AN EXPERIMENTAL STUDY OF FOUNDATION UNDERPINNING BY PILES

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Abstract Existing buildings sometimes experience excessive settlement under their design loads or face the prospect of excessive settlement in the future if a change of building use is required and increased foundation loadings will occur. Several methods of foundation enhancement are available to arrest settlements or improve the future performance of existing foundations including the method of underpinning by piles. To investigate further the behavior of underpinning piles, which are installed beneath a settling foundation, two series of controlled model underpinning tests have been carried out in normally consolidated clay with different loading levels and different pile lengths. In this paper, the test procedure is described, and results of the two different test series are presented. Some comparisons are also made between the observed behavior and predicted from numerical finite element analyses and these are discussed briefly.

Key Words Underpinning, Foundation, Pile, Model Test, Settlement

چکیده ساختمانهای موجود گاه با نشستهای فزاینده روبرو گردیده یا چنانچه تغییر کاربرد ساختمان مورد نظر باشد و بالنتیجه بارهای وارد بر آن افزایش یابد، پی ساختمان با نشست روز افزون روبرو خواهد شد. روشهای متعددی برای بهبود و تقویت پی ساختمانهای موجود از جمله روش پی بندی بوسیله شمع در دسترس می باشد. برای بررسی رفتار شمعهای تقویتی که در زیر پی در حال نشست نصب می‌شود، دو دسته آزمایش پی بندی در خاک رس تحکیم عادی یافته در دو حالت بار گذاری و شمع با طولهای مختلف انجام شد. در این مقاله روش انجام آزمایش تشریح و سپس نتایج آزمایشها ارائه گردیده است. همچنین بین نتایج حاصله در آزمایشها با پیش‌بینی عددی مساله مقایسه بعمل آمده و بحث شده است.

INTRODUCTION

Existing buildings sometimes experience excessive settlement under their design loads or face the prospect of excessive settlement in the future if a change of building use is required and increased foundation loadings will occur. Several methods of foundation enhancement are available to arrest settlements or improve the future performance of existing foundations.

The method of underpinning by piles is widely used, but despite the long-standing use of this method, approaches to the design of piles for underpinning are not well developed. Moreover, there appears to be an incomplete understanding of the way in which loads are transferred from an existing foundation to an upgraded foundation. In previous papers [1-5] a numerical study of underpinning or upgrading of foundations by piles has been presented. In order to study the problem of underpinning experimentally, a laboratory apparatus has been designed and manufactured. In order to compare the results of those underpinning and upgrading tests with behavior of a footing without underpinning piles, some model footing tests have also been carried out. In this paper, the test procedure and the various test stages in the model underpinning tests are described briefly. The results of model underpinning tests are then presented and compared with the results of a finite element numerical analysis. The results of upgrading tests, when an extra load is added to the existing footing load, have already been published in another paper [9].

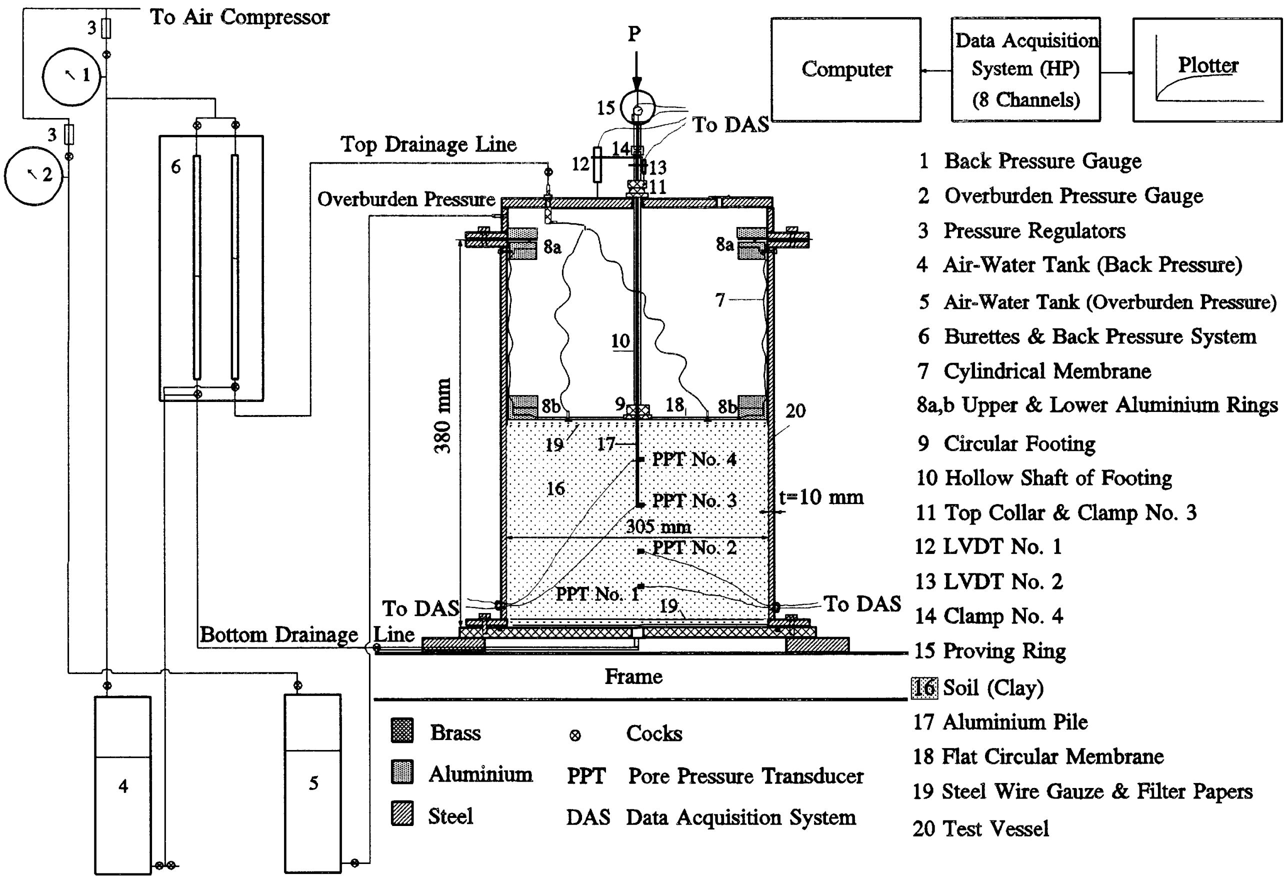

Figure 1. Apparatus set-up for underpinning and upgrading tests.

