MITIGATING FOUNDATION DISTRESS

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ABSTRACT: Mitigation of foundation distress deals with the science and art of saving foundations from distress or failure. Foundation distress refers to serviceability failure or may cause failure during the life of the structure. The approach for mitigating foundation distress is similar to that of Forensic Geotechnical Engineering, without involving court of law. Evaluation of what went wrong and why (the **4W's**) is the key to solve the problem and develop appropriate foundation rehabilitation system. The paper presents three case studies demonstrating the approach. In the cases presented, the ultimate failure had not taken place but distress in foundation had affected serviceability criteria and/or resulted in reduction in desired factor of safety.

1. MITIGATING FOUNDATION DISTRESS

1.1 The Approach

Foundation distress refers to serviceability failure or may cause failure during the life of the structure. Mitigating distress is a step taken before a disaster strikes or on observing the first signs of distress. It is a preventive action that helps taking action to avoid failure. An experienced geotechnical engineer may be able to point out telltale signs even prior to any significant distress / damage. It also includes restoring/rehabilitating foundations that have experienced damage / distress due to excessive settlement / movement, shear failure, etc.

To mitigate distress, most important is to evaluate why distress has taken place or shall take place and what phenomena are responsible for such distress. In case of failures, it may be possible to estimate ultimate soil parameters and accordingly select the design parameters for foundation restoration. However in case of distress or partial failure, it may not be feasible to evaluate the ultimate soil parameters by back analysis.

As such, it involves a scientific approach to the problem, with clear understanding of sub-strata behavior in conjunction with the response of the structure, soil-structure interaction, and engineering judgment. The distress may not cause disaster / ultimate failure - living example of this is the Leaning Tower of Pisa.

At any stage, one can check the foundation system and evaluate whether it meets the required serviceability criteria with desired factor of safety. The foundation system may then be engineered to conform to the requirements.

Mitigating distress of foundation is, more often than not, an art as much as it is a science. This is because, very often, only limited data is available to take important decisions and the time available may be limited. To arrest a distress from causing a catastrophe, quick and timely action may be required. The geotechnical engineer may have to rise to the situation and come up with effective solutions that can be easily implemented within a short time-span.

From a geotechnical engineering point of view, the main causes for foundation distress are due to shear failure or total / differential settlement. The sub-strata may be engineered to restrict shear failure and / or settlement.

Confinement of the soils is very effective to restrict settlement / shear failure. The foundation system can be engineered even during the construction stage, if any problem is identified. Similarly even for pile construction projects, any abnormal soil conditions, if observed during the construction of piles, the problem can be solved, if adequate and proper measures are taken at that stage.

However, the abnormal situations are to be studied in depth to identify the problems for mitigating the distress or failure, which may occur subsequently.

1.2 Forensic Geotechnical Engineering

Forensic generally refers to failure / disaster / distress causing loss of life or property leading to litigation. The dictionary meaning of the word FORENSIC is "*connected to scientific tests used by the police to solve a crime*".

The approach to mitigating foundation distress is based upon the principles of forensic geotechnical engineering.

Forensic Geotechnical Engineering / Mitigating Foundation distress involves the following steps:

- Identifying the problem

- Investigation / evaluation of foundation failures, excessive settlement, slope failure, other damages /defects
- Risk-assessment, in cases where failure has not yet occurred
- Review and interpretation of geological and geotechnical data in conjunction with structural data
- Conducting a site investigation, if required to obtain data for analysis
- Back analysis of failures to assess causes, detailed analysis of foundation behavior in cases where failure has not yet occurred
- Developing technically feasible solutions to strengthen foundation and restore structure
- Reviewing merits and demerits of each scheme
- Selecting suitable solution based on availability of equipment / technology, time schedule for construction, costs, etc.
- Implementing the foundation strengthening scheme on site
- Monitoring the foundation restoration activity, conducting in-situ tests, if appropriate, to evaluate the efficacy of the strengthening measures.

