Forensic Geotechnical Distress Evaluation of Damaged Buildings in Alluvial-Loessic Soils; A Case History

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FORENSIC GEOTECHNICAL DISTRESS EVALUATION OF DAMAGED BUILDINGS IN ALLUVIAL-LOESSIC SOILS; A CASE HISTORY

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ABSTRACT

The city of Hyderabad is a part of lower Indus Basin with arid-tropical climatic conditions. Geologically, the soil deposits near Hyderabad are of alluvial-loessic nature underlain by limestone beds alternating with clay layers. Groundwater is present at shallow depth which fluctuates to even shallower depths during monsoon season in the months of July and August. In recent past, large number of buildings built over shallow foundations in the city suffered structural damages of varying scale in the form of cracks and settlements. Some of these buildings were declared dangerous from safety and stability view point and got vacated by local administration.

A forensic geotechnical distress evaluation was carried out to identify the causes and process of damages. The study comprised survey of structural distresses and review of original geotechnical investigation report, selected design parameters, construction materials used and quality controls implemented. Additional geotechnical field and lab investigations using conventional and geophysical techniques were carried out to characterize the existing foundation soil conditions. Presence of problematic soil layers of swelling nature were found within the zone of influence of all the damaged structures. Investigations indicate swell pressure to be the major source of distresses leading to foundation failure. Leakages of water from supply lines, sewerage pipes and fluctuating ground water table are identified as the sources of water responsible for swelling.

The paper includes detailed methodology of geotechnical distress evaluation, recommendations to enhance geotechnical investigation for problematic soils and selection of appropriate design parameters. It is hoped the lessons learnt from this case history would enhance practical geotechnical engineering practices in Pakistan and elsewhere.

INTRODUCTION

Problems associated with construction on problematic soils are well known all over the world. However, in Pakistan this important subject of geotechnical engineering apparently lacks significant study. Main reasons for this could be that these soils have not been encountered in major projects so far and secondly, problems actually associated with problematic soils have been overwhelmed by poor quality control in construction industry and tendency of over safe designing.

Forensic Geotechnical Evaluation deals with analysis of distresses / failures in structures which are attributed to geotechnical origin, not only from technical, but also from legal and contractual viewpoints. Geotechnical based distress in structures due to natural hazards including seismic damages also come under this purview. The commonly adopted standard procedures of testing, analysis, design, and construction may not be adequate for forensic analysis. Thus, in the forensic investigations, every micro aspect of the design, construction and maintenance actions are studied in detail to analyse what, when, how, and why something went wrong and more importantly, who is responsible for it. This procedure not only assists in litigations, but also helps in improving the standards of geotechnical aspects of a project.

Settlement of buildings in Hyderabad City had been a much talked about phenomenon quite since long. These buildings were constructed in the early years of 1970's. Since year 2002, Hyderabad is facing with ever increasing soil problems manifesting in differential settlement and cracks in the buildings. In Northern part of the city, 24 out of 54 buildings were excessively settled and 8 out of these were declared dangerous and recommended for demolition.

The authors of this paper carried out distress measurements in 2009 and later in 2012. Comparison of distress pattern (cracks and tilts) with those observed two years earlier indicated an increase in all previous distresses while new cracks and tilts are also emerging. The paper includes:

- Review of previous geotechnical investigations, foundation designs, building and utility layouts
- Nature of distresses
- Afresh geotechnical investigation including evaluation of index, mechanical, shear strength, consolidation, chemical properties, etc.
- Geotechnical findings
- Remedial measures
- Geotechnical guidelines for future construction

REVIEW OF PREVIOUS GEOTECHNICAL INVESTIGATION, FOUNDATION DESIGN AND BUILDING LAYOUTS

The research team liaised with the concerned offices for acquisition of documents such as Geotechnical Investigation Report, foundation & building design criterion, shop drawings, and construction & monitoring records. The documents of the recent buildings were obtained while those of old buildings, the documents were not available. The team was however able to meet one of the supervisor who had served at Hyderabad City while the distressed buildings were being constructed. Salient features of this review are as following:

- Site investigations were made using conventional field and lab tests
- Geotechnical investigation was carried out up to a depth of 1 m where strata are predominantly gravelly (such a stratum would always suggest relatively better foundation soils with good bearing capacity)
- Bearing capacity was evaluated using results of Standard Penetration Tests (SPT) performed at 1 m depth and Unconfined Compressive Strength (UCS) Tests performed on samples collected from 1 m depth
- Foundation soil bearing capacity of 1 TSF (ton per square foot) was recommended
- Buildings were designed with strip foundation for bearing capacity of 1 TSF
- Depth of foundation was kept at 1 m
- Neither any soil problem was identified nor any special provision was envisaged for the foundations
- Bathrooms and kitchens were placed along two sides and sewerage lines were also place along the sides of the buildings. On sides with kitchen and bathrooms, sewerage tanks were also provided. These arrangements are shown in Figure 1.

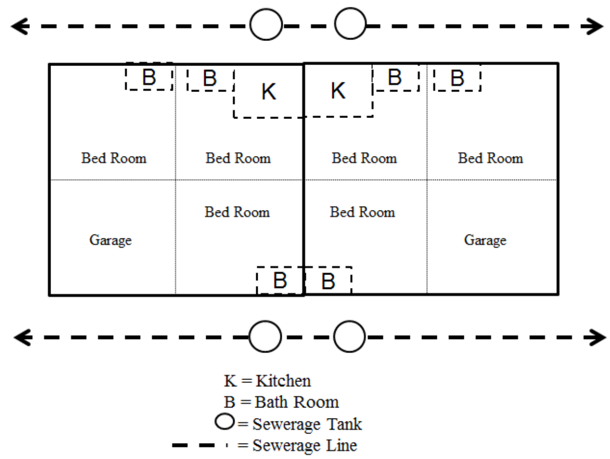


Fig. 1. Line plan of damaged buildings showing layout of utilities and location of bathrooms and kitchens

NATURE AND SEVERITY OF DISTRESSES

Distresses in the damaged buildings include cracks and tilts. For the purpose of this paper, cracks are openings in the walls while tilts are out of plumb movement of the walls. The causal factors of cracks and tilts would be summarized later under heading of geotechnical findings. The nature and extent of distresses is outlines as following:

- Distresses are most prominent in walls in the nearest vicinity of kitchen, bathrooms and sewerage tanks shown in Figures 2 through 4
- Distresses are relatively much lesser in walls with only the bathrooms, Figure 5
- Walls in the immediate vicinity of kitchen, bathroom and sewerage tanks are also tilting either inward or outward
- Distresses are almost non existing in the internal walls located in the centre of the buildings
- Most of the cracks are diagonal; initiating from floor and window sills to the corners in the roof
- Width of cracks varies from 10 mm to 50 mm
- Tilt of walls varies from 12 mm to 40 mm

Fig. 2. Cracked walls along kitchen, bathroom and Sewerage tanks

Fig. 3. Walls showing inward and outward tilts

Fig. 4. Walls of the kitchen suffered the severest distresses

Fig. 5. Garage walls suffered the least distresses

FORENSIC GEOTECHNICAL INVESTIGATIONS

Review of previous investigations revealed a lack of information on the engineering behaviour of soil layers within the zone of influence of the single story buildings. Afresh geotechnical investigations were therefore performed up to a depth of 6 m to develop an understanding of the foundation soil. The focus of this investigation was to evaluate geotechnical site conditions and ascertain engineering behaviour of the foundation soil within the zone of influence of the structures up to a depth at which applied loads are 20% of total applied load, Figure 6.

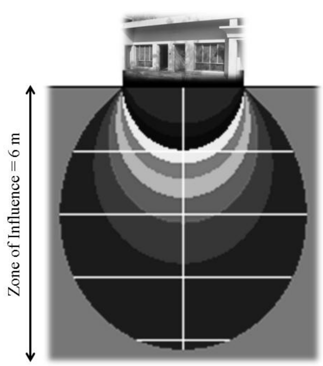


Fig. 6. Walls showing inward and outward tilts

Geological Site Conditions

Geologically, the upper soil of research site is alluvial-loessic while deeper layers are a product of spontaneous weathering of underlain layers of limestone of *"Lucky Formation"*. Occasionally, shale intercalating with limestone layers have also been reported at some location. The limestone layer is encountered at varying depths starting at shallow depth of 3m. Geologically the soils are classified as *"Marley Clays"*. At one of the building site, three soil layers above the bed rock were encountered. The problematic "CH" layer as shown in Figure 7 while it's close up is shown in Figure 8.