TEST PROCEDURE

Test Set-Up The laboratory apparatus is shown diagrammatically in Figure 1. Makarchian [5-6] gives details of the model footing tests and the procedure for test set-up. The soil used for tests was a kaolin clay (denoted as C1C kaolin), which was selected because of its relatively slow rate of consolidation, and its relatively high plasticity index (LL=74, PL=32, and PI=42). In order to obtain the deformation and strength properties of the C1C soil (E_u, s_u, ϕ', ν', E', c') for use in numerical simulations so as to compare the experimental and numerical results, a number of triaxial tests were carried out. For the model underpinning tests, the soil was consolidated under K_0 conditions (no lateral strain), so that for an appropriate simulation of the actual tests, this condition was also used for the triaxial tests. A special method of K_0 consolidation test was employed by using a type of fluid pump apparatus (so called digital pressure/volume controllers, DPVC, or GDS). The basic concept of this method is to maintain the ratio of the volume change rate to the axial strain rate (both rates with respect to time) equal to the cross-sectional area of the sample with aid of a computer linked to the triaxial apparatus and the GDS. Details of the method of testing, its procedure and results have been presented by Makarchian [5]. Table 1 presents a summary of the relevant average deformation and strength soil parameters obtained from the triaxial tests.

The required water was added to the consolidated clay from the previous test in a galvanized steel bin to bring the moisture content of the soil up to approximately 80% and left soaking for two hours. An electronic low speed power drill fitted with a propeller was used to mix the clay mechanically and to form a uniform clay mixture

TABLE 1. Summary of Results of Triaxial Undrained and Drained Tests after K_0 Consolidation.

K_0	$\nu'^{(1)}$	c_u (s_u) (kPa)	$E_u^{(2)}$ (kPa)	c' (kPa)	$\phi'^{(3)}$ (°)	$\phi'^{(4)}$ (°)	$\nu'^{(5)}$	$E'^{(6)}$ (kPa)	s_u/σ_v'
0.57	0.36	46	17700	6.8	19.4	21.5	0.24	1150	0.23

(1) During K_0 Consolidation (3) if $c' \neq 0$ (5) During Drained Tests
(2) at 50% failure (E_{50}) (4) if $c' = 0$ (6) at 1/3 failure ($E_{1/3}$)
ν' and E' are evaluated according to Poulos [7].

(i.e. a loose mud). Usually two moisture content samples were taken from the mixture and the bin was sealed with its lid and left over for 24 hours. Then the required water was added to the clay and again mixed until a moisture content of 85% was achieved.

For soil placement in the test vessel, all drainage lines were first filled with water. Then, two moist filter papers and coarse wire gauze in between them were placed on the base plate of the test vessel, and fishing lines for holding the pore pressure transducers were attached to the internal wall of the vessel at different vertical positions. The clay was then poured into the test vessel and leveled with a rubber spatula. The clay was poured in several stages, and efforts were made to minimize entrapped air until the vessel was filled to the required height. Three moisture content samples were taken from the bottom, middle, and top of the soil during soil placement.

A special cylindrical membrane system was designed and manufactured which could move down as the soil surface was settling due to consolidation. At the beginning of a test, a small overburden pressure (about 10-20 kPa) was applied to expel out the air from the top section of the vessel and around the cylindrical membrane until water bled from the screw at the top of the lid. Then that screw was tightened, and the overburden and backpressures were set to 300 and 100 kPa while all cocks were closed. The cocks were then opened simultaneously and overburden pressure applied to the soil surface. Miniature pore pressure transducers (Druck PDCR 81) were used at different vertical positions (usually on the center line of the vessel) to measure the total pore water pressure within the saturated soil mass during consolidation, footing tests, underpinning, and upgrading tests (Figure 1). The locations of pore pressure transducers were investigated during removal of the soil at the end of each test, and typical locations are shown in Table 2. The pore pressure transducers were not embedded at a fixed location, and they were allowed to settle as the soil was consolidating. The Data Acquisition System except the volume of expelled water, which was manually recorded, recorded the data. The initial consolidation was continued until the "final" consolidation settlement and total dissipation of excess pore water pressure was achieved. At this stage, a homogeneous normally consolidated soil was ready for the next stages of the test. The duration of this stage of the test usually was about 10 days.

PILE INSTALLATION AND UNDERPINNING TESTS

Makarchian [5-6] has described the model aluminum pile and the pile jacking system. The model pile was made of solid aluminum in 12.7 mm diameter (½") with a 45° conical shape at its tip. The pile was instrumented for axial load by two pairs of strain gauges (No. 3/120LY13 made by HBM) at each side of the pile.

TABLE 2. Location of the Pore Pressure Transducers after Tests.

Test No.	H_f (mm)	L_P (mm)	D_p (PPT1) (mm)	D_p (PPT2) (mm)	D_p (PPT3) (mm)	D_p (PPT4) (mm)
FT1	175.4	-	85 (1)	85	-	-
FT2	177.8	-	62.5	102.5	-	-
FT3	179.6	-	45	80	-	-
PT1	177.6	100	35	65	-	-
PT2	175.1	100	47	80	-	-
PT3	179.0	50	45	80	-	-
PT4	169.0	75	40	75	80	115
FT4	182.6	-	70	-	50 (1)	130
PT5	172.8	125	60	-	70	95
PT6	179.1	75	50	-	75	97
FT5	183.1	-	45	-	85	92.5
PT7	175.4	125	40	-	85	100

H_f = Final height of soil layer after consolidation
L_P = Pile length PPT = Pore Pressure Transducer
D_p = Final distance of pore pressure transducer from the bottom of test vessel
(1) Pore pressure transducers usually were put approximately at the center line of the vessel, except when there is a (1) in which case the pore pressure transducer was put approximately at the half-radius of vessel.

The aluminum pile had a series of six holes that could be used to allow different lengths of the pile to be jacked into the soil (50-125 mm), and after placing the pin at the correct hole; a pile-footing system could be modeled. It should be pointed out that in all underpinning tests, piles with different lengths were installed at the center of the footing while the footing was restrained from any movement during pile installation.

