DISTRIBUTION OF STRESSES AND SETTLEMENTS BELOW FLOOR SLABS SUPPORTED BY RAMMED AGGREGATE PIERS

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ABSTRACT

Heavily loaded floor slabs overlying soft compressible or fill soils pose the risk of excessive settlements that lead to floor slab cracking. To reduce this risk, the compressible soils are often "overecavated" or pile-supported structural slabs are used. Both of these options are costly and may significantly lengthen the time required for building construction. In recent years, *Rammed Aggregate Pier*^{TM} elements have been increasingly used as a cost-effective solution to support heavily loaded floor slabs. The system is designed using classical principles of geotechnical mechanics that include the concepts of stress concentration, composite behavior, and the reduction of compressibility by increasing stiffness.

This paper presents design methods used to estimate stress concentration as well as the results of recent instrumentation readings collected for a heavily loaded floor slab. This work is of particular significance because it provides design verification for an innovative and cost-effective means of controlling settlements.

RÉSUMÉ

Des plaques de fondation sous charges élevées et reposant sur des sols compressibles ou des remblais présentent un risque de tassements excessifs pouvant conduire à la fissuration des plaques. Afin de réduire ce risque, les sols compressibles sont souvent « sur excavés » ou bien des plaques structurales supportées par des fondations profondes sont utilisées. Ces deux options coûteuses peuvent allonger significativement le temps de construction. Depuis quelques années , on utilise de plus en plus le système appelé Rammed Agregate Pier ^{TM} comme une solution financièrement intéressante pour supporter ce type de plaques. Le système utilise les principes classiques de la mécanique géotechnique prenant en considération les concepts de concentration des contraintes, de comportement des composites et de réduction de la compressibilité par augmentation de la rigidité.

Ce document présente des méthodes de conception pour estimer la concentration des contraintes ainsi que des relevés d'instrumentation récents recueillis pour une plaque fortement chargée. Ce travail a une importance particulière puisqu'il fournit une méthode de vérification de conception par un moyen de contrôle des tassements innovant et intéressant financièrement.

1. INTRODUCTION

The design of heavily loaded slabs constructed over soft compressible or fill soils is a common problem in geotechnical engineering practice. Engineers must consider total and differential settlements and their impact on the performance of the floor slab. Traditional solutions used to reduce structural distress include overexcavation and replacement of the compressible soils, use of deep foundation elements with a structural slab to bypass settlements in the compressible soils, and the use of waffle slabs to provide for increased rigidity. These traditional options are expensive and may lengthen the time required for building construction. In recent years an alternative solution has emerged involving the use of *Rammed Aggregate Pier*^{TM} *(RAP)* elements. Use of *RAP* elements has become a popular, cost-effective solution for projects involving heavily loaded floor slabs overlying weak and compressible soils. The added benefits of this solution are that it reduces construction schedules compared to the other options, and it minimizes the risks of weather-related delays associated with massive overexcavation. This paper describes the geotechnical principles involved in the *RAP* solution for projects involving heavily loaded slabs over soft compressible soils. This paper also summarizes and discusses the monitoring results of a large food processing warehouse project involving a heavily loaded floor slab founded over compressible soils. Design verification of this new technology (*RAP*) was provided by the detailed instrumentation involved in this project.

2. PROJECT DESCRIPTION

The project involved the construction of a warehouse addition for a large food processing manufacturer. The project is located in Granite City, Illinois, USA in the floodplain of the Mississippi River. The project consisted of an approximately 34,000 m^2 (366,000 ft^2) addition to an existing warehouse building. The proposed column bays were approximately 12 m by 16 m. The warehouse floor slab was designed for a floor loading pressure of 34 kN/m^2 (700 psf).

To keep the floor dry during high Mississippi River stages, and to match the floor elevation of the warehouse addition with the floor of the existing building, grades at the site were required to be raised by 0.9 m to 2.4 m (3 ft to 8 ft). The average thickness of the fill was about 1.5 m (5 ft). A schematic cross-section of the construction requirements is shown in Figure 1.

2.1. Subsurface Conditions

The project is located within the Mississippi River floodplain, comprised of alluvial soils. Subsurface conditions were explored by Geotechnology, Inc., Maryland Heights, Missouri. The soil stratigraphy at the site consists of 1.8 m to 4.9 m (6 ft to 16 ft) of soft to medium-stiff, lean and fat clay (CL,CH), underlain by medium-dense to dense, clean and silty sand (SP, SM).