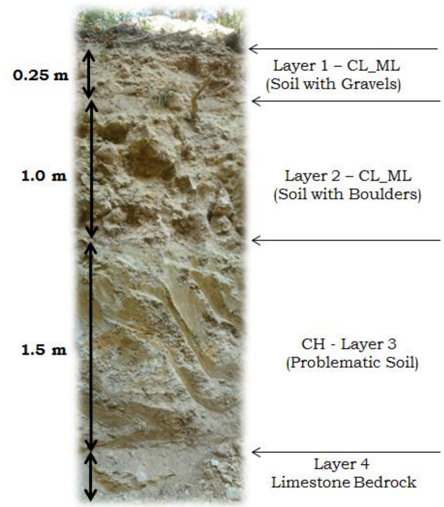


Fig. 7. Soil Layers in the zone of influence

Fig. 8. Closer view of problematic layer; CH with calcite

Index and Engineering Properties

Mineralogical evaluation revealed the soil belongs to *"Carbonate and Silicate Mineral Groups"*. Under carbonate mineral group, the sub-group is traced to *"Calcite"* while under silicate group; the subgroup is *"2:1, Smectite (Montmorrolonite)"*. The soil therefore is rich in calcium carbonate, calcium chloride and silica besides other compounds. Field and lab investigations were carried out at three different buildings. Index and engineering properties are summarized in Figures 9 and 10.

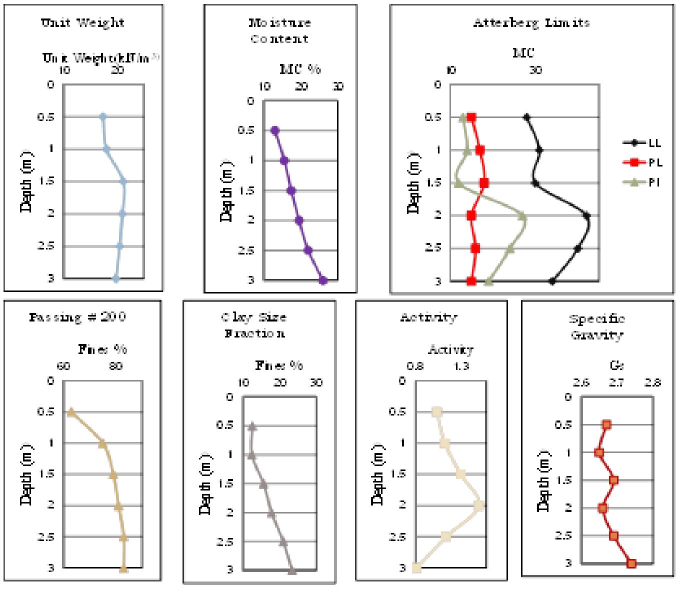


Fig. 9. Index properties; average of three buildings

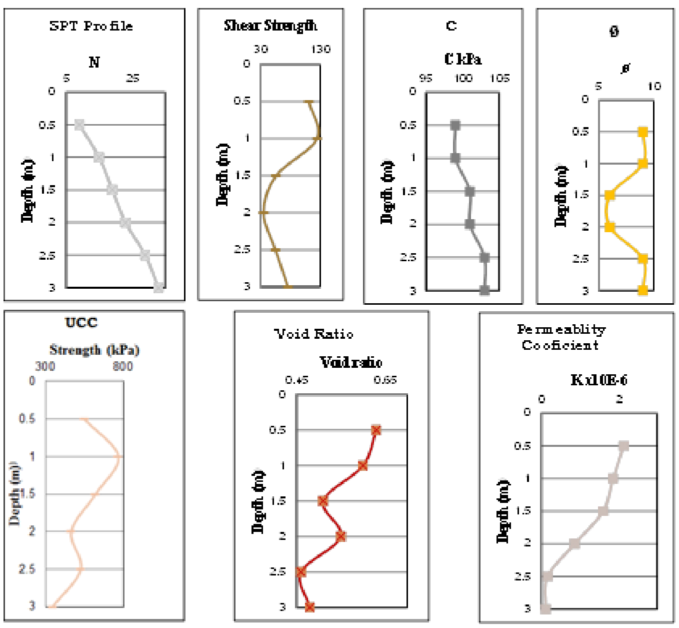


Fig. 10. Engineering properties; average of three buildings

Swell Properties – Free Swell Test

To study the swell potential of soil samples and to study the findings of consolidation test, free swell test was performed. The tests indicated higher free swell in the range of 115% to 185%, Figure 11.