A simple multi-purpose system was developed which consisted of the following components: a pulley system, proving ring, hanger with steel bucket, and lead shot. The mechanism could be used for the following purposes:
1. Downward and upward movement of the vessel lid during set-up and after finishing the test.
2. Jacking the pile with required length into the soil,
3. Loading the footing or pile-footing system.
4. If necessary, lifting the test vessel, for example during mounting the vessel on the frame, or when the aluminum rings stuck to the vessel and soil had to be emptied from the bottom of the vessel.

A pulley system was used to jack the pile into the soil while the footing was restrained from upward and downward movements by a clamp during pile jacking. After pile installation, a monolithic pile-footing system test could be performed.

The length of pile varied from 50 mm to 125 mm, and two different lengths of pile for each test series were examined. Five different model-footing tests were carried out. The purpose of test No. FT1 was to measure the bearing capacity of the model footing (undrained conditions). In test series (I), three tests (FT2, FT3, and FT5) were carried out with a loading of 257 kPa, but tests No. FT2 and FT3 were discarded due to the existence of friction in the hollow shaft of the footing with an O-ring inside the top collar and clamp No. 3 (see Figure 1). In test series (II) test No. FT4 was carried out with a lower level of applied loading (200 kPa).

To examine different lengths of pile for underpinning of the model footing, tests No. PT1 to PT6 were carried out with two levels of loading (test series I and II). To examine the effect of pile installation time t_i, Test No. PT7 was performed.

In the first test (PT1), immediately after pile installation, the load was applied without any delay, and the pile was found to have little effect on settlement reduction. Due to pile installation, the pore water pressure was increased significantly resulting in reduced effective stress, a factor that was not taken into account in the numerical analysis [1-4]. Therefore, in subsequent tests (Test No. PT2 to PT6), the pile was firstly jacked into the soil, and after complete dissipation of the excess pore water pressure, loading was applied to the pile-footing system to represent the pile installation at the commencement of loading. With this procedure, pile installation time at t_i=0 could be achieved conveniently. In fact, excess pore water pressures due to pile installation were found to be several times higher than those due to loading of the footing. Therefore, pile installation reduced the vertical effective stress significantly, so that the pile had no beneficial effect on settlement reduction, and could even in fact increase the settlement, if loading were applied immediately after pile installation.

Due to the high level of excess pore water pressure, detailed testing of the underpinned footing by a pile at different times of pile installation (rather than at t_i=0), was abandoned. For this reason, different pile installation times were not examined, and only in one test (PT7) was a pile installed after loading commenced. In that case, the pile was installed as quickly as possible after loading had been applied on the footing and had reached its maximum value. Then, loading was held constant at its maximum value on the footing. However, again due to the high excess pore water pressure generated by pile installation, the pile had no meaningful effect on settlement reduction (see next section). The excess pore pressures due to loading were also dissipated after one day, but in some tests, data logging was continued for three days during the development of creep settlements.

TEST RESULTS

In order to illustrate the results non-dimensionally, the following dimensionless parameters are defined:

RSR = Ratio of Settlement Reduction
= S_{TFP} (with pile)/ S_{TF} (without pile). (1)

LTR = Load Transfer Ratio=P_P / P_{Tot} at the end of consolidation. (2)

RAP = Ratio of Applied Pressure
= applied foundation pressure/ultimate bearing capacity of the foundation. (3)

in which:

S_{TFP} = total final settlement of the foundation with pile.
S_{TF} = total final settlement of the foundation without Pile.
P_P = pile load.
P_{Tot} = applied load + weight of foundation.

Test Series (I) Figure 2 shows the effect of pile length on settlement reduction of an underpinned circular footing by a pile at the center (Test series I). This figure also shows when the loading was applied to the footing straight after the pile installation without dissipation of the excess pore water pressures; the pile did not reduce the settlement effectively. However, in tests PT2 and PT3, where loading was applied after complete dissipation of the excess pore water pressure, the installation of the pile led to significant settlement reduction.

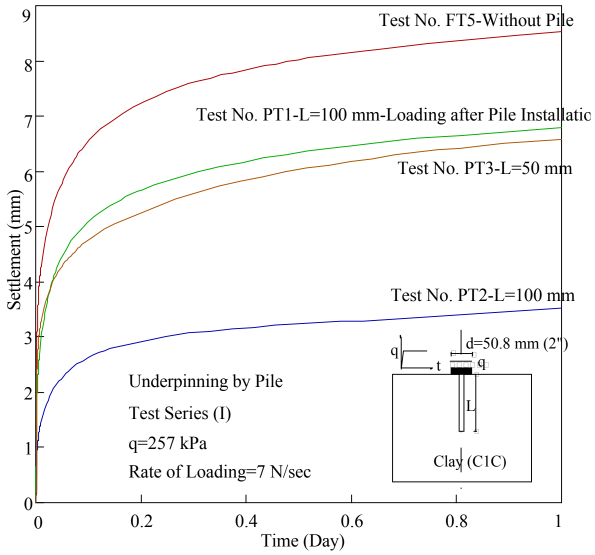

Figure 2. Effect of pile length on settlement reduction and effect of loading applied directly after pile installation.

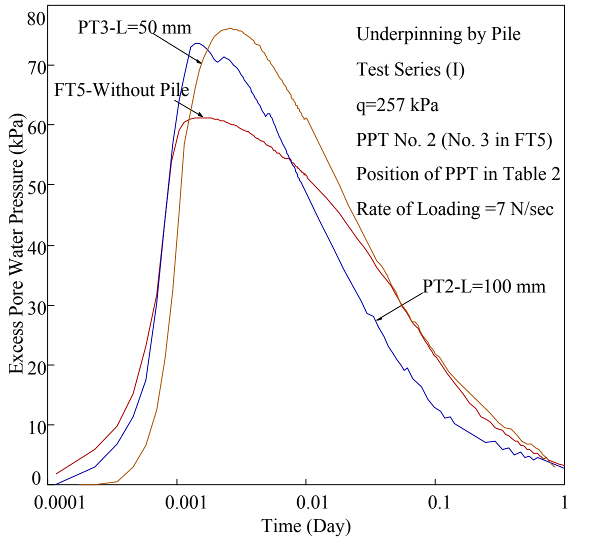

Figure 4. Time-excess pore water pressure behavior of footing and pile footing with different pile lengths.