Fig 1 presents a flowchart illustrating the steps involved.

1.3 When Does Forensics Come into Play?

The word "FORENSIC" has a legal connotation. It conjures up images of a court battle with lawyers arguing to put forth the case of their client and the prosecution trying to placate the accused.

Does this pre-suppose that (a) a failure has occurred resulting in some casualties (loss of property, human life, inconvenience to public, etc.), (b) someone has been blamed for it, and (c) the matter has gone to court / arbitration? Does the geotechnical engineer have to "*wait for the extreme*" to investigate the cause of failure and propose solutions to mitigate the distress?

While the extreme situation is definitely a case of engineering being used to solve a legal tangle, geotechnical engineers are involved in evaluating failures as well as possibility of failures much before the matter becomes a subject of debate or legal controversy.

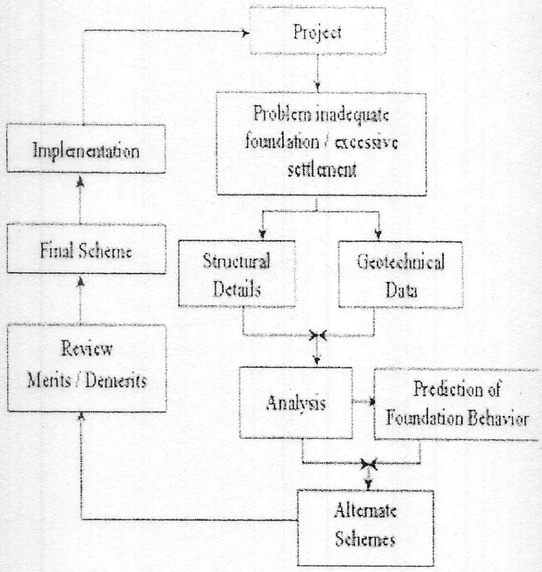

Fig. 1: Foundation Distress Mitigation - Flowchart

Therefore, geotechnical engineering activity related to "studies to predict whether or not failure is likely to occur, taking necessary steps to limit / avoid further foundation distress, etc." are also covered under the ambit of forensic geotechnical engineering. It is tantamount to taking necessary steps that will avoid an arbitration case or a civil liability suit.

The forensic geotechnical engineer may be involved with the case as a policeman, helping the owner to find out whether the contractor is responsible for the failure; he may be providing the technical input in an arbitration case involving claims. He may also be involved as a friend guiding the contractor or owner for restoration of a structure that has experienced distress or for resolving a potential problem.

Distress may occur due to some unforeseen catastrophic events such as earthquakes, floods, cyclones, tsunami, etc. In such cases, no "*culprit or accused*" may be identifiable. Geotechnical engineers involved in restoring foundations damaged by such events are obviously doing forensic work - identifying how the foundation behaved during the catastrophic event, why it failed, and what needs to be done to rehabilitate it. Above all this is the lesson to be learnt from the disaster how to prevent future damage to structures that have not yet failed.

1.4 What Went Wrong & Why (The 4W's)

Before taking up any foundation restoration activity, It is essential to evaluate / identify what went wrong and why 4W's. In most of the cases, understanding of 4W's can give an insight into how the foundation behaved under the particular combination of site conditions and applied loads.

For mitigating foundation distress, behavior, characteristics, in depth study of soil / sub strata, structure as a whole, foundations in particular, stress / loading patterns, suspected failure / distress mode are all to be understood for working out a solution to arrest further distress in foundation system. Thus, evaluation of the 4W's is the investigative part of forensics that is essential to solve the problem.

The commonly reported types of geotechnical failures include:

- Shear failure of foundations due to low bearing capacity of soils,
- Excessive settlement of foundations resulting in major cracks in the building,
- Adding additional floors to existing building without proper appreciation of soil conditions,
- Scour of soil beneath bridge foundations,
- Failure of soil/rock slopes,
- Failure of deep excavations due to steep slopes, water seepage, etc.,
- Migration of fines from beneath road pavements resulting in formation of potholes,
- Unidentified cavities/tunnels beneath structures,
- Seepage of water beneath embankments/dams, rock mass in hilly areas,
- Poor quality construction, incorrect design, etc.

