Large Mat on Deep Compressible Soil

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Synopsis: This case history describes the design of a load compensated mat foundation on highly compressible soil. The mat was used to support over 800,000 square feet of variable height building. While the design of the mat was mostly routine, the behavior at the mat edges was difficult to determine. The deformations at mat edges were the major concern since they were influenced by the need to raise grades around the building perimeter. The design procedure incorporated soil-structure interaction analysis to determine the extent of light weight fill zones required to control edge deformations. Settlement monitoring over a period of 2 years has confirmed the design approach.

1. KEYWORDS: MATS, FOUNDATIONS, SOFT SOILS,
SOIL STRUCTURE INTERACTION

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In 1990, a 1.4 million square-foot regional shopping center was opened. It included a basement level and was supported on a mat foundation as shown in Figure 1. The mat covered over 800,000 square feet and rested on nearly normally consolidated varved silt and clay from 80 to 200 feet thick. Since the subsoils were compressible and it was necessary to surround the building with new fill, a significant design problem was to avoid bending down of the building perimeter. The selection and design of the mat were somewhat unusual and are described in this paper. This paper also describes the performance of the mat during its first two years which confirmed the critical design assumptions.

SELECTION OF A MAT FOUNDATION

When a two and three-story regional shopping center with a 6-story central tower was proposed initially without a basement level in 1987, it was known that difficult subsurface conditions existed at the site. First of all, much of the site had been used as the city dump between 1920 and 1960. Before that, it had been used as a waste bed for an industrial by-product. Although the site had a prime lakefront location, the difficult subsurface conditions had discouraged previous developments except for oil storage and scrap yards.

Study of the local geology indicated that below the man-made fills, there was a deep subsurface bedrock trough that had been filled completely with dense glacial and soft compressible lacustrine soils. The area had once been a salt marsh that had been fed by deep artesian salt springs whose source was several hundred feet below the surface.

Local experience had indicated that the whole area had problematic subsoils. Several tanks at a nearby large sewage treatment plant had settled as much as 4 feet during the 1960's and 1970's. A large oil tank on the proposed shopping center site had settled almost 3 feet during hydrotesting in the 1970's. Nearby highway embankments had settled over 4 feet. A light metal structure at the site had settled over 3 feet. With such experiences in the neighborhood, most later structures had been supported on piles.

Since the shopping center was to have sensitive interior finishes, many large glass skylights, and a 120-foot high central atrium tower with offices and banquet facilities, it was initially a foregone conclusion that the project would be supported on piles.

The subsurface investigation confirmed the difficult subsoils by disclosing up to 15 feet of miscellaneous fill and waste that had been placed on top of several feet of peat and organic silt. Below were from 60 to 180 feet of compressible marl and varved silt and clay, as shown in Figure 2. The groundwater table was shallow.

As a consequence of the thick man-made fills being relatively young and of the previous deep artesian pressure, the subsoils lacked any significant preconsolidation. Accordingly, the addition of even small loads to the soil surface would cause significant settlement. Two feet of fill were estimated to cause as much as 8 inches of settlement during a period of 20 years. These estimates were consistent with records from previous development in the area.

Much of the 30-acre site was low and the existing 7 foot grade variation would require an average of 2 feet of fill to establish proper surface drainage. The lowest acceptable building floor level was chosen because it was important to minimize the amount of new fill, saving the cost of importing as well as for minimizing settlement.

Project plans proceeded with the design of a pile foundation. Since the site was so sensitive to settlement and the compressible soils were as thick as 200 feet, the pile design required special measures to overcome the effect of negative skin friction.

The costs of overcoming the negative skin friction led to reconsideration of the design concept. It was noted that by adding a basement level, it would be possible to remove enough soil to compensate for the weight of the entire structure. Therefore settlement could be controlled without piles.

The developer required the basement level to be 17 feet below the ground floor to provide for basement retail space. Therefore the basement level would have to extend below the water table. Another requirement was that all excavation spoil would have to be kept on site.

It was recognized that the main design problem would occur at the mat edges where the required surrounding new fill would cause differential settlement. Since the compressible soil was so deep, fill placed even a substantial distance away from the building could contribute to settlement. While it was recognized desirable to minimize new fill thickness near the building to reduce edge settlement, it was unfortunately necessary to place some of the large volume of spoil generated by the basement excavation within the zone of load influence because there was no other suitable spoil area.

If the basement was too deep, the groundwater table would have to be permanently lowered to prevent buoyancy. The dewatering effort and cost would increase with basement depth. In addition, a deeper basement would create more excavation spoil and therefore more new fill to accommodate.

To reach a workable and practical compromise among the various constraints, it was found necessary to set the top of mat level about 12 feet below the average existing grade. At that level all fill and organic soil could be removed below the building.

The Developer was faced with a choice of two alternatives, a mat foundation with a basement or a pile supported building with no basement. The decision was based on an economic analysis. While the mat with basement was more costly, it had additional benefits. The mat was chosen largely because the basement provided additional retail space and convenient parking.

ANALYSIS AND DESIGN

As stated, the main design problem for the mat occurred near the edge. However, most of the large mat was determined to behave as an interior condition not influenced by the fills and large settlements that would occur outside the building.

Therefore the interior was modeled by the conventional Winkler approach (an elastic subgrade reaction to the mat loads alone) using the PCA-MATS program with no modifications.

The design assumptions regarding the mat thickness were based on the preliminary analyses of mat interior. The mat thickness of 24 inches for the 2 story area and 30 inches for the three story area, were estimated on the basis of allowable two way shear and flexural capacity for the assumed maximum column spacings and minimum column sizes.

The mat top elevation was set to optimize the load bearing condition, load compensation, superstructure loads, foundation loads, excavation volume, and earthwork balance. Within the project constraints, the top of mat was set at a constant level that ranged from 8 to 15 feet below existing grade and yielded the foundation stresses given in Table 1. The mat at that level would be sufficiently weight compensated if the water table were maintained below the mat. Theoretically, the building foundation designed as above would not settle due to primary consolidation. However reversal of construction heave and slow long term secondary compression of deep soft soils would create the possibility of several inches settlement during the building's life time.