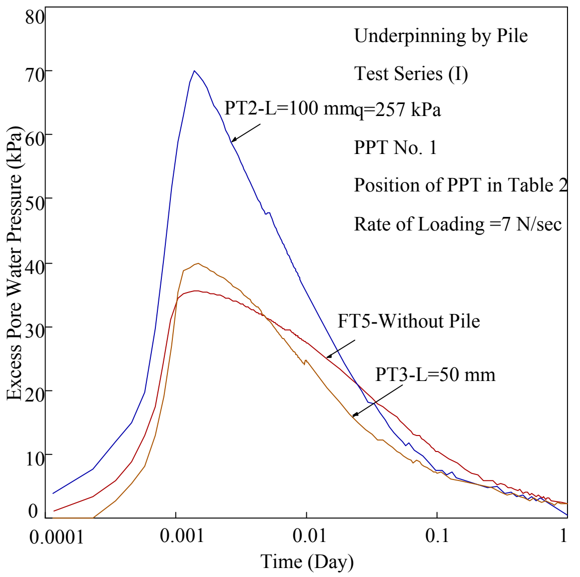

Figure 3. Time-excess pore water pressure behavior of footing and pile footing with different pile lengths.

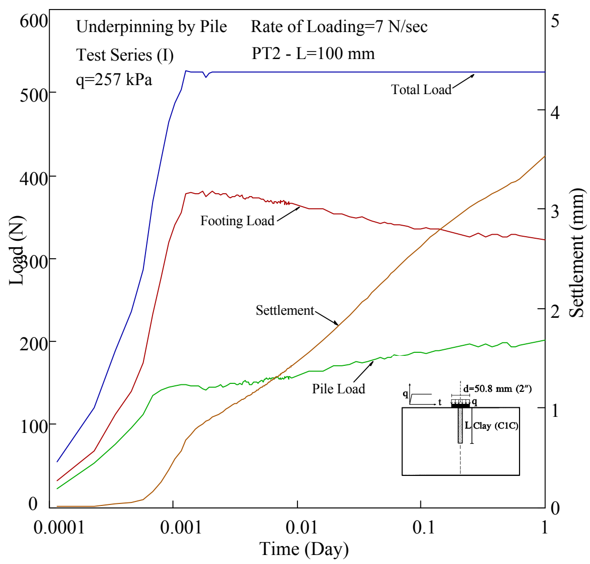

Figure 5. Load transfer to the pile during loading on the footing and with progress of the consolidation settlement.

Figures 3 and 4 show the time-excess pore water pressure behavior below the footing and the pile footing with different pile lengths. Figures 5 and 6 show how load was transferred to the pile during application of the loading on the foundation. With the progress of consolidation settlement, the load transferred to the pile increased gradually. In these tests a very small pile was used (D_p = 12.7 mm = ½") with a limited bearing capacity. During dissipation of the excess pore water pressures that were developed by pile installation, part of the pile bearing capacity was mobilized.

In the underpinning test, the pile reached its full capacity and no more load could be carried. Use of

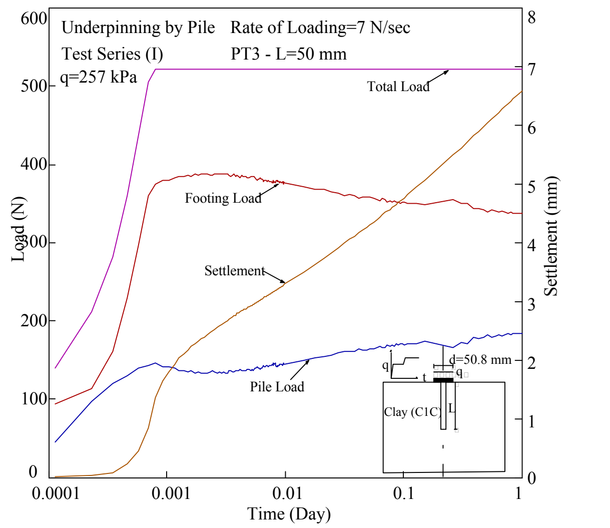

Figure 6. Load transfer to the pile during loading on the footing and with progress of the consolidation settlement.

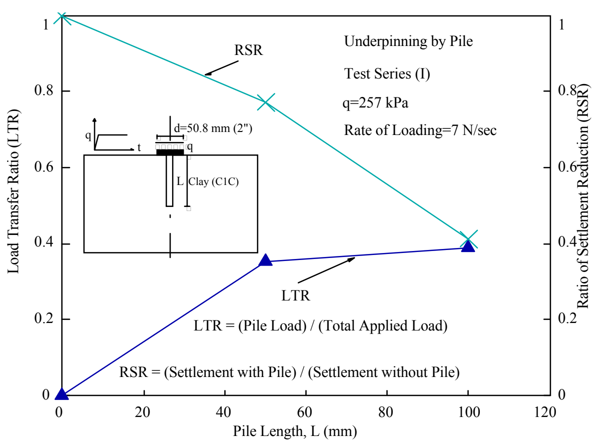

Figure 7. Effect of pile length on settlement reduction of the footing and load transfer to the pile.

a higher capacity pile might have led to more loads being transferred to the pile, and to a greater reduction in settlement. The value of load transferred to the pile may have been slightly more than the values shown in Figures 5 and 6, because of the friction between the O-ring inside the footing and the aluminum pile. The amount of this friction in dry conditions was measured to be 40 N, but in the presence of water and clay in a long-term test, it could have been less.

Figure 7 summarizes the test series (I) and plots the Ratio of Settlement Reduction RSR and Load Transfer Ratio LTR versus pile length L. This

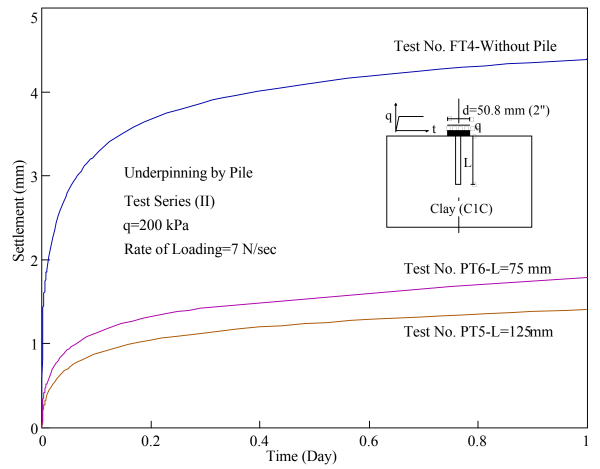

Figure 8. Effect of pile length on settlement reduction of the footing.