Mitigation of foundation distress need not necessarily be only in the case where distress has taken place. It may also be to avoid any distress at a later date. The approach is similar to retrofitting.

In mitigation of foundation distress, the principles of forensic geotechnical engineering, basic soil engineering, principles of ground improvement i.e. to engineer the ground, foundation and structural behavior, etc. all play important role.

Various strengthening methods include retrofitting of weak foundations, underpinning, micro-piles, lateral confinement of the soils to restrict movement, ground improvement, grouting, etc.

With this background, the paper demonstrates the approach to mitigation of foundation distress. Three case studies illustrating these concepts demonstrate successful implementation of foundation strengthening / stabilization. In the cases presented, the ultimate failure / disaster had not taken place but were referring to the distress in foundation affecting serviceability criteria and reduction in desired factor of safety.

The cases focus on issues like

- misinterpretation of soil conditions due to poor appreciation of geology and inadequate geotechnical data.
- designing and constructing the foundation based upon the experience of other project at different location.
- not referring to proper reference levels and drawings resulting in construction of structures without proper / adequate foundation.

2. CASE STUDY 1: THE JANMABHOOMI TEMPLE AT MANGARH

The Janmabhoomi Temple, constructed at Mangarh (UP), the birthplace of His Holiness Acharya Kripalu Maharaj, was planned as an elegant structure in granite stone blocks. A photograph of the temple's model is presented on Fig. 2.

2.1 Concepts and Mythology

Drawing from ancient temple architecture, the construction primarily uses granite masonry. Granite blocks have been used for the foundation and up to the platform level. The super-structure consists of carved granite pillars and domes. The main block, the Garba Griha and the Mandap, are surrounded by peripheral granite stone walls on either side for small temples and corridors.

Modern construction materials such as reinforced concrete, steel etc., have not been used. The philosophy is that steel should not be used in the construction. The reason is the belief that steel will obstruct the divine vibrations between the Devotee and God.