As shown in Figure 2, Standard Penetration Test (SPT) N-values for the upper compressible layer typically ranged between 2 to 8 blows per 0.3 m. The moisture contents in this layer ranged from 24 to 48 percent. A typical consolidation curve from a sample of this unit is also shown in Figure 2. The compression ratio ($C_{\varepsilon c}$) and recompression ratio ($C_{\varepsilon r}$) were found to be 0.18 and 0.025 respectively. The overconsolidation ratio of this layer was found to be about 7. At the time of the borings, the groundwater table typically varied between 1.85 m (6 ft) and 5.8 m (19 ft) below grade.

3. TRADITIONAL FLOOR SLAB SOLUTION

Calculations performed by the project consultant indicated that the placement of 0.9 to 2.5 m of engineered fill coupled with the high design floor slab pressures (34 kN/m^2) would result in well over 10 cm (4 inches) of settlement within the in-situ clay soils. The high magnitude of the expected settlements and associated large potential differential settlements, ruled out the possibility of supporting the new fill and floor slab directly on an unimproved subgrade without extensive construction delays, and required the search for alternative geotechnical solutions.

Several options were investigated to reduce the excessive settlements. Conventional massive overexcavation and recompaction would involve removing and recompacting the upper 1.8 to 2.5 m of existing soft alluvial soils. However, this option had four main drawbacks: 1) The high groundwater table at this site and possibility of site flooding during high river stages would add risk to the excavation process, 2) The high soil moisture content would impose problems and challenges in achieving the desired level of compaction, 3) The project was to be constructed in the fall and winter months with a significant likelihood of heavy rains, site flooding, and soil saturation, and 4) The high cost of this solution, as well as the expected associated construction schedule delays led to the decision of abandoning this option and exploring other alternative solutions.