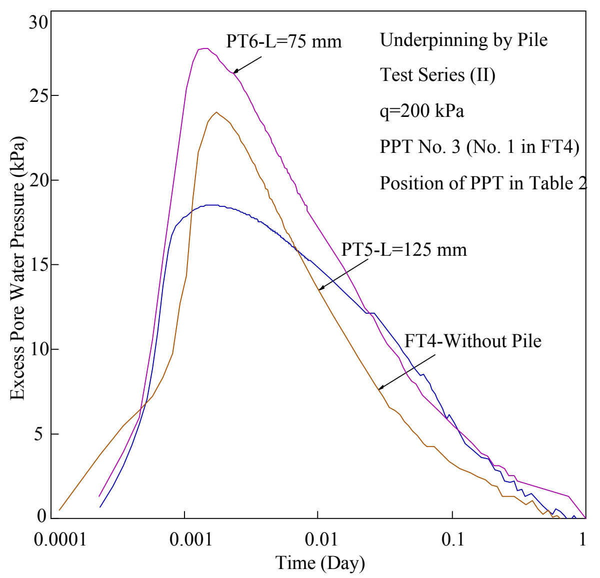

Figure 9. Time-excess pore water pressure behavior of footing and pile footing with different pile lengths.

figure reveals that a significant settlement reduction can be achieved using a relatively small diameter pile with a short length.

Test Series (II) In test series (II), two different pile lengths with the same diameter of pile and footing were also examined under a lower level of applied loading. Figures 8 to 11 show the time-settlement, time-excess pore water pressure, and time-load behavior of the pile footing for these

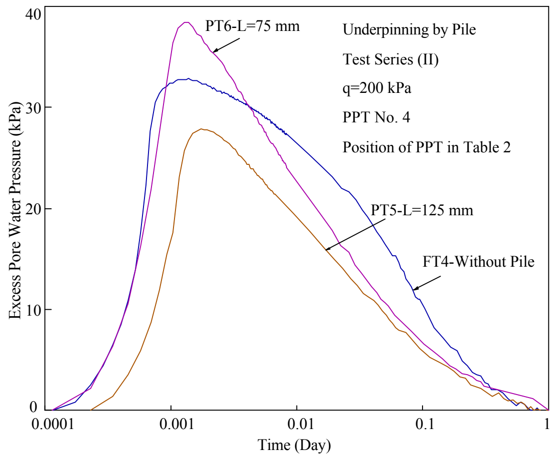

Figure 10. Time-excess pore water pressure behavior of footing and pile footing with different pile lengths.

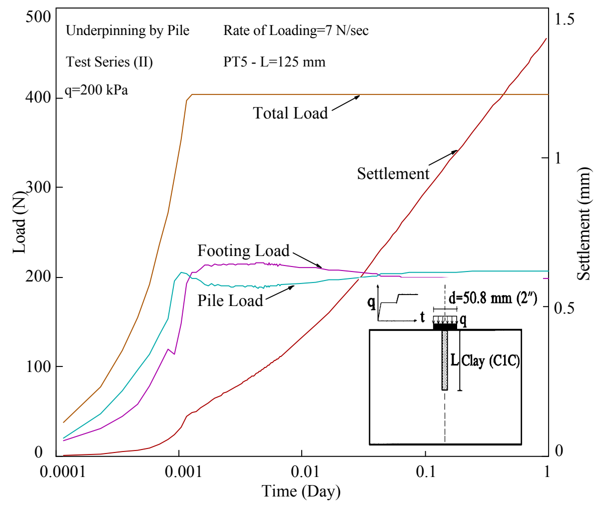

Figure 11. Load transfer to the pile during loading on the footing and with progress of the consolidation settlement.

tests. The results are similar to test series (I) as was explained above. Due to problems in reading the strain gauges of the pile, reasonable data for the pile load was not logged in test No. PT6.

Figure 12 summarizes the results of tests series (II) via a plot of the total final settlement S_{TFP} and Ratio of Settlement Reduction RSR.

As explained before, only one test (PT7) was performed with a different time of pile installation t_i, and Figures 13 and 14 show the results of this test in which pile was installed as the load reached its maximum value. After pile installation, the load was held on the footing at its maximum value. As Figure 13 highlights, because of the

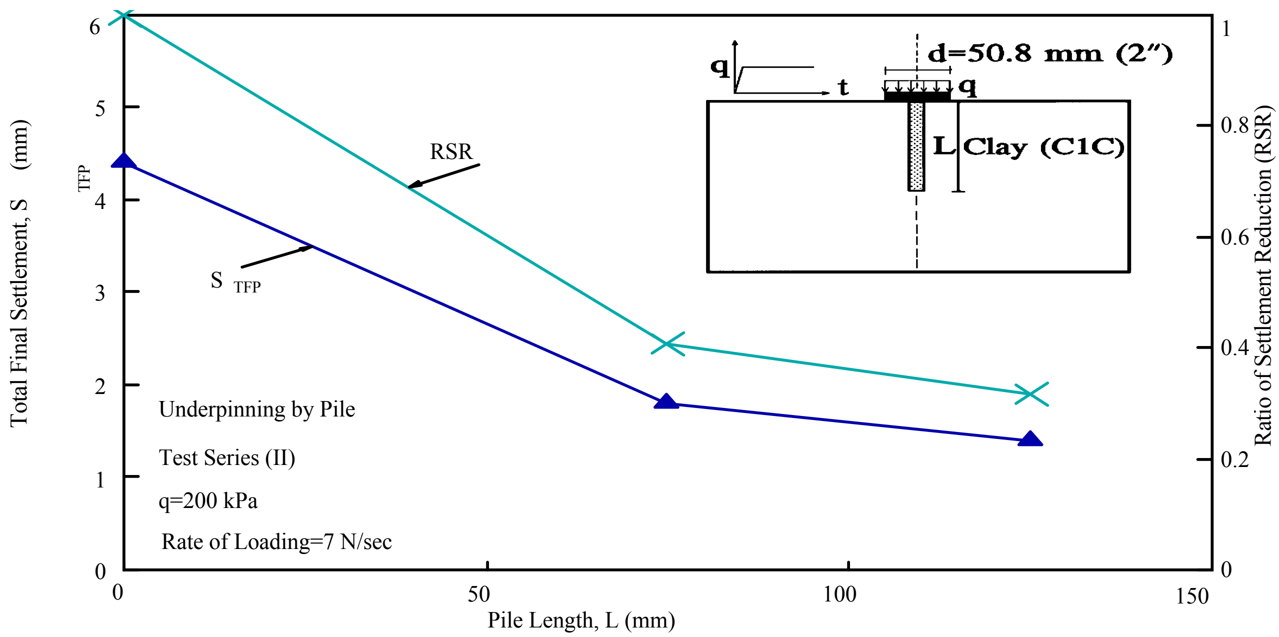

Figure 12. Effect of pile length on settlement reduction of the footing.

