A Case Study on Rectification of Damaged Structures on Expansive Soil Deposits

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ABSTRACT

During the year 1995, at Anta (India) gas power project township a large number of structures, which were constructed 4 to 6 years back started exhibiting damages of varying degree. From the nature and pattern of damages it appeared to be typical of distress due to expansive soil deposits underneath. In order to assess/investigate the causes for damages and suggest remedial measures, boreholes were drilled at suitable locations and soil samples were collected from different depths. Free swell index, percentage swell, swelling pressure and other relevant characteristics of soil samples were determined.

The corrective measures suggested to salvage/rectify the distressed structures were treatment of expansive soil through lime slurry pressure injection (LSPI) process. In addition to LSPI, to maintain moisture equilibrium within the soil beneath the structure, plinth protection apron alongwith low density polyethylene film laid beneath and concrete curtain wall were constructed all around the structures. Post treatment performance of these structures was monitored. All these rectified/renovated structures are under observations since last eleven years and until this date exhibit satisfactory performance. The details of this case study are presented and discussed in the present article.

INTRODUCTION

The expansive soil deposits are considered to be highly problematic especially for foundations of civil engineering structures. The seasonal moisture fluctuations in these soils cause alternate swelling and shrinking resulting into up and down movements of foundations leading to structural damages. The annual monetary loss due to such damages to all types of civil engineering structures the world over is estimated to be several billion US $, which far exceeds the loss due to natural calamity/disaster.

Amongst very few techniques/processes available for salvage/rectification of damaged structures on expansive soils, experience have shown that the lime slurry pressure injection (LSPI) is one, which is most practicable, economical and effective. It is desirable to provide moisture barrier to protect the zone of lime treated soil against the movement of free water as it would loose the strength on saturation due to leaching of lime. Another equally important aspect to salvage/safeguard such structures is to maintain moisture equilibrium beneath and around the foundation within the influence zone in expansive soil. The construction of plinth protection apron and curtain wall all around damaged structures serve not only as moisture barrier but also help in maintaining moisture equilibrium beneath the structure.

This article presents the details of case study regarding rectification of damaged structures on expansive soil deposit at Anta (Rajasthan State, India). The problem faced at the gas power project township at Anta during 1995 was that, a large number of structures, which were constructed just about 4 to 6 years earlier, started exhibiting damages of varying degree. The concerned authority referred this problem to author for suggestions and recommendations to salvage/rectify these distressed structures. It was noticed during inspection that the nature and pattern of damages clearly represented typical of distress due to presence of expansive soil deposits underneath. The methodology of approach to investigation, tests conducted remedial measures and their implementation and other relevant aspects are presented and discussed in the subsequent sections.

OVERVIEW

Expansive Soils and Structural Damages

Serious problems posed by expansive soils to civil engineering structures are well realized by engineers and researchers the world over. Expansive soils when come in contact with water swell considerably, exert swelling pressure and exhibit low shear strength. When the moisture is dried up in hot season, these soils shrink and give high shear strength.

The swell/shrink phenomena is attributed predominantly to the presence of montmorillonite clay minerals in these soils.

The seasonal moisture variations in expansive soil deposits around and beneath the structure lead to alternate upward (wet/rainy season) and downward (hot/summer season) movements of structures leading to damages of varying degrees. The damages generally noticed in the buildings are in the form of distortions in the floor (inverted dish shaped due to moisture concentration with time in the centre), crackings in the walls (diagonal cracks extending upwards from doors and window seals), breaking of joints between structural members, etc.

Lime Treatment

The most common and widely accepted method to control swelling and improve the strength of expansive soil is stabilization using lime additive. Lime stabilization has been acknowledged as an effective and economical method for improving the behavior of expansive clay soils. The addition of lime, quicklime (CaO) or hydrated lime [$Ca(OH)_2$] to expansive soil has stabilizing effect, which reduces swelling & swelling pressure and improves strength. Such behavior of treated soil may be attributed to (i) Cation exchange, (ii) Flocculation, (iii) Carbonation and (iv) Pozzolanic reactions. Generally, cation exchange takes place by initial addition of 1-2% of lime (by dry weight of soil), further addition of lime is responsible for pozzolanic activity. The amount of lime required to stabilize expansive soil ranges from 2 to 7% depending upon swelling potential and quality of lime.