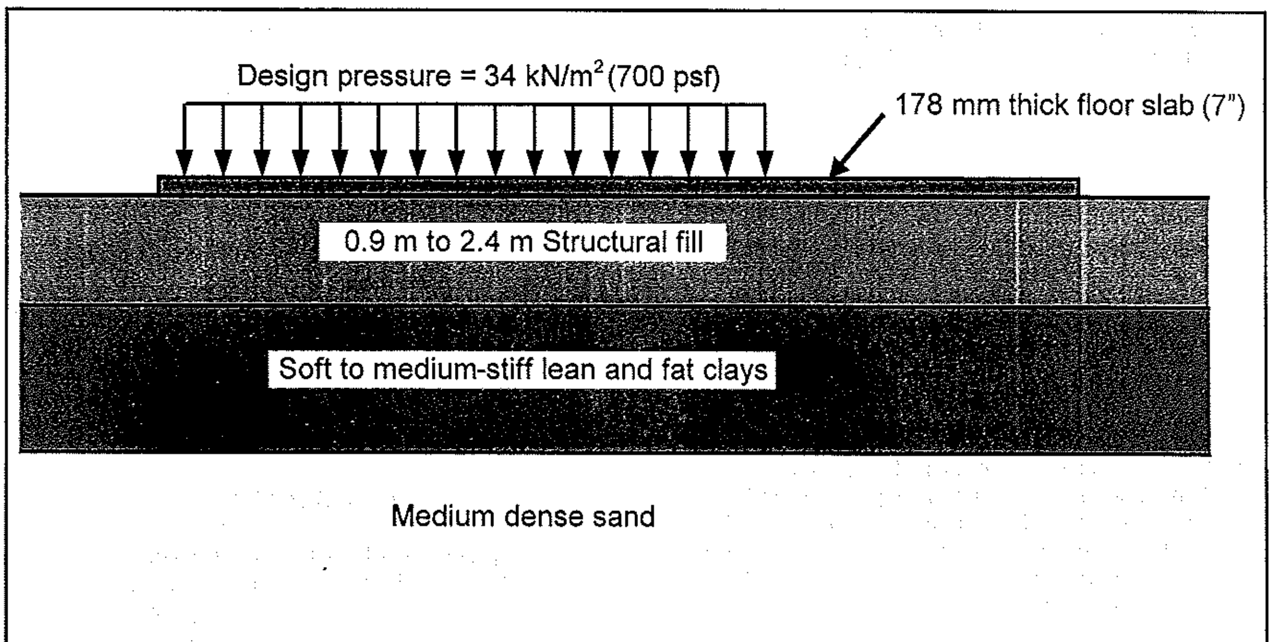


Figure 1. Construction Requirements

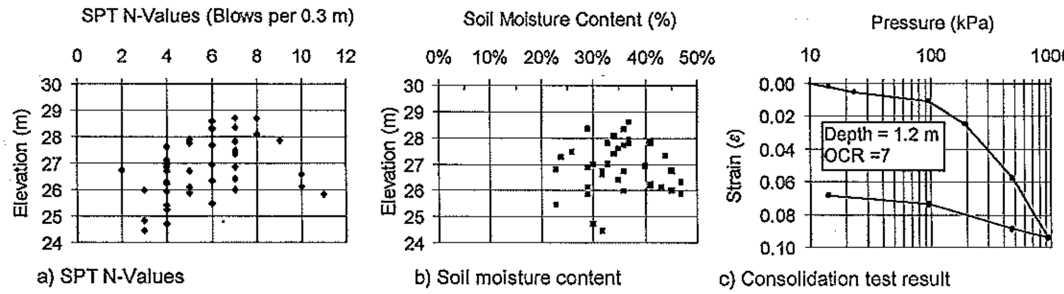


Figure 2. Characteristics of In-situ Clay Soils (Note: El. 30.48 m = El. 100 ft)

Because of the challenging conditions of this project, the project team decided to consider the use of a *Rammed Aggregate Pier*[TM] *(RAP)* reinforcement system. The following subsections describe in more detail the *RAP* system and provide as well a description of the proposed alternative solution for this project.

3.1. Description of Aggregate Pier Installations

Rammed Aggregate Pier construction is shown in Figure 3. The piers are installed by drilling 610 mm (24 inch) to 915 mm (36 inch) diameter holes to depths ranging between 2.1 m and 6.1 m (7 ft and 20 ft) below the bottom of footings or floor slabs, placing controlled lifts of aggregate stone within the cavities, and compacting the aggregate using a specially designed high-energy beveled impact tamper. The first lift consists of clean stone and is rammed into the soil to form a bottom bulb below the excavated shaft. The bottom bulb effectively extends the design length of the aggregate pier element by one pier diameter. The piers are completed by placing additional 0.3 m (one-foot) thick lifts of aggregate over the bottom bulb and densifying the aggregate with the beveled tamper. During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface.

For high bearing pressure footings, with bearing pressures typically ranging between 240 kN/m^2 (5,000 psf) and 430 kN/m^2 (9,000 psf), *RAP* elements typically cover 30% to 40% of the gross area of overlying footing elements. For floor slabs with floor pressures typically ranging from 20 kN/m^2 (400 psf) to 50 kN/m^2 (1,000 psf), *RAP* elements typically cover approximately 2% to 5% of the gross area of overlying floor slab. For this project the *RAP* elements covered approximately 3 % of the floor slab area.

3.2. Proposed Solution for this Project

As an alternative to massive excavation and replacement, *RAP* elements were installed within the compressible clay soils to control settlements. The elements are 0.75 m (30 inches) in diameter and were installed on 4.25 m (14-foot) centers from the ground surface to the top of the underlying sand. Fill materials, consisting of lime-stabilized clay soils, were then placed over the elements to achieve site grade. A sketch of construction conditions is presented in Figure 4.

Several critical design issues were identified at the initial design stages of the project. Of particular interest were the anticipated magnitude of total and differential settlement, the degree of stress concentration to the tops of the elements, and the amount of confinement afforded by the fill soils.

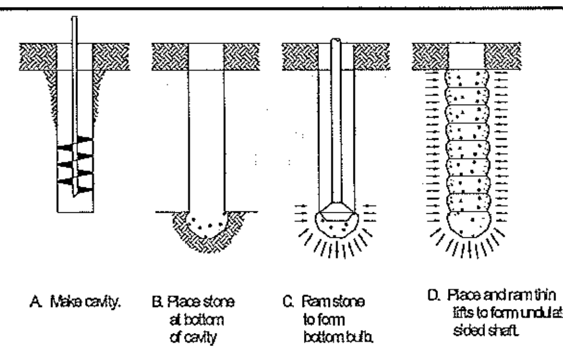


Figure 3. Construction Process

4. DESIGN APPROACH

To develop an estimate of the anticipated settlement below the floor slab, the design team developed a simple design approach that included the assumption that the settlement of the tops of the piers would be the