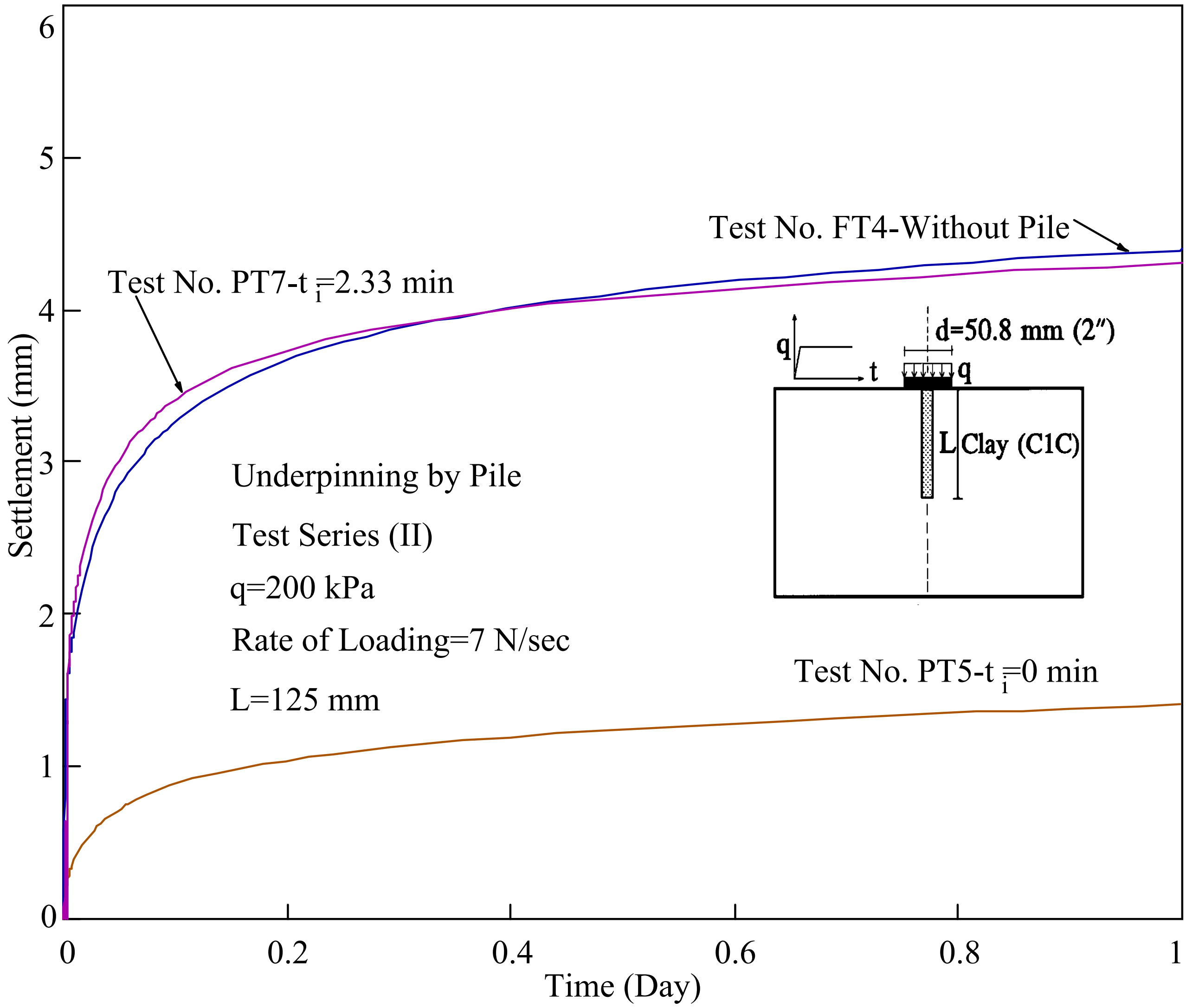

Figure 13. Effect of time of pile installation on settlement reduction of the footing with and without dissipation of excess pore pressure due to pile installation.

high excess pore water pressures built up by pile installation, there was no beneficial effect by installing underpinning piles. It is a known fact in pile design that shaft resistance of the pile is related to the effective stress. Therefore, a delay in loading pile foundations in clay is desirable to allow dissipation of excess pore water pressures to occur. In some cases of underpinning, temporary methods of support may be necessary to prevent increases in the settlement of the footing during the pile installation.

SUMMARY AND COMPARISON WITH NUMERICAL ANALYSIS

Figure 15 summarizes the results of both series of underpinning tests for different pile lengths and load levels, and shows that the longer the pile is, the more settlement reduction can be achieved by the use of underpinning piles. It should be pointed out that due to higher level of applied loading in test series (I), the RSR is less than that in test series (II). Figure 16 summarizes the results of