Analysis of the mat foundation was problematic near the edge because of the 2 to 8 feet of fill required around the building.

As previously mentioned the deep compressible soils required structure load compensation in order to prevent excessive settlements. However the influence of placing the required fill outside the building was so severe that it could not be overcome at the edge merely by the effect of the building load compensation. This was particularly true at the corners. The opposite direction of the subgrade loading inside and outside the building (loading outside, unloading inside) would cause an abrupt settlement change near the edge. Estimated settlements up to 15 inches at the building edge and up to 48 inches in the parking area beyond showed that special measures would be necessary, such as those shown in Figure 3.

The possible solutions to reduce excessive edge settlements of the superstructure were to:

1. Increase the mat stiffness to allow transfer of contact stresses to the mat interior by a cantilevering effect, with tolerable deformation at the mat edge.

2. Extend the basement level beyond the superstructure. This would both reduce edge loading and allow the mat edge zone

to adjust to the soil settlements without affecting superstructure deformations.

3. Replace site backfill outside basement with a collar of lightweight fill to force the settlement transition beyond the super-structure.

4. Raise the water table in order to increase buoyancy.

5. Provide releveling ability for the superstructure.

Solution one would have required a 50 foot wide strip 6 feet thick around the building perimeter and was cost prohibitive. The other solutions were found to be impractical or inadequate, if applied individually. However using the interactive approach, described later, an effective combination was found. It incorporated the following:

1. A 7-foot basement extension beyond the building perimeter.

2. Extensive placement of expanded polystyrene (EPS) blocks and other lightweight backfill.

3. Water table maintenance 5 feet above the top of the mat.

4. Releveling devices at the top of each basement column.

The perimeter section representing the typical solution is shown in Figure 3.

The effect of subgrade settlement at the edge of the mat was a soil-structure interaction problem that transcended the capability of PCA-MATS and other known programs. It was therefore necessary to develop a supplemental procedure to account for subgrade settlement within the PCA-MATS framework. The proposed procedure modeled the interaction between the mat and subsoil by determining a variation of subgrade modulus k consistent with a subgrade settlement from outside influences. It was an engineering approach that approximated the requirements for equilibrium and compatibility as defined in Figure 4.

The edge condition design procedure is described by the flow chart in Figure 5. The procedure incorporated two design phases:

1. Preliminary evaluation of settlements at mat edge.

2. Iterative design incorporating soil-structure interaction.

When preliminary evaluation showed that the subgrade settlement transition occurring within the mat footprint was too abrupt (more than 2 inches between the mat edge and a second column row), the loading outside the mat was revised by additional replacement with lightweight material. The preliminary evaluation of settlements at mat edges and corners was essential to expedite the interaction analyses by establishing a reasonable magnitude of outside loading. That evaluation eliminated consideration of the unsatisfactory cases involving total loss of contact between the mat and the subsoil which led to excessive slab deformations.

Since the required settlement computations for the many different conditions were too laborious to perform manually for the interactive mat design, the decision was made to develop a custom computer program. The program allowed generation of subgrade settlement profiles for varying surface loads within and outside the mat footprint.

The iterative use of the settlement program and the PCA-MATS program to model the soil-structure interaction was as follows:

1. The area of mat subjected to analyses was divided into interior and exterior zones. The regions assigned to interior zone (not influenced by the outside loading) corresponded to the column geometry alone and shared a constant value of subgrade modulus. The exterior zone, covering the area of a minimum 47 feet wide band around the mat exterior boundaries, was divided into maximum 2 foot wide regions with mostly a single row of elements. This dense grid of regions was necessary in order to vary the value of subgrade modulus k that was required to model the influence of exterior loading on subgrade settlements within the mat edge.

2. The MATS program using the varying values of subgrade modulus k, that were assigned to exterior zone regions, generated the deformed mat shape Z1 and a contact stress W1.

3. The above calculated contact stresses W1, were assigned to the settlement program as the loads, -W1, on the soil combined with the effects of exterior loads, W3, to generate the shape of deformed subgrade Z2.

4. The computed shapes Z1 and Z2 were compared for compatibility of shape, the k values readjusted and the procedure was repeated until the compatibility criterion was met.

5. The stress level in the mat and the mat's converged deflected shape were further compared against the

allowable stresses and tolerable superstructure deformations. When it was found unsatisfactory, the loading W3 was readjusted and the compatibility re-evaluated.

An example of final deflected shape and contact stresses is shown in Figure 3. Corresponding k values typically were about 3 times as much near center of the mat as at the edge.

The safe response to all possible states of stress that could occur throughout the structure's life-span was secured by sizing the reinforcing bars on a basis of moment envelope that combined initial distribution of stresses (constant k without settlement effects) and a final distribution of stresses from the previously described iterative procedure. The required area of reinforcement resulting from flexural analyses was further increased by approximately 15% to account for uneven soil properties as well as tension forces associated with volume change effects. The magnitude of internal forces resulting from the volume change effects was established by the computation of maximum drag forces that could develop due to friction between the mat and subsoil. The sidewalls of depressions required for escalators were separated from the subgrade with a compressible filler in order to reduce the drag. The area of steel of top and bottom bars required in mid-strips was detailed with full tension splices throughout the extent of the mat. Examples of reinforcing for an edge panel and for an interior panel are shown in Table 2.

The entire building footprint was divided into continuous panels not exceeding 400 feet in either direction. Joints were located at third points between columns. At expansion joints, shear transfer between the adjacent panel was accomplished by use of a shelfed joint.

The six-story atrium supported by four pairs of columns required greater load compensation and a much stiffer mat, since each column carries up to 1200 kips. A depressed cellular egg-crate substructure was determined to be the best way to provide the required stiffness, strength and necessary load compensation. It consisted of an 18 inch thick bottom slab with criss-crossing 7-foot-deep heavily reinforced beams spaced 12 feet on centers with a 12 inch thick top slab. Regrading around the building perimeter required using over 1,000,000 cubic feet of expanded polystyrene blocks in a band ranging from 8 feet to 40 feet wide and up to 13 feet thick.