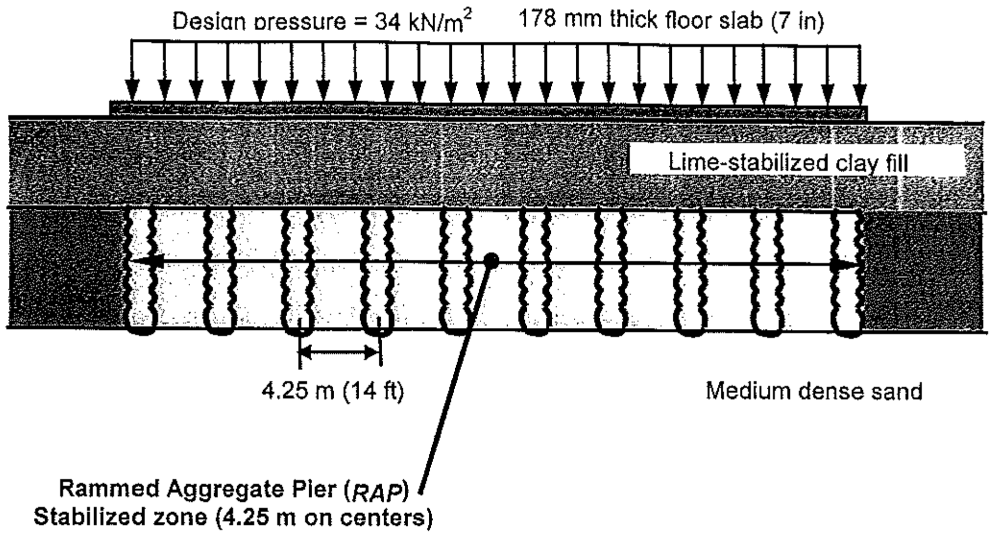


Figure 4. Proposed Rammed Aggregate Pier Stabilized Zone Solution

same as the settlement of the matrix soils as well as the following concepts.

- The settlement of the matrix soil, between the reinforcing elements, is estimated using conventional geotechnical approaches derived from one-dimensional consolidation tests.
- The settlement of *RAP* elements is estimated from the quotient of the stress applied to the tops of the piers (q_g) and the stiffness modulus of the piers (k_g). The stiffness modulus value is estimated from a database of historical modulus tests and verified by an on-site modulus test. A typical modulus test setup is shown in Figure 5.
- The stress transmitted to the tops of the *RAP* elements will depend on the total load applied by the fill soil and floor slab, the stiffness ratio between the *RAP* elements and the surrounding matrix soil, and the percentage of area covered by the *RAP* elements.

