing*

The RAP installation commenced in August 2017 and was completed in February 2018. The RAP construction quality assurance testing comprised crowd testing (downward pressure applied by the RAP installation rig to check displacement), plate load testing of RAP heads, modulus testing of RAP heads (similar to a plate load test with measurement of RAP toe deflection), grout testing (strength, quality, flowability), aggregate testing (crushing, grading, weathering) and coring through a grouted RAP to check its integrity and stiffness (Figure 7). Unconfined compressive strength (UCS) testing of three grouted RAP cores with strain measurement indicated a Young's modulus of 5 GPa for the grouted RAP's. RAP installation records included installation dates and duration, aggregate volumes, design depth and spoil volumes.

Figure 7: Grouted RAP core samples.

A full-scale load test was specified by Aurecon to validate the RAP design philosophy in respect of settlement mitigation and to confirm the load-settlement behaviour. The test was conducted at an actual footing location with plan dimensions of 3.5 m x 3.5m supported by five grouted RAP's, each 10 m long (note the upper 2m of each RAP was designed to be non-grouted). The ground conditions at the test location had not been subject to previous surcharging, and included 3m of fill, 3m of peat, and 4m of estuarine deposits. A CPT trace at the test location is shown in Figure 8.

The load test footing was excavated to the true design depth and dimensions, followed by an inspection of the subgrade by an Aurecon engineer. A 200mm thick, 3.5 m x 3.5 m reinforced concrete slab was constructed at the approximate design subgrade level. Four concrete blocks (crane weights) weighing approximately 25 tonne each were placed on the slab, providing a test load of 1000kN (82kPa) (Figure 9). The serviceability design load on the tested footing was 900kN (74kPa), so the test load exceeded the design load by roughly 10%.

A baseline level was taken on each side of the slab (four points) prior to placement of the concrete blocks. Settlement was then monitored regularly over 11 days and construction activities were restricted within approximately 10 m of the load test during the monitoring period. The time-settlement data is shown in Figure 10. The load test monitoring data showed approximately 6 to 8mm of 'bedding in' immediately following application of load, then a further 4 to 5mm of settlement over the 11 day period. Based on the logarithmic time-settlement chart, the total settlement could potentially reach 17 to 21mm over the next 50 years considering ongoing consolidation and creep effects. The entire cost of the load test including settlement monitoring was approximately $NZ16,000.

The design-estimated settlement for the footing that underwent the load test was 35mm. This estimation was made using a three-layered analysis; settlement of the upper 2m (non-grouted RAP length) based on the stiffness measured by a nearby modulus test, settlement of the grouted length of RAP's based on soil-RAP composite stiffness parameters from Geopier experience, and settlement below the RAPs using traditional 1D linear settlement theory. The estimated settlements were 4mm (upper 2m), 4mm (grouted RAP's length) and 27mm (below RAP's), for a total of 35mm. In comparison with the results of the footing load test, one could infer that the settlement was well estimated through the RAP improved depth and overestimated for the soil below the RAP's. This overestimation is most likely due to the underlying soil being less compressible than expected. No other types of settlement analysis are available for comparison (e.g. PLAXIS) as they were not undertaken for the tested footing.

4 CONCLUSIONS

A thorough understanding of the site ground conditions has been fundamental to inform solutions to progress the Tauranga Crossing shopping centre development. Much value was gained from compiling historical site information such as earthworks induced settlement data and surcharging exercises undertaken by previous site owners.

The use of RAP's proved to be a successful ground improvement technique for the site, in variable ground conditions including peat, soft estuarine deposits and fluvially reworked volcanic sediments. This is the first known occurrence of grouting RAP's beneath building foundations in New Zealand. It is important to be critical when undertaking this type of ground improvement design, and validate the design parameters and philosophy through quality assurance testing.

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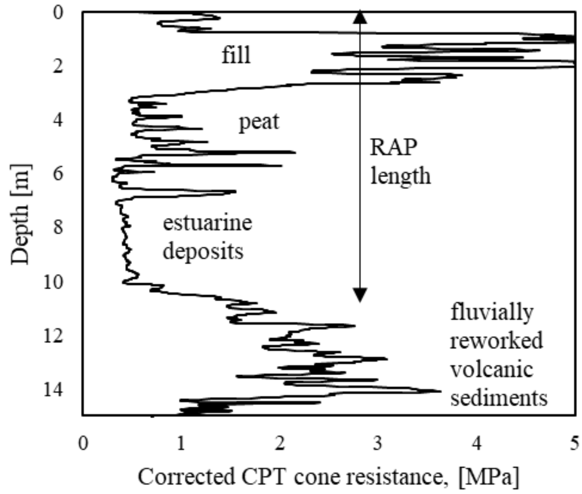

Figure 8: CPT trace at the footing load test

Figure 9: Footing load test

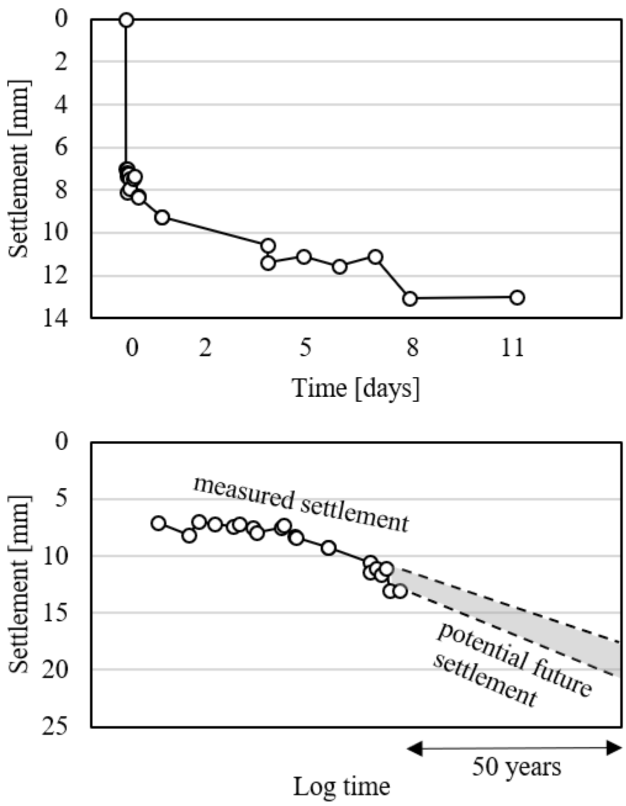

Figure 10: Settlement monitoring data of the footing load test.