PERFORMANCE

Construction was completed and the facility was opened on October 15, 1990. Because of a construction delay, the northern end of the structure had been completed several months before construction of the southern end could begin. Consequently, during the unanticipated delay, the groundwater level had to be maintained 2 feet below the base of the mat. When the south end construction progressed, construction dewatering was terminated as soon as practical and the 9-foot rise of the water table became the geotechnical equivalent of permanently removing a 500 psf surcharge.

Building settlement records showed that some of the northern foundation edges settled rapidly during the construction delay clearly representing virgin soil consolidation. Most of the structure settlement was relatively uniform totaling less than 0.5 inches during this period, however at some edge and corner areas, the settlement totaled as much as 1.5 inches. When the groundwater table rose at the end of construction, settlement rates decreased sharply or reversed. Figure 6 illustrates typical center and edge settlement during and following construction.

One area continued to settle at a high rate, even after the groundwater table had been maintained at the design level for some time. A plan of the area, Area A, is shown in Figures 1 and 7. Area A was at a corner location adjacent to an area that had been deeply filled with crushed stone for use as a temporary construction access ramp. The replacement of the light weight site soil with the heavy crushed stone was causing virgin soil consolidation under a building corner. The crushed stone was replaced with expanded polystyrene blocks in July 1991 causing the reversal of settlement shown in Figure 8. The performance of this part of the structure demonstrated how sensitive the site was and how effectively the use of expanded polystyrene has reduced differential building settlement.

Besides Area A, predicted settlement has been exceeded only at a few edge locations and was due primarily to the need to keep the water table depressed longer than had been anticipated.

The current rate of settlement compares well with predictions. Geotechnical analyses for secondary compression of the underlying compressible soils indicate that the future settlement magnitudes and rates at the south end will exceed that at the north end where the compressible soils are thinner. Another 10 years will be required before a good comparison can be made between predicted and actual secondary compression rates.

During October 1991, a small section of the superstructure at Area A was elevated to compensate for the settlement shown in Figure 8. The elevating was performed by jacking and shimming at fixtures built into the top of each column for that purpose. The maximum column elevation was raised 1¼ inches and was accomplished during a period of two weeks.

The water table has been maintained at 4.5 feet above the basement floor with permanent dewatering volumes on the order of 5 gallons per minute. Dewatering rates peak after rainstorms, but rarely exceed 30 gpm and have been at 0 gpm for weeks when it hasn't rained. Groundwater fluctuations and recharge volumes have been minimized through the installation of a surrounding slurry trench cut-off wall located 50 to 100 feet from the building. The slurry trench was also one of the keys to construction dewatering. The mat underdrain and perimeter drain system are provided with many overflow points in the basement walls so that water would spill into the basement parking garage floor if the groundwater control system malfunctioned. The overflows are set to prevent excessive hydrostatic uplift.

CONCLUSIONS

1. This project has demonstrated that large mat foundations supported on deep compressible soils are feasible alternates to pile foundations.
2. The effects of subgrade settlement at the edge of a mat can be simulated by interactive use of the PCA-MATS and settlement programs.
3. Edge and corner settlement were critical design considerations for this structure.
4. The use of lightweight fill was an effective component for controlling edge settlements.
5. This project has demonstrated that providing the ability for preplanned releveling for a superstructure can be an effective means in dealing with excessive localized settlement.

ACKNOWLEDGMENTS

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TABLE 1

FOUNDATION STRESSES

[psf]

STRESSES	NO. OF LEVELS		
	3	4	7
buoyancy, fb	440	470	810
gross building pressure, f1	700	850	1475
effective building pressure, f2	260	380	665
preconstruction effective stress at foundation level, f3	770	950	1250
net bearing pressure, f4	-510	-570	-585
value of foundation compensation, fc	1210	1420	2060

NOTES: 1. Number of levels include basement

2. Net bearing pressure $f4 = f2-f3$

3. Value of foundation compensation $fc = f3+fb$

TABLE 2

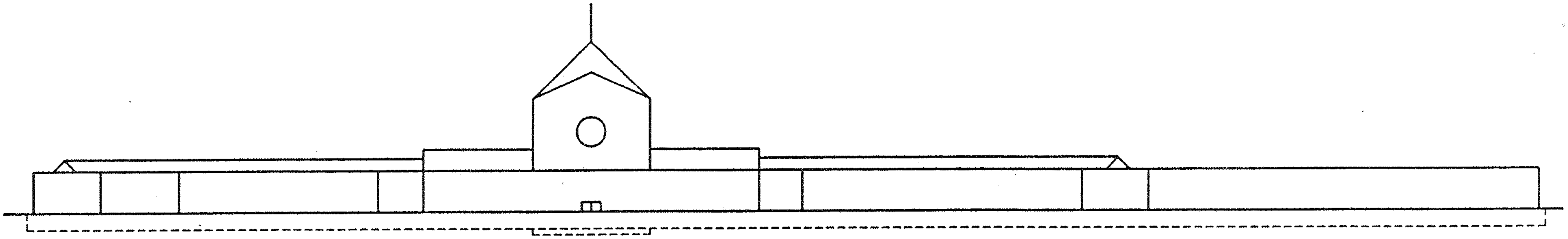
SELECTED REINFORCEMENT FOR TYPICAL 20'-0"x20'-0" BAY OF 24" MAT IN DIRECTION PERPENDICULAR TO MAT'S EDGE

ZONE	LAYER	COLUMN STRIP	MID-STRIP
EDGE	TOP	#7@8"	#7@8"
	BOTTOM	#6@12"+#9@12"	#6@12"
INTERIOR	TOP	#7@12"	#7@12"
	BOTTOM	#6@12"+#9@12"	#6@12"