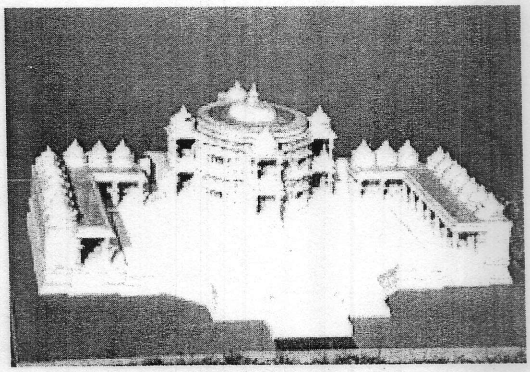

Fig.2: Photograph of the model of the Janmabhoomi Temple at Mangarh

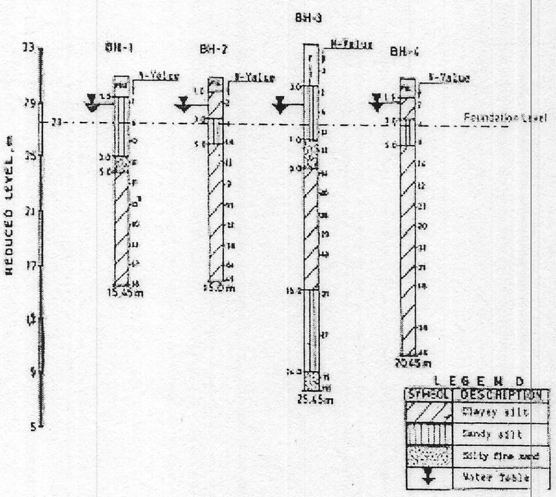

Fig. 3: Site Stratigraphy, Mangarh

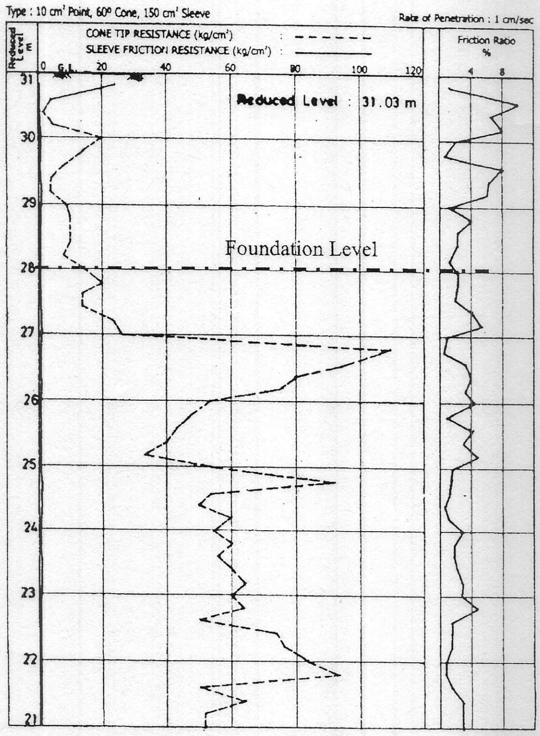

Fig 4: Static Cone Penetration Test Results

It was also felt that steel will rust over a period of time and will not only destroy the sanctity of the temple but also reduce the life of the structure. The temple has been planned for a life span of 500 years.

2.2 Foundation Block and Loading

The foundation bearing at 3 m depth was a 5.4 m thick massive block made of granite masonry. Considering the density of granite as 2.85 g/cc, the gross bearing pressure applied by the 5.4 m thick platform (raft) works out as about 15.5 T/m^2. The net bearing pressure at 3.0 m depth works out as 10.5 T/m^2 even before construction of the superstructure.

As per the design, the load expected in the main temple area over the platform below the Garba Griha is about 25~27 T/m^2. In the small temple area, the anticipated loading is about 20-21 T/m^2. Over the platform area beyond the Garba Griha, the loading is expected to be about 15~16 T/m^2.

2.3 The Problem

When the platform was constructed up to +2.4 m level, some cracks were observed in the foundation block. The designers and construction engineers also had an apprehension regarding the soil bearing capacity and whether the soils will safely withstand the design loads. In particular, since the loading condition varies across the foundation block, it was felt that differential settlement could be critical.

2.4 Forensic Geotechnical Activity The Approach

After review of the site conditions and loading data, the forensic geotechnical engineering activity to assess the problem and work out the engineering solution was undertaken in the following steps:

- Evaluation of the soil conditions;
- Prediction of likely foundation behavior;
- Determining the need for foundation strengthening;
- Developing a technical solution that respects the religious sentiments involved; and
- Executing the foundation-strengthening scheme.

2.5 Soil Conditions

The soils at the site are alluvial in nature. Below a surficial fill, that extends to about 1.5-3.0 m depth, the natural soils below foundation level consist primarily of sandy silt and clayey silt of low to medium plasticity to 25.0 m depth. Water table was encountered at about 2.0 m depth (RL 29 m) and is likely to rise up to GL during rains.

The stratigraphy at the site is illustrated on Fig.3. The results of a typical static cone penetration test are plotted on Fig. 4.

2.6 Geotechnical Considerations

The platform (foundation block) is expected to behave as a massive raft foundation. Considering the size, the authors are of the opinion that total settlement is not likely to be a serious problem. However, the granite masonry structure may not be able to withstand any significant differential settlement or tilting. Particularly, the dome of the Garba Griha is expected to be very sensitive to differential settlement.