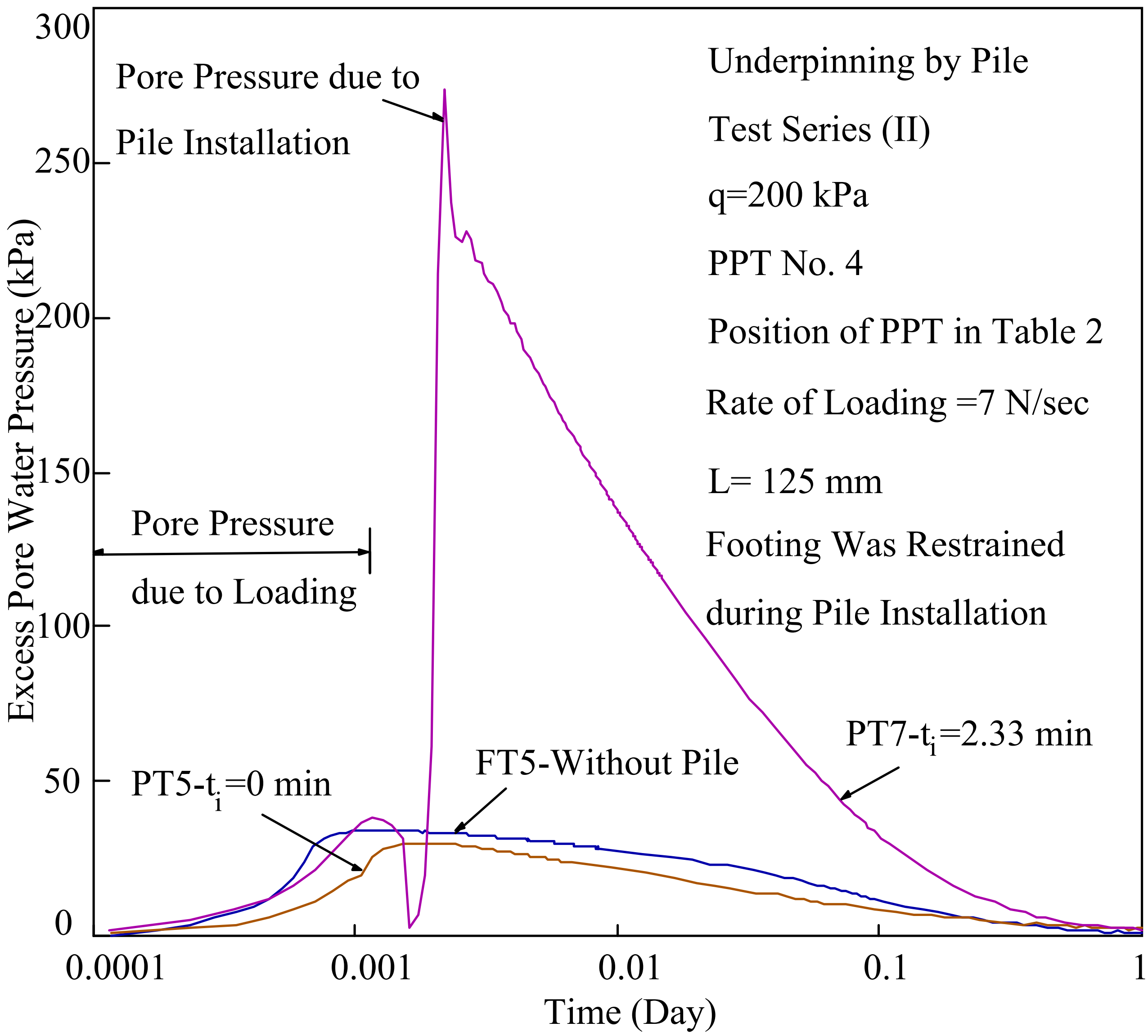

Figure 14. Time-excess pore water pressure behavior of footing underpinned at two different times of pile installation.

underpinning tests for two Ratios of Applied Pressure RAP. This figure also presents a comparison between the numerical analysis using the finite element program AFENA [8] and the test results. In the numerical analysis (elasto-plastic consolidation with Mohr-Coulomb criterion) undrained soil parameters have been used during the loading period to obtain the initial settlement, and drained soil parameters for calculating the consolidation settlement. The soil parameters have been obtained by triaxial tests (undrained and drained conditions), after K_0 consolidation stage (Table 1). The approximate amount of creep settlement measured during the tests has been added to the computed final settlement to obtain a more realistic estimate of total settlement for comparison with test results. Reasonable agreement between analysis and measurement has been found, although the effects of creep make prediction of settlements difficult. Makarchian [5] have mentioned more details. More research is required to understand the important influence of creep on the settlement of both shallow footings and piled foundations.