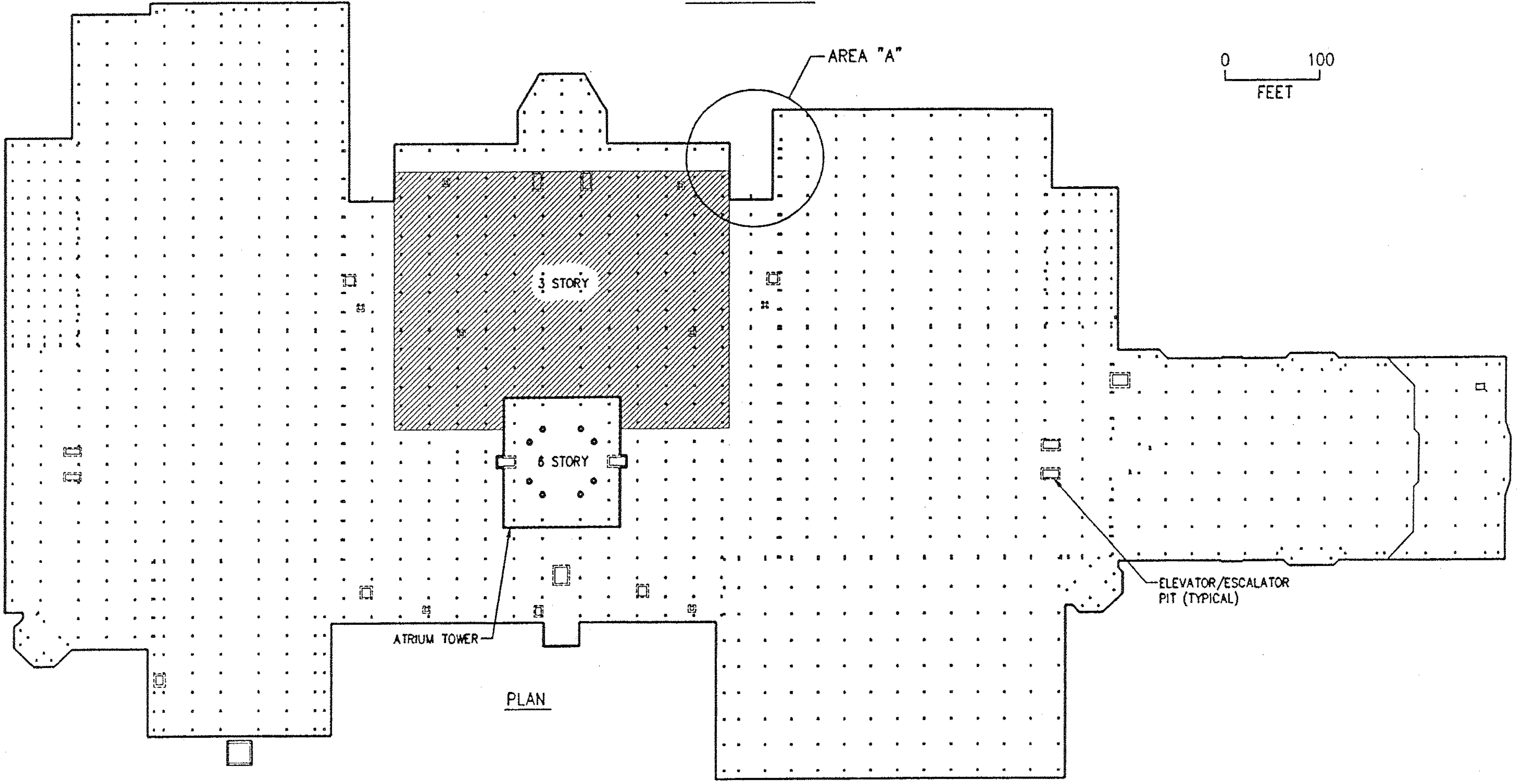
LIST OF FIGURES

FIG.

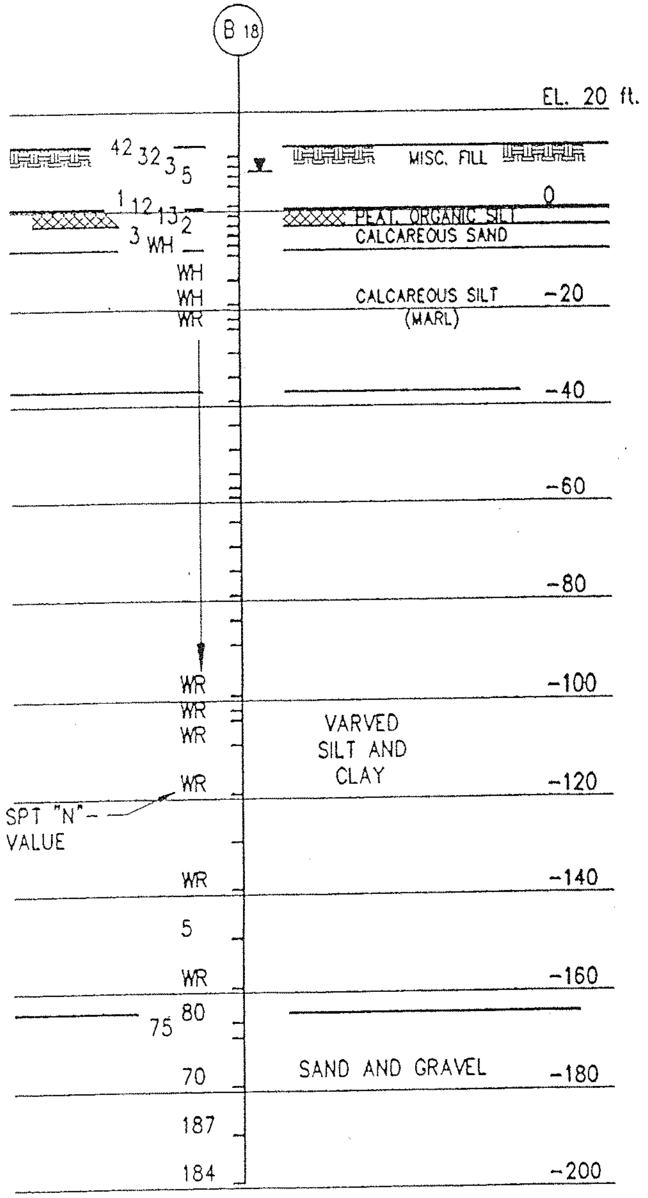
1. BUILDING PLAN AND ELEVATION
2. SOIL PROFILE
3. SUBGRADE LOADS AND DEFORMATIONS NEAR EDGE
4. SOIL-STRUCTURE INTERACTION NEAR MAT EDGES
5. MAT EDGE ANALYSIS ALGORITHM
6. TYPICAL MAT SETTLEMENT
7. SETTLEMENT AT AREA "A" PRIOR TO REMOVAL OF HEAVY BACKFILL
8. SETTLEMENT AT AREA "A"