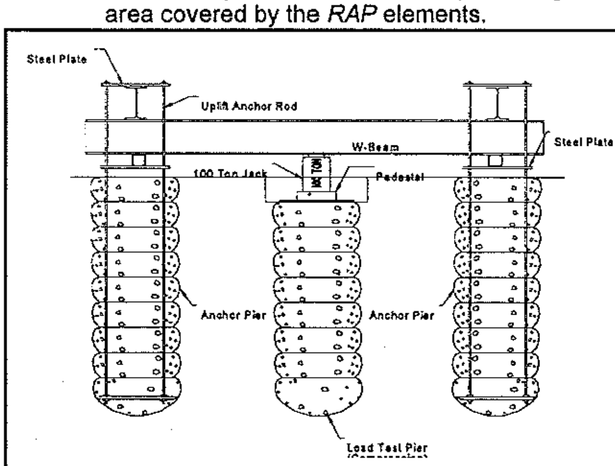


Figure 5. Typical Modulus Load Test Setup

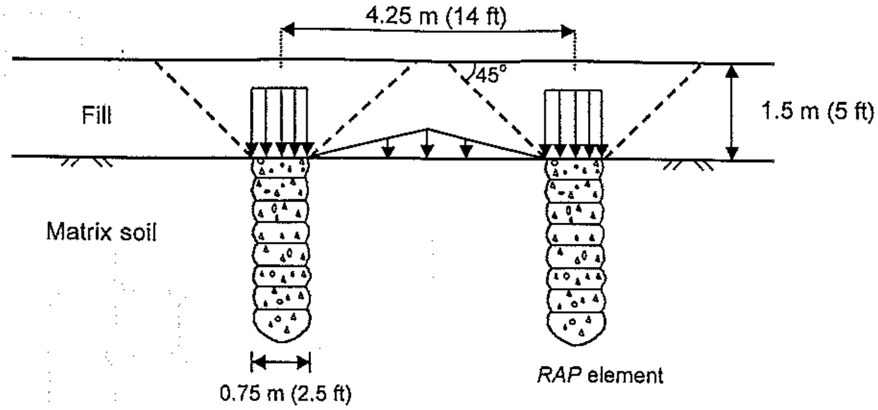
4.1. Response During Fill Placement

As the fill soil is placed over the reinforced subgrade soils, a portion of the load will arch to the tops of the stiff aggregate piers. The design team assumed that the zone of arching would resemble a truncated conical surface extending upwards from the tops of the aggregate pier elements. As shown in Figure 6, a 45-degree inclination was assumed for the cone.

Using the design method described above, the stress estimated at the top of the *RAP* element due to the placement of the average 1.5 m of fill thickness was computed to be about 296.9 kN/m^2 (6200 psf). Similarly, the estimated average pressure acting on the matrix soil, from the placement of the fill soil, was computed to be about 22 kN/m^2 (460 psf). At the midpoint between two adjacent *RAP* elements (spaced 4.25 m center to center) the estimated maximum pressure acting on the matrix soil was computed to be about 29 kN/m^2 (600 psf).

To verify design assumptions, four pressure plates were installed in a full-scale area fill test. Two plates were installed at top of *RAP* elements and two plates were installed between *RAP* elements to measure the pressure distribution and possible arching of stresses. The pressure plate readings are shown in Figure 7. The readings indicate a top of *RAP* stress of about 60 kN/m^2 (1250 psf). This value is smaller than the predicted stress of 296.9 kN/m^2 (6200 psf). This discrepancy could be due to possible conservatism involved in the selected arching mechanism model or to instrument errors. The pressure plate readings for the soil matrix indicated a contact pressure of about 29 kN/m^2 (600 psf), the same value as estimated above.

The average settlement in the soil matrix, due to fill placement loading only, was estimated using the average soil pressure estimated above (22 kN/m^2)



- Fill load arches to tops of stiff elements
- Calculated pressure on piers = 296.9 kN/m^2 (6,200 psf)
- Calculated average pressure on matrix soil = 22 kN/m^2 (460 psf)
- At center, calculated maximum soil pressure = 29 kN/m^2 (600 psf)

Figure 6. Load distribution calculations

and a recompression ratio C_{er} = 0.03 developed from the results of oedometer tests. It was assumed that 50 percent of the fill-induced settlement would occur prior to placement of the floor slab. Long-term consolidation settlement, after slab construction was estimated to be about 11 mm (0.43 in) using conventional 1-D settlement analysis.

4.2. Response During Slab Loading

As shown in Figure 6, the truncated arching cones nearly touch at the midpoints between RAP elements. For this reason, the amount of load transfer to the tops of the RAP elements and to the in-between matrix soils was assumed to be dependent on the relative stiffness of the materials. As noted above, the design approach includes the assumption of uniform settlement.

4.3. Settlements

The settlement of the *RAP* elements is estimated as the quotient of the stress applied to the tops of the piers (q_g) and the stiffness modulus of the piers (k_g):

$$S = \frac{q_g}{k_g} \qquad (1)$$

The stress applied to the top of the piers is computed by summing the stress induced due to fill placement ($q_{g,fill}$) and the stress applied by the floor slab ($q_{g,slab}$):

$$q_g = q_{g,\text{fill}} + q_{g,\text{slab}} \qquad (2)$$

As shown above, $q_{g,fill}$ was anticipated to be about 296.9 kN/m^2 (6200 psf). Based on experience with similar soil conditions, a *RAP* stiffness modulus of 150 lbf/in^3 (41 MN/m^3) was selected for preliminary design purposes.

This stiffness modulus value was later verified by a modulus load test performed at the site. Test results are shown in Figure 8.

The modulus load tests of *RAP* elements often incorporate telltales at different elevations within the pier. The telltale consists of a horizontal steel plate that is attached to two sleeved vertical bars extending to the top of the pier. The telltales are used to monitor deflections at the elevation where the steel plate is installed inside the pier.