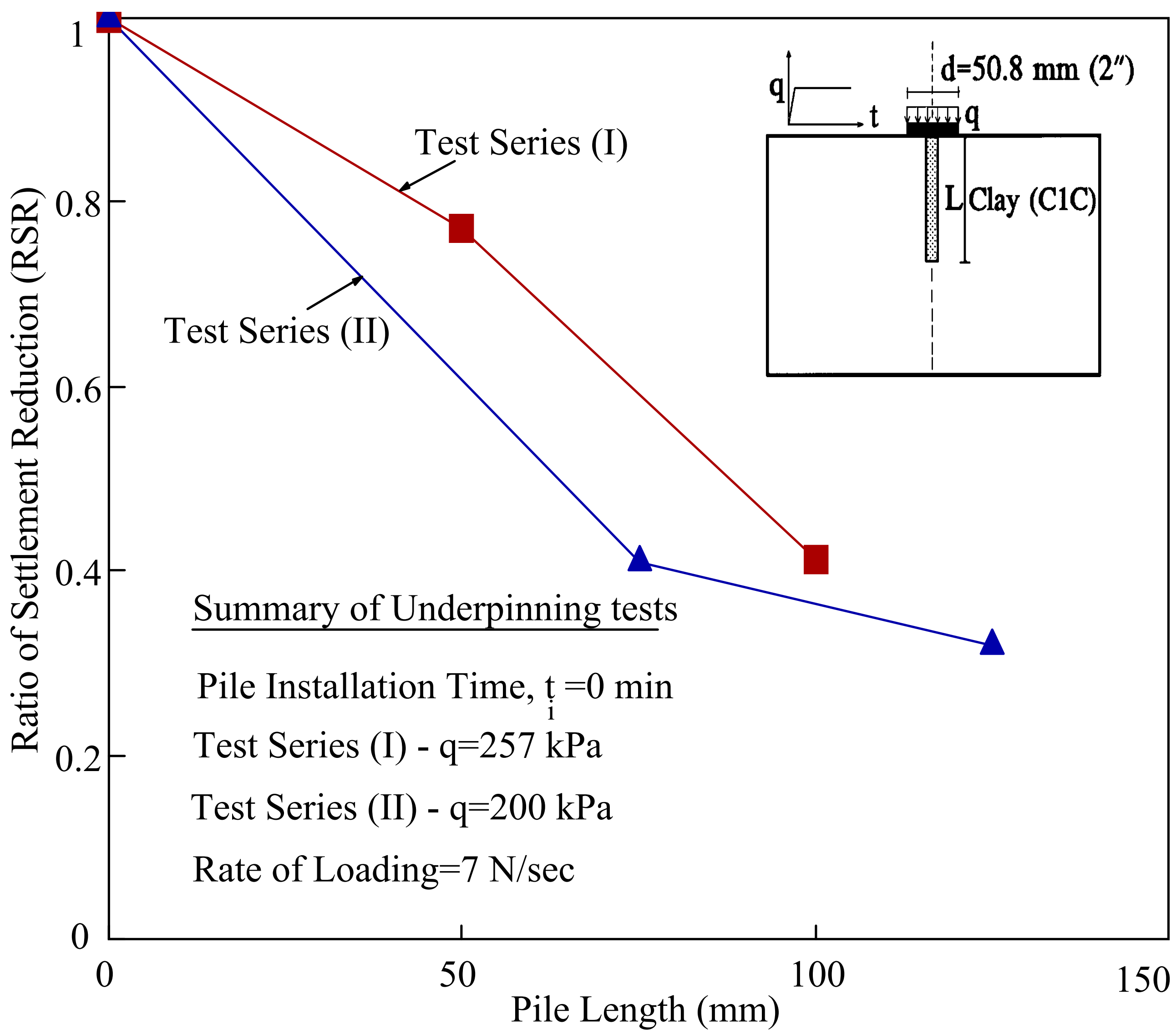

Figure 15. Summary of underpinning tests - plot of non-dimensional ratio of settlement reduction versus pile length for test series I and II.

Due to the long duration of the model tests, only a limited number of tests could be carried out. However, the results of these underpinning tests, together with the numerical analyses, have indicated the factors that may influence the behavior of foundations with underpinning piles. Nevertheless, it is considered that the results presented in this paper together with results of numerical analyses [1-5] may provide a benchmark for future researchers, and may also provide a basis for the development of simplified methods of design of piles for underpinning projects. Such a simplified method has been presented in another paper [10].

CONCLUSIONS

In this paper, it was shown that when piles are used for underpinning and upgrading the footings, the pile length and load level both have an effect on settlement reduction, and the tests have provided data on excess pore water pressures, both during pile installation and due to loading, and load transfer from the footing to the underpinning piles. It has also been shown that a high level of excess pore water pressure can be built up by pile installation in clay, such that, if the load is applied immediately after pile installation, the pile may have

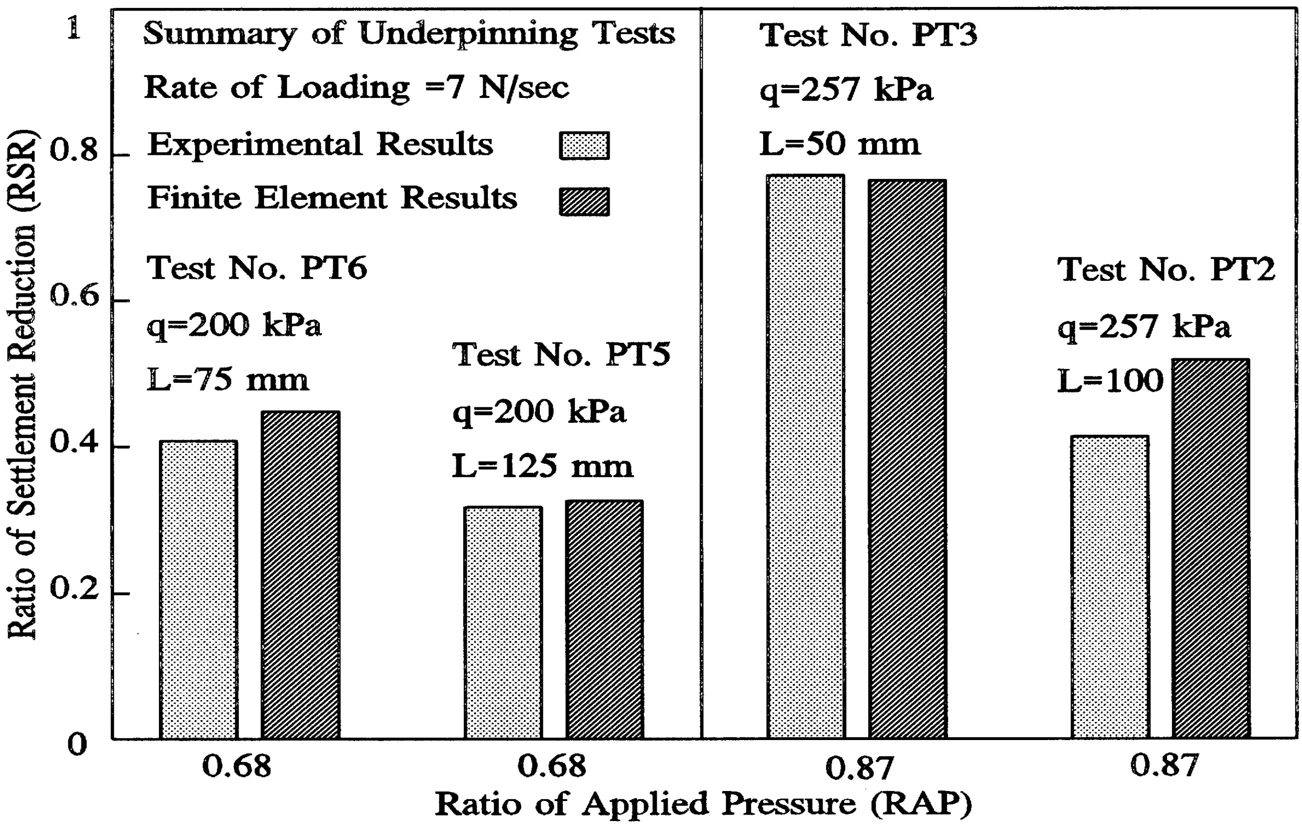

Figure 16. Summary of underpinning tests and comparison with numerical analysis - plot of non-dimensional ratios of RAP versus RSR.

no beneficial in settlement reduction. Reasonable agreement between analysis and measurement has been found, for those cases in which the excess pore pressures due to pile installation are allowed to dissipate prior to the load being transferred to the underpinned footing, although the effects of creep make accurate prediction of settlements difficult.

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