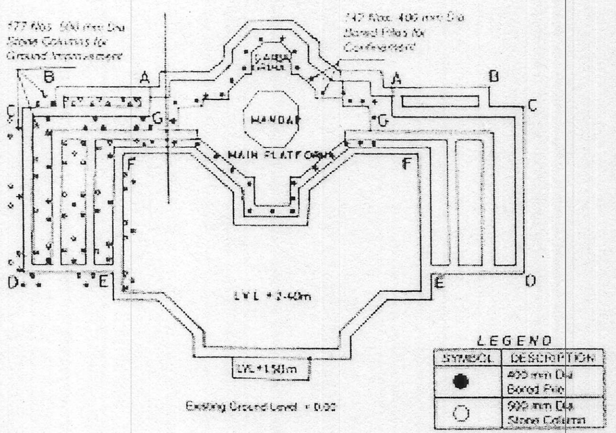

Fig 5: Foundation Strengthening Scheme

A settlement analysis of the raft indicated that under a uniform loading of about 25 T/m^2, the total settlement is expected to be on the order of 130-160 mm. At the time the problem had been referred for evaluation, platform had already been in place for about 6-8 months. During this period an estimated 20-30 percent of the total settlement may probably have occurred.

However, the main matter of concern was that the platform is not uniformly loaded. While the loading in the Garba Griha area is about 25 ~27 T/m^2, bearing pressure under the rest of the platform is only about 15-16 T/m^2. Further, the small temples area, which consists of parallel strip footings (granite walls), is relatively less stiff in comparison to the platform block.

In view of this, it was felt that differential settlement is a matter of serious concern. The granite masonry structure is unlikely to be able to withstand the tensile stresses due to differential settlement

2.7 Engineering Solution

The engineering solution had to take cognizance of the fact that a massive foundation block has already been constructed. Therefore, limited workspace was available for any additional foundation system.

The following issues were identified to work out a foundation system that will not only address the geotechnical issues but also ensure that the temple stands the test of time:

- Create a confinement for the soils beneath the Garba Griha;
- Restrict any potential for outward flow of soil;
- Ensure that the settlement is relatively uniform, thereby minimize the chances of differential settlement/tilt; and
- Limit potential for upward movement of soil / shear failure in the Mandap area by plugging it effectively.
- Reduce the total settlement of the foundations in the small temples area by strengthening of soils.

Certain constraints / limitations specified by the Temple architect has to be respected to maintain the sanctity of the temple structure. These include

i) No steel should touch the temple structure;

ii) No steel should be used in the Mandap area;

iii) The basic structure, as constructed, cannot be altered; and

iv) Avoid use of RCC to the extent possible. No RCC member should touch the stone masonry.

After evaluation of all aspects of several possible solutions, the following measures were adopted:

(1) The confinement of the main temple block was achieved by provision of closely spaced RCC bored piles (without touching the stone masonry).

(2) The Mandap area was plugged by provision of plain concrete piles (no steel to be used).

(3) The soils around wall foundations (strip footings) of the small temples/corridor area were strengthened by rammed stone columns to increase confinement and reduce potential for shear failure.

The foundation-strengthening scheme is illustrated on Fig.5.

Confinement of the main temple structure was ensured by provision of closely spaced piles. A total of 142 nos. 400 mm diameter, 12 m long reinforced concrete piles were provided. The cut off level of the piles was 0.7 m below the platform level. The piles were spaced 750 mm centre-to-centre.