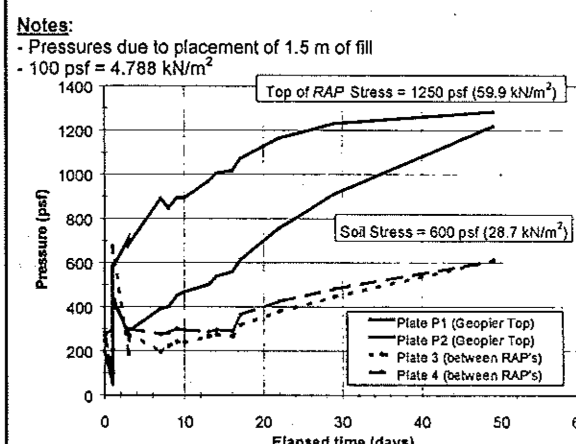


Figure 7. Pressure Plate Results

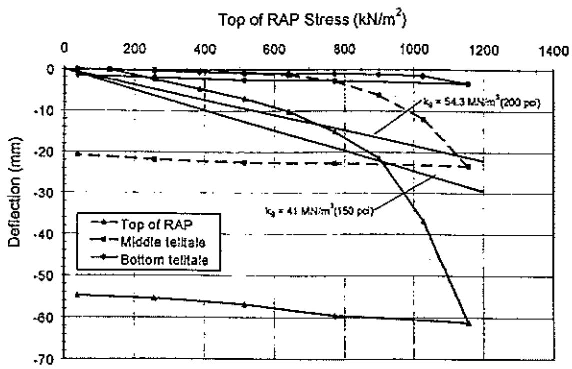


Figure 8. Modulus Load Test Results

The modulus test carried out for this project incorporated two telltales, one at the bottom of the pier, and a second one at the middle. The test pier for this project was constructed with a nominal diameter of 76 cm (30 inches) and a shaft length of 3.7 m (12 ft). The test *RAP* was loaded to a maximum pressure of 1156 kN/m^2 (24150 psf). The three curves shown in Figure 8 correspond to the top of pier, the middle telltale, and the bottom of pier telltale.

The settlement of the matrix soil was estimated by summing the estimated fill-induced settlement (11 mm = 0.43 in) with the settlement that will develop from the slab loading. The settlement of the matrix soil from slab loading is estimated as:

$$S_{m,slab} = 0.03 \cdot 9\text{ft} \cdot \text{Log}\left[\frac{q_{m,slab} + 1000\text{psf}}{1000\text{psf}}\right] \quad (3)$$

where $q_{m,\,slab}$ is the average pressure acting on the soil matrix due to slab loading. The pressure of 1000 psf (47.9 KN/m^2) corresponds to the average soil stress after fill placement (1.5 m).

Using the approach described above and Equations 1 through 3, and incorporating the concepts of uniform settlement, the following solutions are obtained:

$q_{g,slab}$ = 621.4 kN/m^2 (12,979 psf)

$q_{m,slab}$ = 18.4 kN/m^2 (384 psf)

q_g = 918.3 kN/m^2 (19,179 psf)

S = S_g = S_m = 22.5 mm (0.89 inches)

5. Area Fill Test

To verify the general design of the *RAP* stabilized zone and to determine the likelihood of differential settlements, a full-scale area test fill was constructed. The area test fill consisted of 25 *RAP* elements (0.75 m nominal diameter) installed in a grid spacing of 4.3 m (14 ft) center to center that were loaded with surcharge fill to simulate the loading conditions expected in the project. The layout of the test is shown in Figure 9. Settlements were monitored using settlement plates at the locations shown in Figure 9.

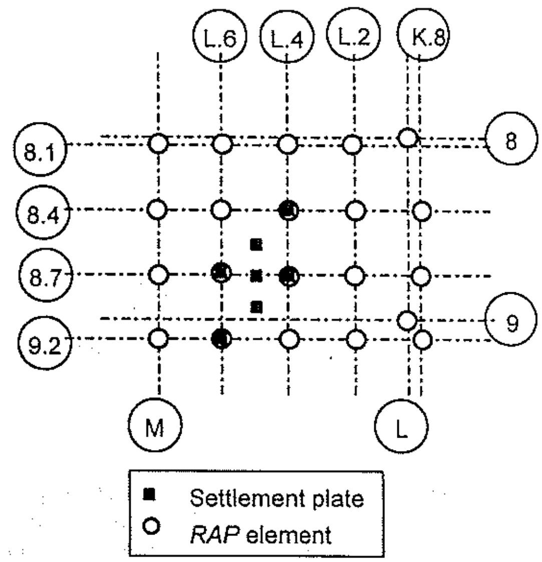


Figure 9. Area Fill Test Layout

The *RAP* grid was loaded to simulate the construction sequence expected for the project. After 1.5 m of Lime treated fill was placed over the *RAP* grid, the floor slab pressure (700 psf) was simulated by placing an additional fill surcharge equivalent to this pressure. To evaluate the differential settlement potential the settlement plates were placed at two locations; aligned with the top of the *RAP* element, and also between *RAP* elements.