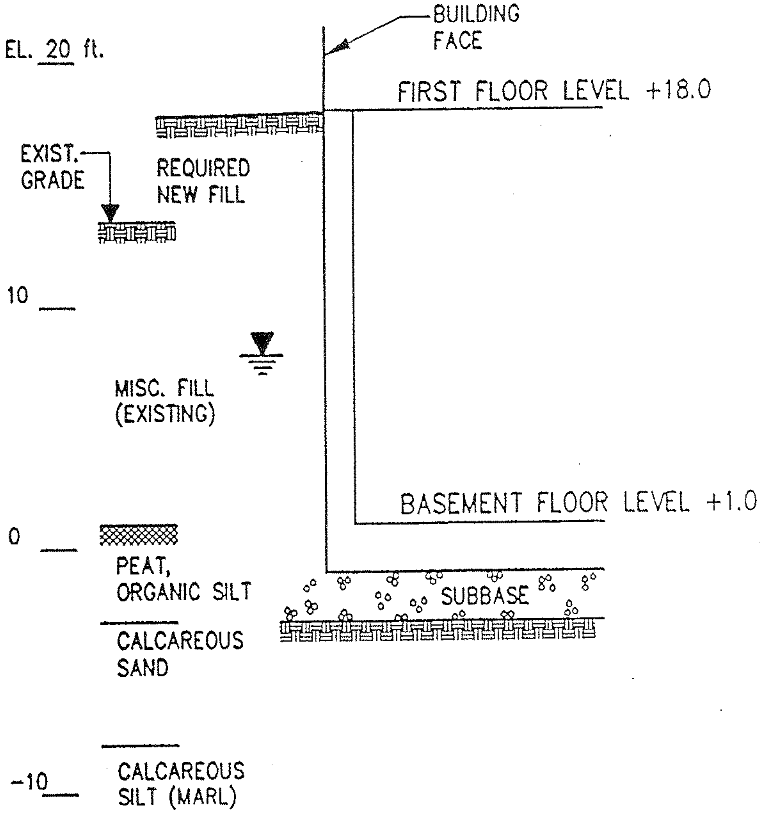


EAST ELEVATION