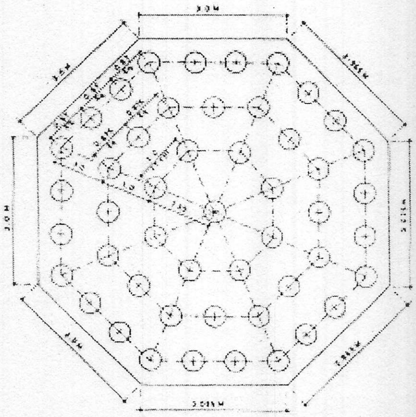

Fig. 6: Piles in the Mandap Area

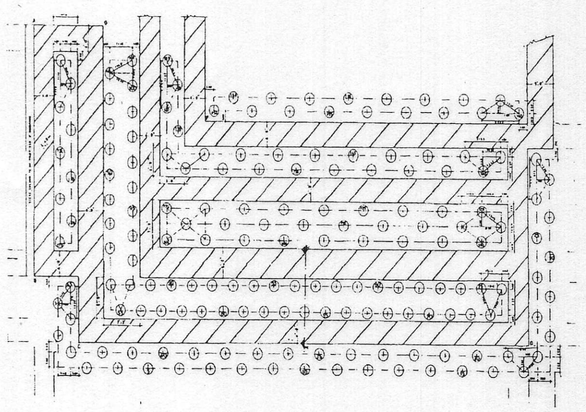

Fig 7: Stone Columns for the Small Temples Area

A tie beam interconnecting the piles was provided. The piles were designed to resist the lateral thrust developed due to the confinement effect.

The Mandap area is an octagonal opening in the centre of foundation block of the main Temple. The Mandap will have a big dome over it supported by eight columns.

It is an unloaded part of the foundation block; the columns will apply point loads. The concern was that the soil plug in this portion may get squeezed and may move up.

Strengthening the Mandap will make the confinement more effective, thus ensuring a more uniform settlement of the foundation block. However, in this area, use of reinforced concrete was not permitted.

A total of 49 nos. 400 mm diameter plain concrete piles were installed in an octagonal grid pattern. The pile tip was at 12 m depth below ground level (9 m below foundation level) and the pile top was 1 m below the platform level. Over these piles, a 0.3 m thick plain concrete slab was placed with a Shailtex board to isolate the concrete from the stone masonry.

In the small temples area, ground improvement was done by provision of rammed stone columns, 500 mm in diameter, extending to 5 m depth below the foundation level. The ground improvement system achieved the following objectives:

- By providing a composite material with ϕ value in the range of 35-45 degrees, the safe bearing capacity of the soils was increased and the possibility of shear failure was eliminated.
- The total settlement of the wall foundations reduced substantially, thereby ensuring a greater compatibility with the main foundation block and that the total and differential settlements were well within the acceptable limits.

The temple has now been constructed and no distress has been observed in any of the structural elements till date.

3. CASE STUDY 2: TILTING OF AN OVERHEAD TANK

An overhead tank at Tuglakabad, New Delhi had experienced some tilt during hydro-test. The tank was supported over raft foundation of 8.5 m diameter and the tilt was due to excessive settlement under a part of the foundation.

3.1 Site Conditions

Soil investigation revealed that the underlying silty soil was in loose state till about 4 to 6 m depth below which a hard layer/severely weathered rock was present. Fig.8 presents a borehole profile at the site. The thickness of the loose soils above the hard layer varied from 4 m at one end of the raft foundation to about 6 m at the other end.

The tank was located along the alignment of an underground water flow channel draining into a nearby nallah. The cause was identified as being due to migration of fines when flow of groundwater took place and the varying thickness of the overburden above the weathered rock resulting in variable settlements across the raft foundation.

3.2 Foundation Strengthening Scheme

In order to arrest further settlement/tilting of the tank, the authors developed a scheme for providing a curtain wall to arrest any further migration of fines/soil particles. The scheme was implemented in two phases.

In the first phase, 300mm diameter bored auger piles were installed at close spacing all around the periphery of tank raft foundation. The piles were extended to the top of the refusal stratum. A conduit pipe was provided in the pile bores and the underlying hard layer was grouted through the conduit pipe after the pile was concreted.

In the second phase, grout holes of 75mm diameter were drilled in the space between the piles and raft foundation up to the refusal/hard layer. The grout holes were plugged at foundation level up to gravel bed was pressure grouted with cement slurry under a pressure of 2 to 2.5 kg/cm^2.