Crumb Test

Crumb test was performed to study the dispersive potential of clay. High slaking of soil samples was observed for all the samples of three test pits but turbidity was observed to be low, Figure 12.

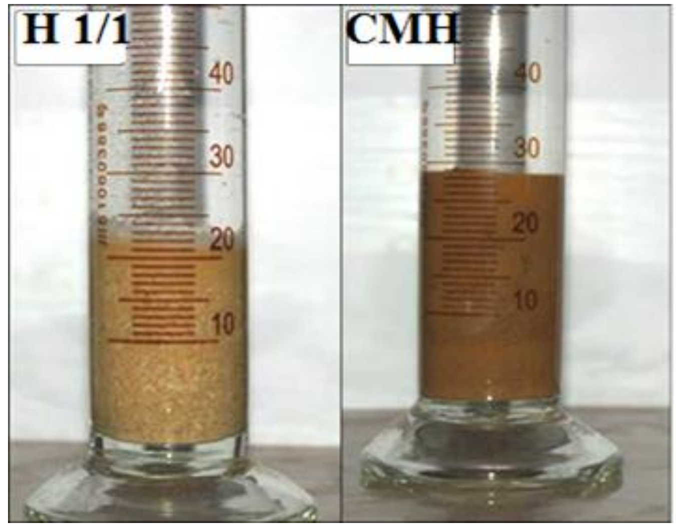


Fig. 11. Free Swell Test at two different soil samples

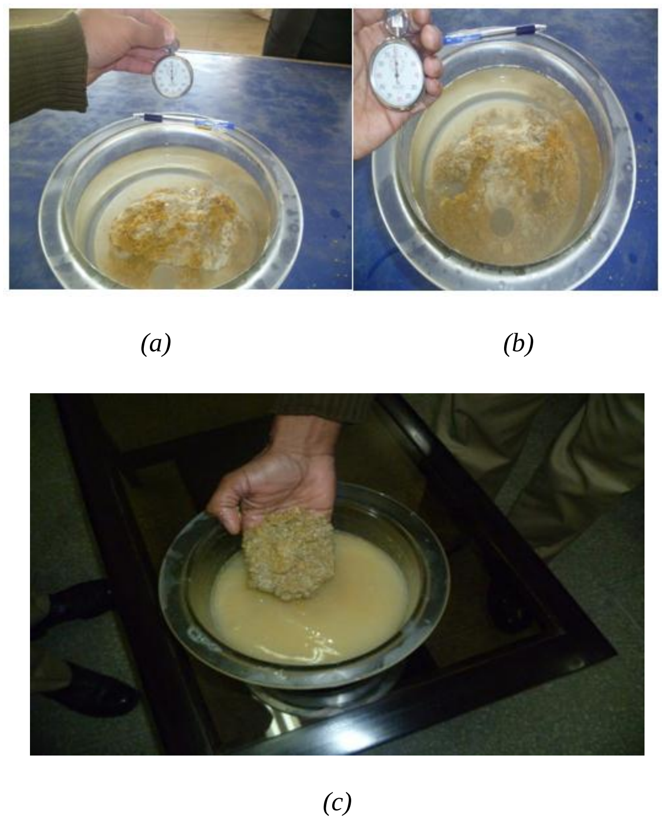
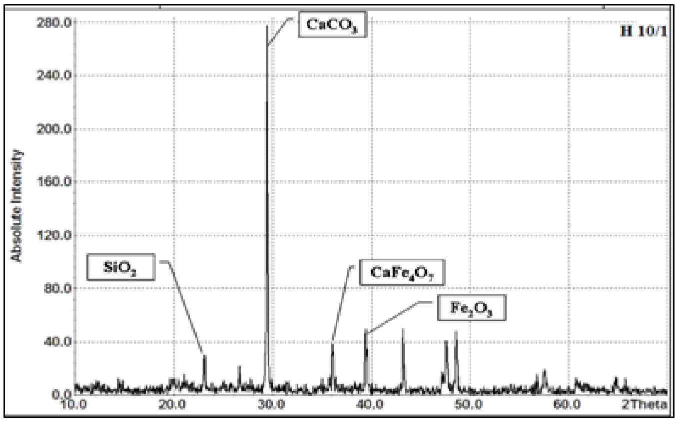