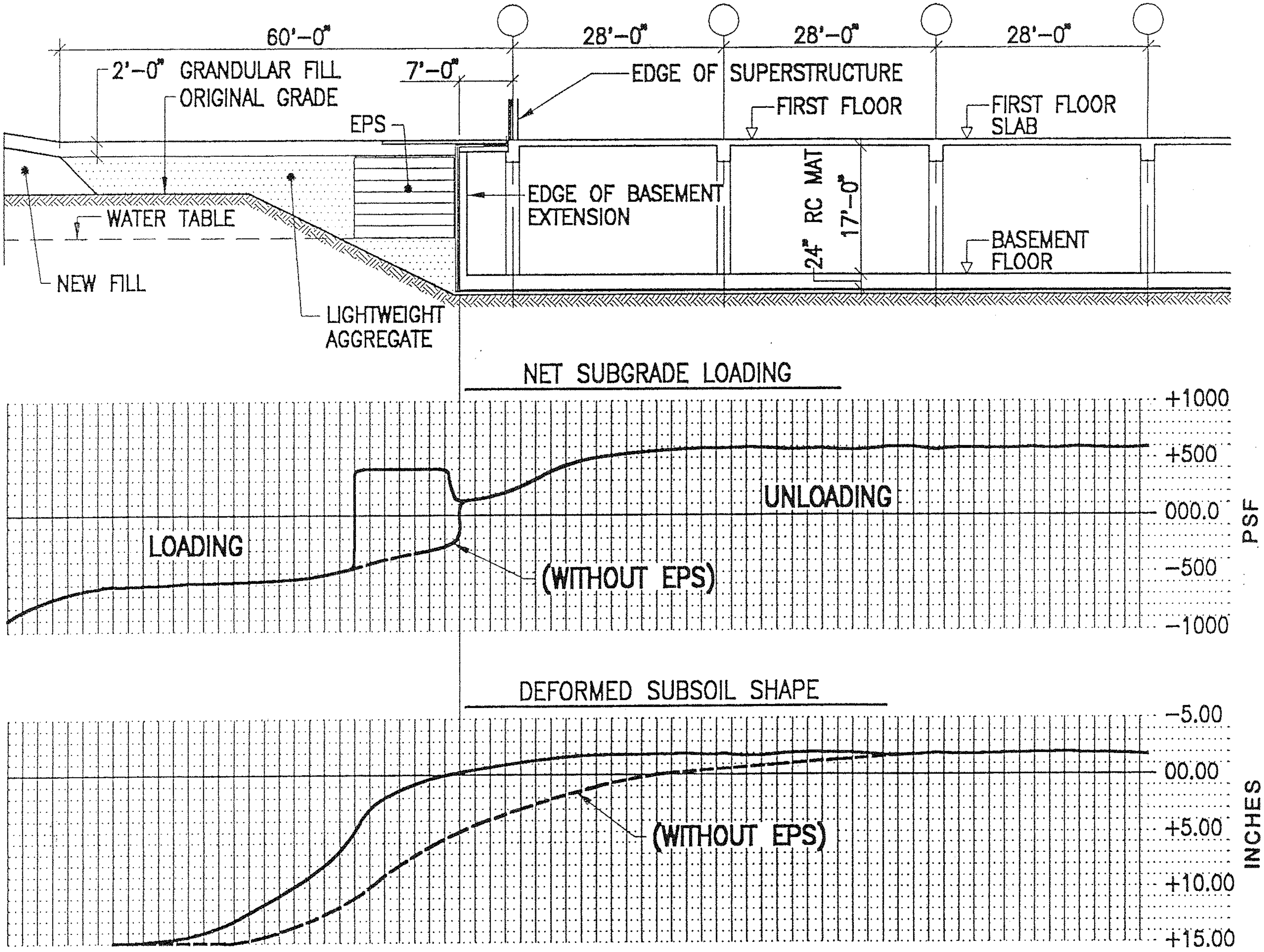
PLAN





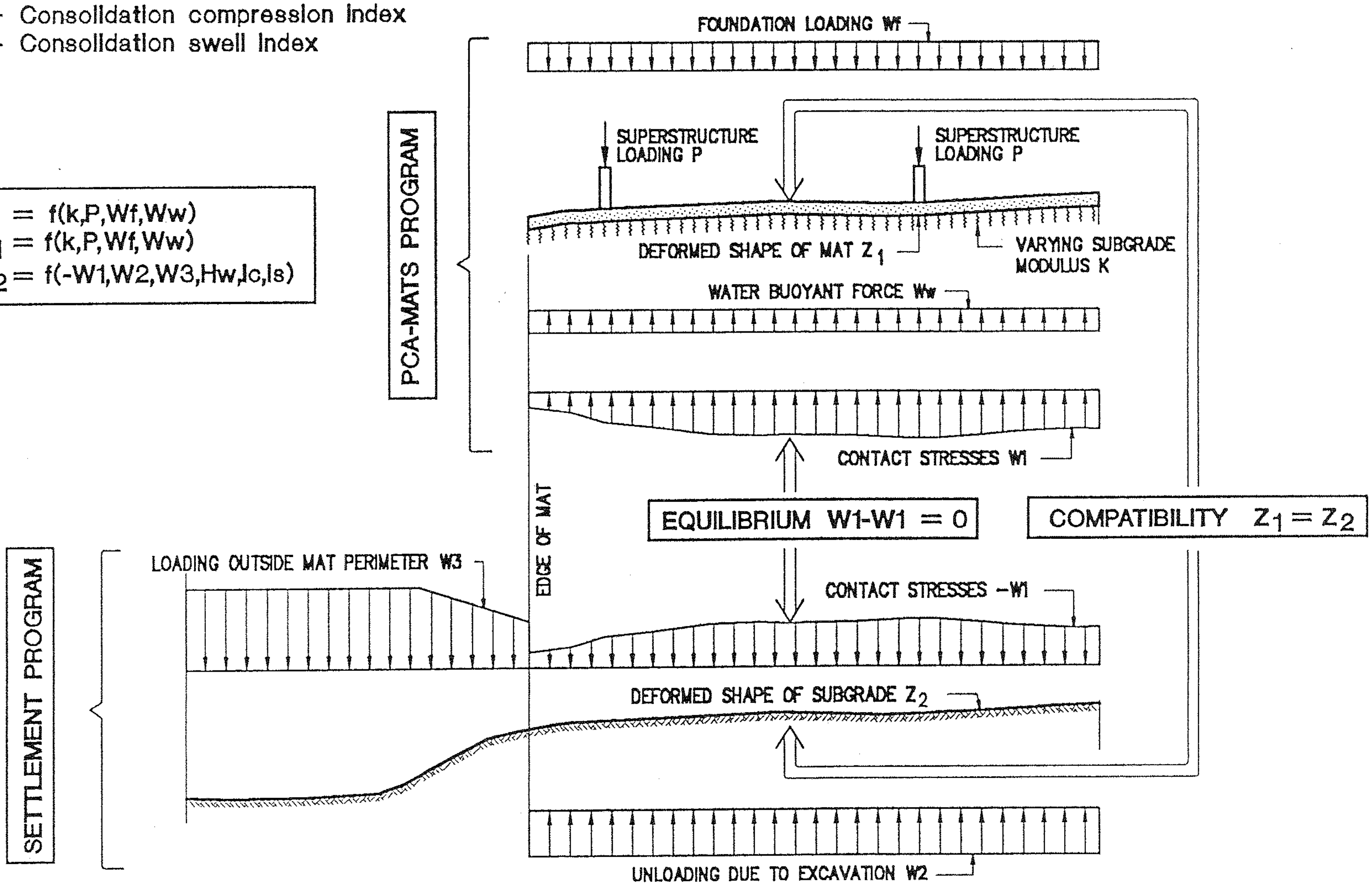
NOTES:

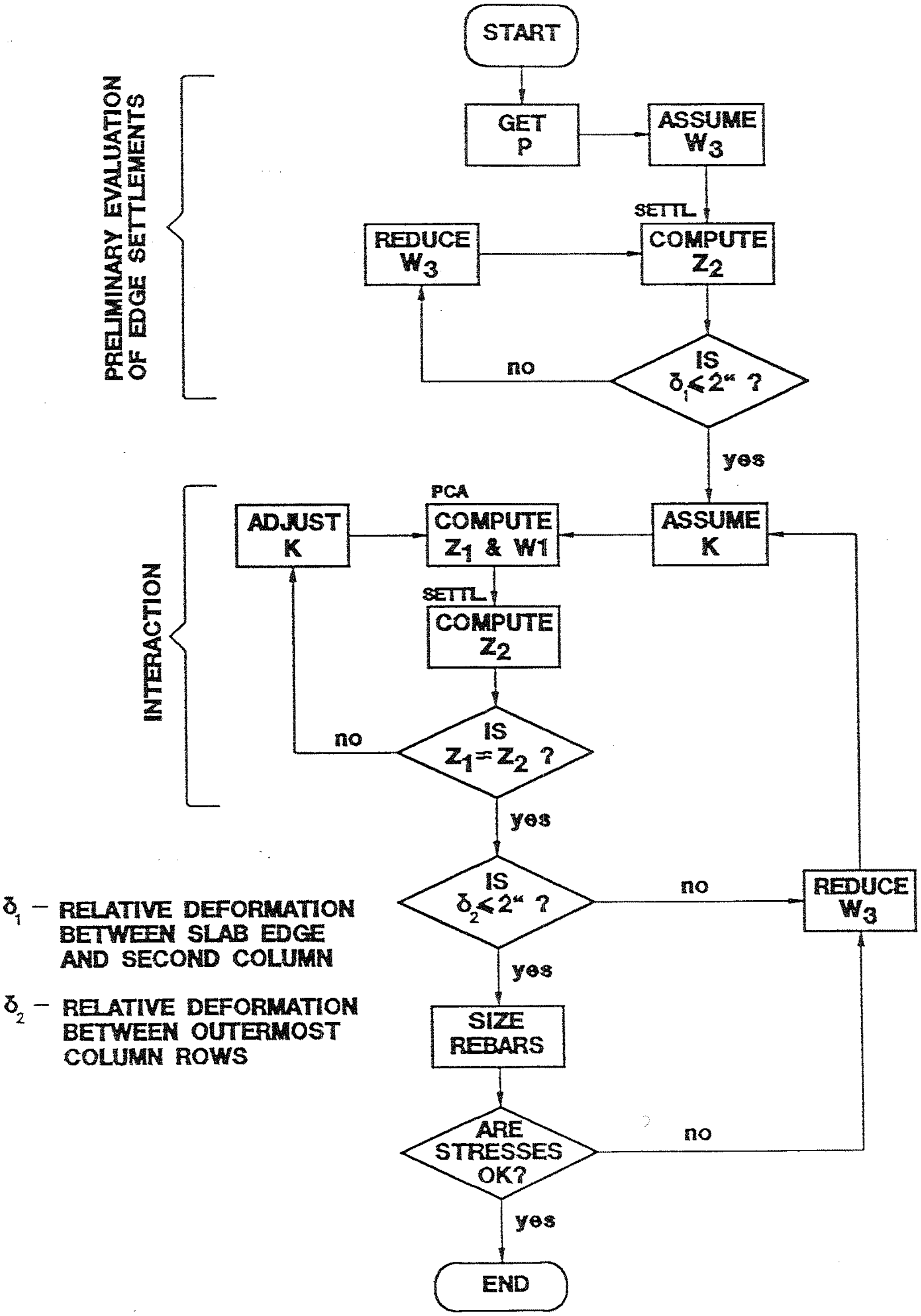
SPT N-VALUES
WH = WEIGHT OF HAMMER
WR = WEIGHT OF RODS
▼ = WATER TABLE


60'–0"
28'–0"
28'–0"
28'–0"
2'–0" GRANDULAR FILL
ORIGINAL GRADE
7'–0"
EDGE OF SUPERSTRUCTURE
FIRST FLOOR
FIRST FLOOR SLAB
EPS
EDGE OF BASEMENT EXTENSION
24" RC MAT
17'–0"
WATER TABLE
BASEMENT FLOOR
NEW FILL
LIGHTWEIGHT AGGREGATE
NET SUBGRADE LOADING
+1000
+500
000.0
–500
–1000
PSF
UNLOADING
LOADING
(WITHOUT EPS)
DEFORMED SUBSOIL SHAPE
–5.00
00.00
+5.00
+10.00
+15.00
INCHES
(WITHOUT EPS)

Hw — Water table elevation
Ic — Consolidation compression index
Is — Consolidation swell index