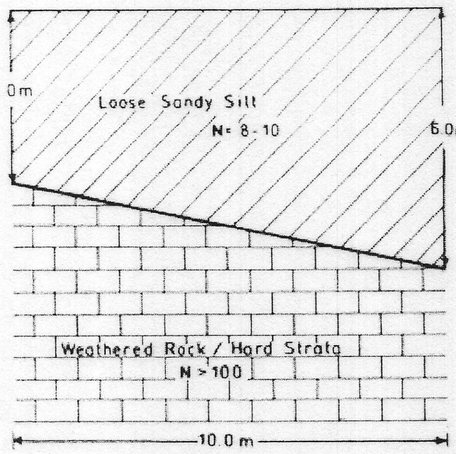

Fig. 8: Soil conditions beneath Overhead Tank

The sequence for providing piles and grout holes as designed in such a way so as to ensure proper lateral confinement. On completion of both the cycles, all locations were again checked for any further grout intake under pressure. Fig.9 presents the schematic plan for piles and grout holes.

4. CASE STUDY 3: FOUNDATION STRENGTHENING OF A RESIDENTIAL COMPLEX

4.1 The Problem

After the construction of a four-storeyed housing complex in South Delhi, it was revealed that the foundations provided were of a width smaller than the designed width. The applied bearing pressure on the soil exceeded the permissible value.

4.2 Site Stratigraphy

The stratigraphy at the site consisted of overburden soils (medium dense sandy silt of low plasticity) to about 5-6 m depth underlain by quartzite rock. The soil conditions are illustrated on Fig 10.

4.3 Assessment of Adequacy of Foundations

Evaluating the site conditions, the foundations were deemed as inadequate, i.e., the factor of safety was less than the minimum acceptable value of 2.5 as per IS codes/normal practice. The actual computed factor of safety ranged from 1.3 to 2.1. However, there were no cracks / signs of any distress in the buildings.

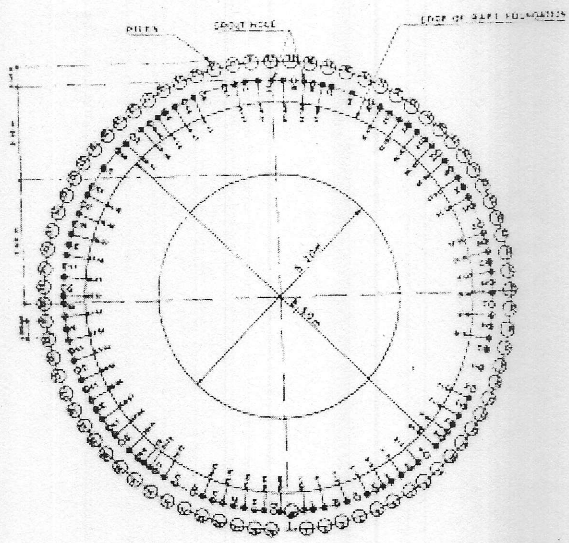

Fig. 9: Overhead Tank Foundation Strengthening

However, for long-term stability/safety, it was felt that suitable remedial measures should be undertaken to provide adequate foundation system to the structures. To develop a suitable foundation strengthening system, each load-bearing wall was evaluated and the inadequacy in the foundation design was worked out.

4.4 The Pile-Needle Beam System

A pit was excavated at selected locations along different walls and the dimensions of the brick-wall spread footing and their depth were measured. From the borehole data, the safe bearing capacity was worked out. For the purpose of this analysis, the bearing capacity safety factor was taken as 2.5 and the permissible total settlement was taken as 50 mm.