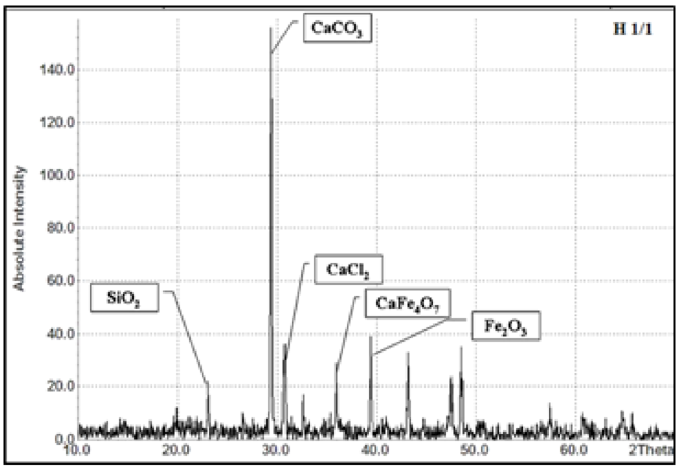
Fig. 12. Crum Test; (a) Sample placed in water, (b) Sample after 20 minutes, (c) Sample after 45 minutes

Chemical Properties

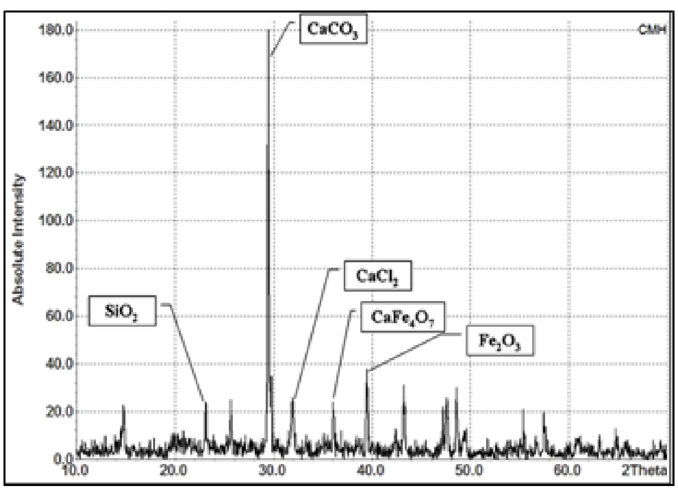
XRD Analysis XRD is a powerful tool for identifying crystal/grain size, inter layer distance and orientation. X-ray peaks intensities are determined by the distribution of atoms within a lattice. Scanning angle (2θ) was kept as 10° to 70°. The results of the samples from three research sites are shown in Figures 13 (a), (b) and (c).



(a)



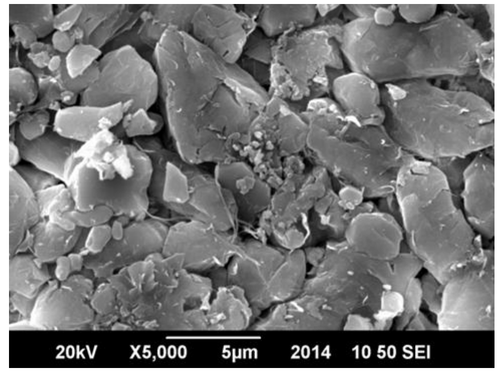
(b)



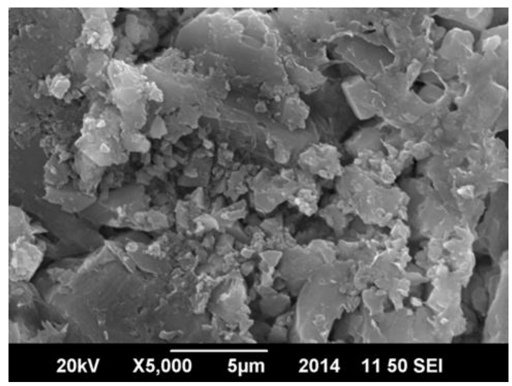
(c)

Fig. 13. XRD analysis of three samples is shown in Figures (a), (b) and (c) above

<u>SEM Analysis</u> SEM testing was a useful tool in visually observing the soil microstructure and complete elemental composition. It provides high resolution and long-depth-of-field images of sample surfaces and near surfaces. Electron microscope images of samples of all three research sites, Figure 14 (a), (b) and (c). The figures clearly show surfaces of montmorrolonite; irregularly shaped with other solids.