Figure 10 shows that the *RAP* settlement, under full design loading, was about 13 mm (0.5 in). The recorded soil matrix settlement was about 15 mm (0.6 in). The corresponding differential settlement, between the soil matrix and *RAP* element, is 2.5 mm (0.1 in), confirming the assumption of minimal differential settlement.

The settlements recorded in the field were smaller than predicted. This is partly due to the higher *RAP* stiffness modulus encountered in the field (about 175 pci) compared to the value of 150 pci used for preliminary design purposes.

6. CONCLUSIONS

This paper describes the geotechnical principles involved in the *RAP* solution for projects involving heavily loaded slabs over soft compressible soils. This paper also summarizes and discusses the monitoring results of a large food processing warehouse project

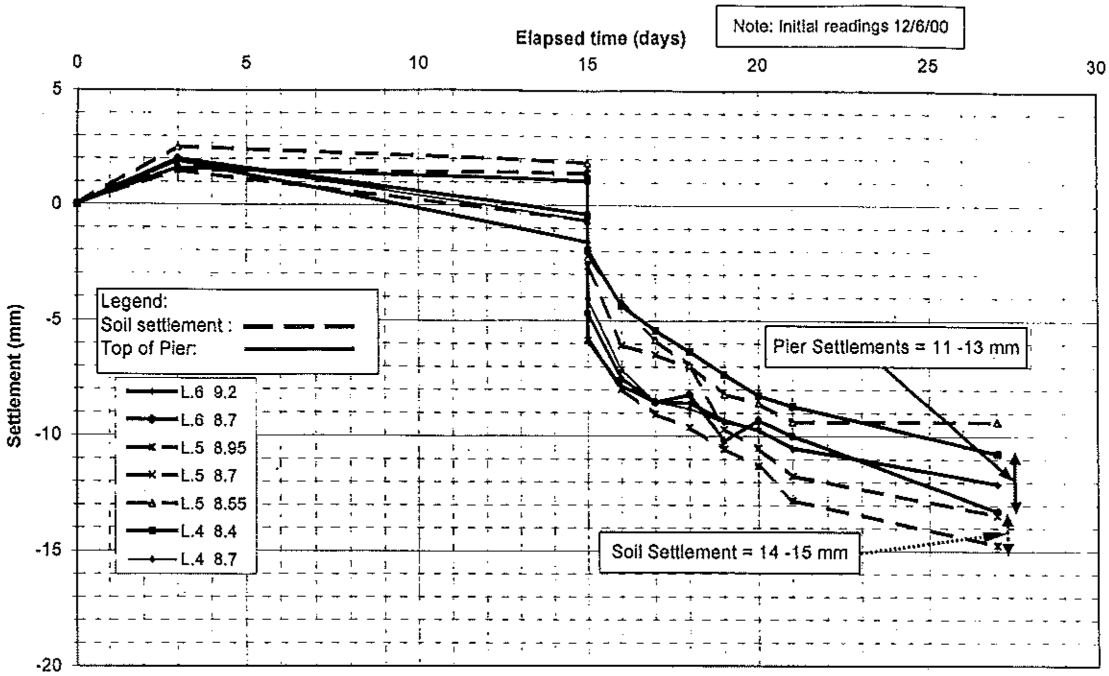


Figure 10. Settlement Monitoring Results

involving a heavily loaded floor slab founded over compressible soils.

Detailed instrumentation readings confirmed that the *RAP* elements controlled slab settlements to less than 0.6 inches with less than 0.1 inch differential settlement between the tops of the *RAP* elements and the matrix soils.

7. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of Dr. Nathaniel Fox (Geopier Foundation Company, Inc.) for his valuable comments and suggestions. The authors would also like to thank Mr. Brendan FitzPatrick for his assistance during the preparation of this manuscript.

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