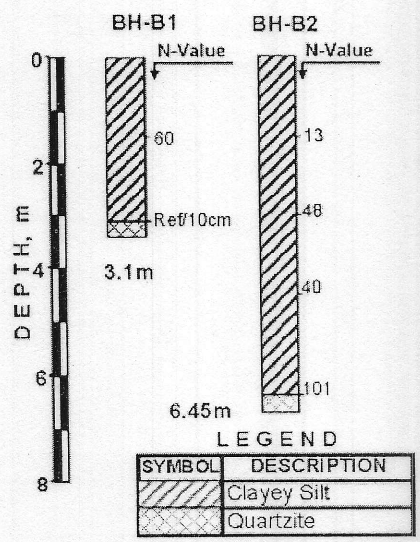

Fig 10: Borehole Data for Housing Complex

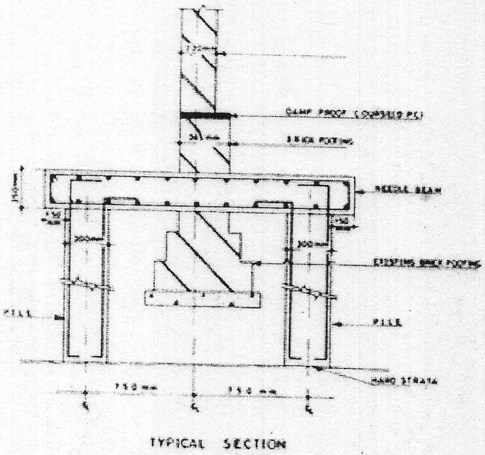

Fig 11: Schematic of Needle Beam-Pile Concept

The foundation load data was then used to assess the load that the foundation can safely transfer as well as the deficiency/excess load that needs to be transferred by the additional foundation system.

The excess load was transferred to piles installed on either face of the load bearing wall by using a needle beam passing through the wall and connecting the pile top. The space between the needle beam and wall was filled with concrete and grouted to ensure proper load transfer of the structures to the piles through the needle beam. Fig. 10 presents a schematic sketch of the foundation strengthening technique.

The spacing between adjacent needle beam-pile systems was decided depending on the deficiency in the load carrying capacity of the wall foundation.

The load bearing walls were also reinforced with steel bars at suitable spacing so as to ensure adequate transfer of loads over the new foundation system. Fig. 12 is a photograph showing the installation of the needle beam.

After installation of the system, the buildings were finished. The structures were load tested using strain gauges etc. It was observed that the loads were getting transferred to additional foundation system. It was established that now the structures have adequate factor of safety.

Several years have gone by and the structures have not shown any signs of distress. But, it did ring a warning bell that poor design and faulty construction can have grave consequences.

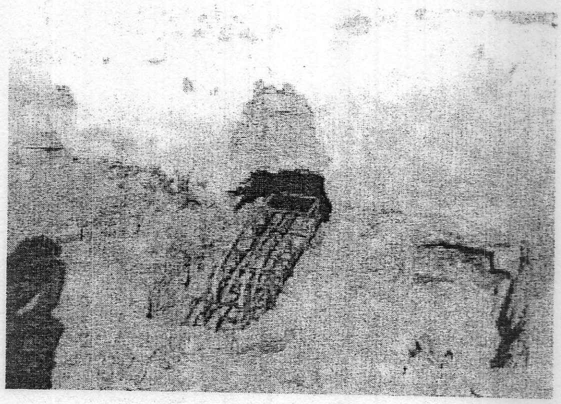

Fig. 12: Needle-Beam being installed across the wall foundation

6. THE LESSONS LEARNT

Forensic geotechnical engineering can come to the rescue of structures that are likely to or have experienced foundation distress/failure. Foundation distress refers to serviceability failure or may cause failure during the life of the structure.

Forensic refers to failure / disaster causing loss of life or property leading to litigation. Without involving court of law, mitigating foundation distress is covered under forensic geotechnical engineering.

As such, it involves a scientific approach to the problem, with clear understanding of sub-strata behavior in conjunction with the behavior of the structure, soil-structure interaction, and engineering judgment.

Detailed investigation of cause and mode of failure together with careful planning and sound engineering practice is the key to successful execution of the foundation strengthening process. The "4 W" approach is the key to mitigate foundation distress.

The aim of a distress mitigation exercise is not to constitute a fault-finding mission but fact finding mission. The purpose is to save structures from major disaster / damages.

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