(a)



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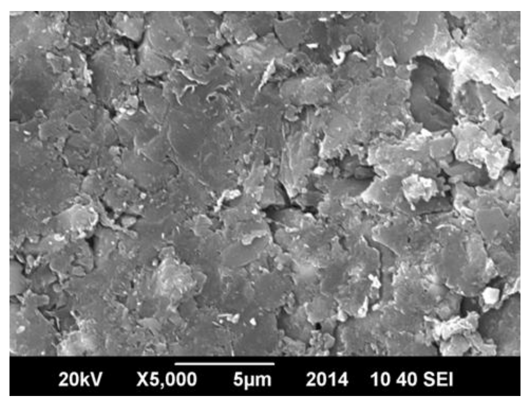

(c)

Fig. 14. SEM analysis of three samples is shown in Figures (a), (b) and (c) above

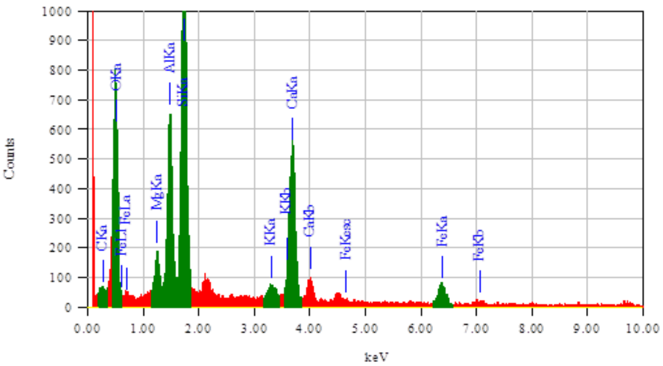

Fig. 15. Complete elemental analysis of a sample

Consolidation Properties One dimensional consolidation test was performed on undisturbed samples. Curves for e – log p are shown as Figure 16. These curves show the relation of void ratio to pressure in loading, unloading and reloading sequence. It is clearly observed that the void ratio is decreased as loading is applied and is increased as it is unloaded. It will again decrease once it is reloaded.