$$W1 = f(k,P,Wf,Ww)$$
$$Z_1 = f(k,P,Wf,Ww)$$
$$Z_2 = f(-W1,W2,W3,Hw,Ic,Is)$$

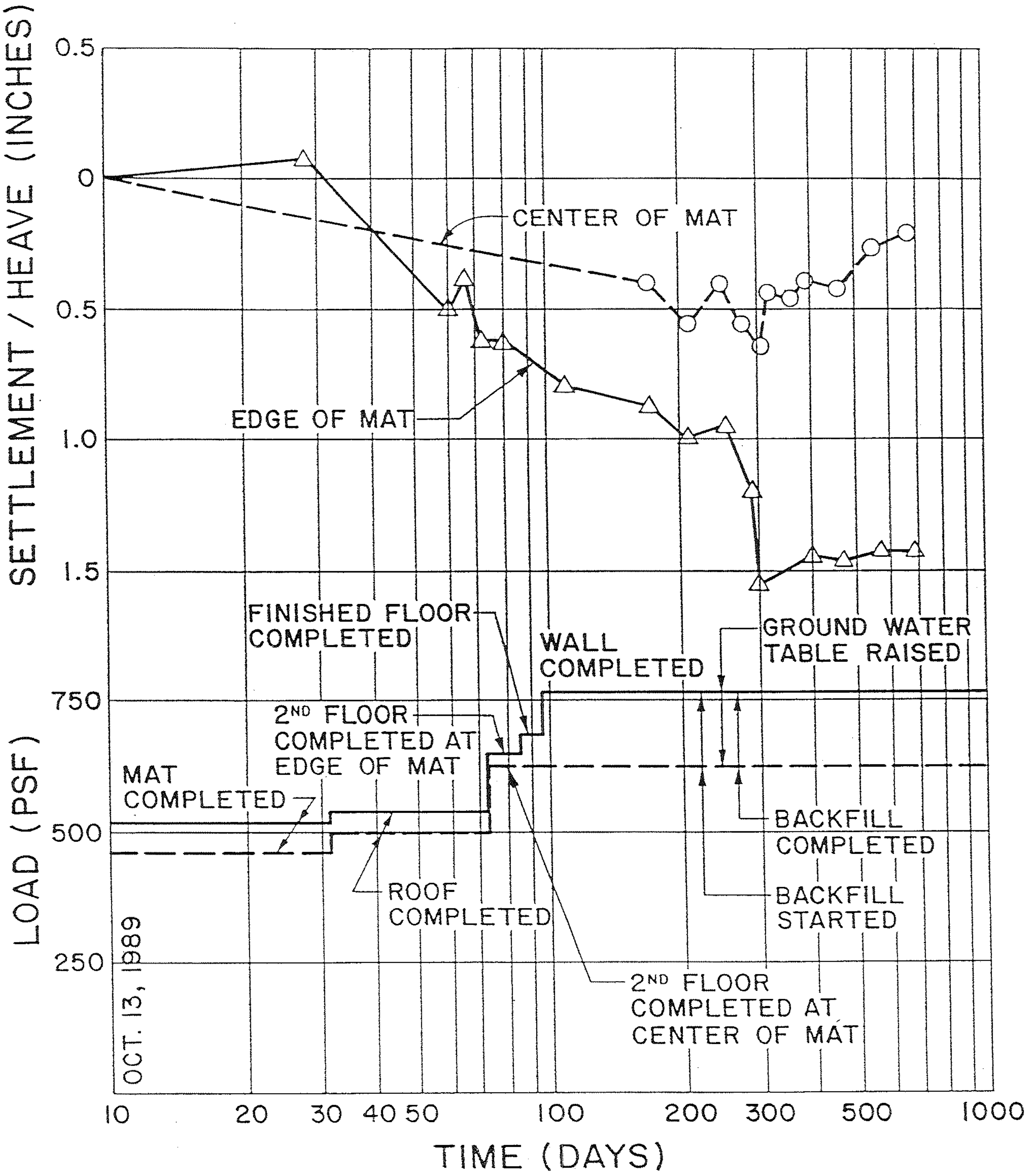




δ_1 — RELATIVE DEFORMATION BETWEEN SLAB EDGE AND SECOND COLUMN

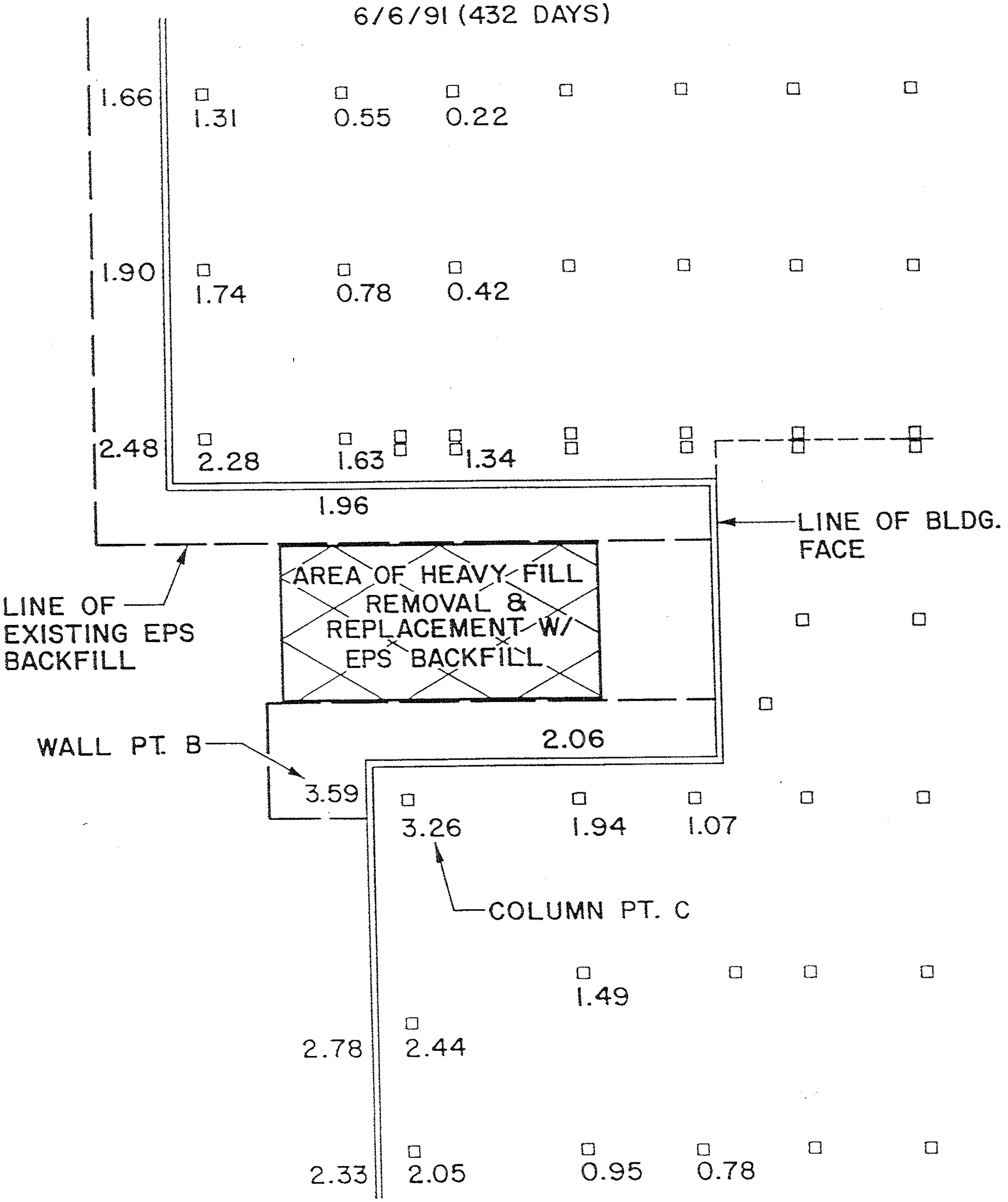
δ_2 — RELATIVE DEFORMATION BETWEEN OUTERMOST COLUMN ROWS

MAT SETTLEMENT



SETTLEMENT OF AREA "A" PRIOR TO REMOVAL OF HEAVY BACKFILL

6/6/91 (432 DAYS)



SETTLEMENT AT AREA "A"