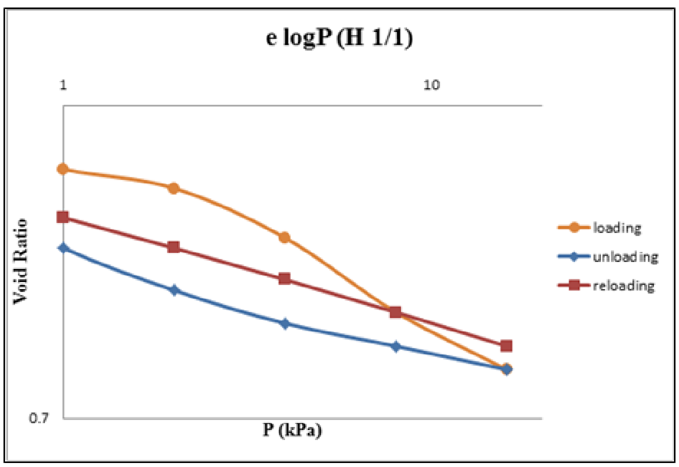

Fig. 16. Complete elemental analysis of a sample

GEOTECHNICAL FINDINGS

- Geologically, the upper 1-2 m stratum comprises of alluvial-loessic deposits underlain by residual soils of *Lucky Marly (clay and silty material with carbonates) limestone formation.*
- The upper alluvial layer containing gravels has typical problems of collapse and differential settlements.
- Marly limestone; a fine-grained silica-rich microcrystalline/micro-fibrous sedimentary rock containing small fossils has typical problems of swelling and heave.
- Under existing normal conditions (in the absence of water seepage exposure to the underlying clay layer), soil exhibits excellent bearing capacity conditions as high as 1-2 TSF while under wet conditions, the bearing capacity reduces to less than 0.5 TSF.
- The upper soil layers are loose agglomerate of fine-grained soils and gravels at and underlying soil layer up to bed rock is high plastic clay.
- Chemical analysis indicates the clay type to be “Montmorollonite belonging to Smectite Group”. Such clays under wet conditions produce substantial swelling pressures.
- The upper layer has high permeability while underlying CH layer has much lower permeability.
- All damaged buildings had leaky water supply and sewerage pipes. Some damaged houses also had storage ponds in the backyards. All damaged houses also had undergone extensive landscape watering.
- The seeping water quickly makes its way to the underlying clay layer, Figure 17 and 18.

Fig. 17. Leaky sewerage and water supply lines, the water seeps into CH layer

Fig. 17. Broken plinth protection walls, the water seeps into CH layer

- Since their construction, foundation soils underwent numerous cycles of wetting and drying. Resultantly, the foundations soils experienced cycles of collapse and heave.
- Repeated cycles of collapse and heave manifested in differential cracking. In the absence of suitable damage control measures, some cracks transformed into tilts.
- In each damaged building, the tilts are much less than cracks.
- If somehow, volume change behaviour of the foundation soils is controlled, the cracks can be repaired and tilted walls can be re-constructed.

- Foundation soils at Hyderabad city is a "Problematic Soil" necessitating special provisions for geotechnical investigations, foundation design, construction quality controls and post construction maintenance.

GEOTECHNICAL REMEDIAL MEASURES

These proposed remedial measures will address damages buildings, buildings in the process of construction, and buildings that would be constructed in future.

Existing Damaged Buildings

The existing damaged building can be rehabilitated by means of a combination of stabilizing foundation soil, underpinning settled foundation and retro-fitting tilted walls as following:

<u>Stabilization of foundation soils</u> The foundation soil within the foot-print and 2 m beyond the foundation need stabilization to prevent effects of volume change phenomenon. Composite columns of 9 inches diameter and varying depths comprising of sand/gravel/lime are recommended. In the upper layers it would comprise of gravel/sand while in lower layers it will consist of un-slaked lime. The depth of these columns will be 3 m or depth of bedrock whichever is shallower. These columns will be installed 0.5 from the outer edge of walls and spaced 1m c/c. Outer walls of the building will have two rows of columns; at 0.5 m and 1.5 m from the outer edge of the walls.

<u>Underpinning of Existing Foundations</u> Cracked walls which are not tilted, are recommended to be rehabilitated using underpinning technique. A field trial would be necessary to optimize the underpinning option.

<u>Retrofitting of Damaged Parts of Buildings</u> Cracks should be repaired while tilted walls should be removed and re-constructed.

Under-Construction Buildings

To avoid damage to the under-construction buildings in the future, following remedial measures are recommended:

- Each under-construction building be re-investigated to determine presence or otherwise of problematic layer within the zone of influence of respective buildings.
- In case, problematic layer exists, remedial measures suggested above should also be applied in the under-construction buildings.

Future Construction of Buildings

To avoid damage to future buildings over problematic foundations soils, following measures are recommended:

- At places where bedrock is within 2 m depth, the soil should be removed and foundations placed on the bedrock. Since the bedrock is Marly in nature, reinforced strip foundation would be necessary.
- In case bedrock is deeper than 2m, removal of upper strata might not be economical. The foundation soil should be stabilized as explained earlier.
- In all circumstances, the steel reinforcement should comply with the structural and relevant seismic provisions for this area.

Common Measures

- Water storage ponds within the house and 10 m beyond must be banned.
- Underground pipes must of non-corrosive material and joints must of highest quality. Overflowing water tanks and water taps must be prevented. Half yearly inspection of pipes and drainage may be planned at the garrison level.
- Landscape watering must be limited to the bare minimum (flood watering should be prevented).
- No trees or flower beds be allowed along the load bearing walls.
- All existing boundary walls over problematic soil should be strengthened with reticulated piles drilled at an angle of 10-20 degrees up to depths of 2m, spaced at 2m c/c (staggered) on both sides.
- All future boundary walls be constructed according to following guideline:
- Foundations of all future buildings/boundary walls with proposed methodology should be placed at a depth of 0.5 m. Other buildings located over non-problematic soils may be placed at depth of 1-1.5 m depths.

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