Lime Slurry Pressure Injection

The foundation of damaged building can be treated by a process known as Lime Slurry Pressure Injection (LSPI). The technique comprises of injecting lime-water slurry under high pressure within the zone of influence in expansive soil mass through pre-drilled holes (deeper than foundation level) all around and inside the distressed building. The reaction of lime-water slurry with expansive soil results into stable material within the zone of influence that transmits less movement to the structure. The technique has been tried successfully at a number of places in India (Sargunan et al., 1980; Karandikar, 1995) to salvage the distressed buildings in expansive soil deposits. Generally the holes of 5 cm to 10 cm dia. are drilled using augers upto the depth much deeper than foundation level so as to penetrate into constant volume zone (Kate and Katti, 1982). The spacing of these holes can range from 0.5 m to 2.5 m depending upon soil characteristics and nature of damages. The lime slurry is prepared fresh using water to lime ratio of 10:1 to 10:3 by weight based on quality of lime and swelling characteristics of expansive soils. The grouting pressure to inject lime slurry will depend on several factors e.g. in-situ (unit weights and moisture) conditions of soil, depth of bore holes, lime slurry viscosity, grout placement method, etc.. The general rule, which suggest adopt high pressure that is safe, is equally applicable in this case also.

PROBLEM AND ASSESSMENT OF DAMAGES

Anta Gas Power Project (ANGPP) township, where the structures were exhibiting distress had been visited during August, 1995. The objectives of this site visit were to assess the nature of problem through spot inspection of structural damages, discuss foundation details and other relevant aspects with the concerned engineers and to indentify the locations, where from the soil samples at different depths could be collected for proposed testing in the laboratory. It was noticed during inspection that, the nature and extent of damages to the structures such as residential buildings, trainee's hostel, school building, etc. were varying from light to extensive type. Some of the extensively damaged structures particularly Trainee's hostel, Central school, etc. showed very wide cracks ranging from 12 to 25 mm width in the walls (exterior as well as interior) extending diagonally from floor level to ceiling with heavy distortions in the floor. The distorted floor(s) formed a pattern similar to inverted dish having maximum heaving in the centre and minimum at the edges in contact with walls. Some of the heavily distressed residential buildings gave a look and feeling that those were really unsafe for the occupants to live there any longer. From the nature and pattern of damages it appeared to be typical of distress due to expansive soil deposites underneath.

The informations emerged out from the detailed discussions with concerned engineers, spot inspection of structures with and without damages, study of available site investigation report as well as foundation drawings and design criteria adopted are as follow. The report of site investigation, which was carried out around 6 years back (prior to the construction of structure in ANGPP township), indicated presence of subsurface stratum of expansive nature in this area. Aware of this fact, the engineers designed the foundations of various structures by adopting suitable methods, which are commonly practiced for foundations on expansive soil deposits (Kate et al., 2004). They adopted conventional method such as sand cushion for relatively small size and less important structures, innovative techniques such as Cohesive Non-swelling Soil (CNS) layer (Katti, 1979) mostly for industrial structures and under-reamed pile foundations mostly for residential buildings, depending upon sub-surface soil conditions (depth to constant volume zone, thickness of expansive soil stratum, etc.). Most of the structures thus constructed were light (single storeyed) to moderately loaded structures (four storeyed).

It was understood through discussions and also noticed during inspection that the structures, wherein CNS layer method was adopted for foundations were free of any such damages and safe. Whereas, the structures with other types of foundations e.g. sand cushion, under-reamed piles were showing distress. During the inspection, the locations of proposed boreholes for soil sampling were identified. These were in the vicinity of structures exhibiting damages of varying degrees. Figure 1 shows these locations from 1 to 6 identified for this purpose in phase-I of ANGPP township map. These locations 1, 2, 3, 4, 5 and 6 are in the vicinity of damaged structures in localities named as ABB colony, Central school, Quarter C-119, Trainee's Hostel, C-Type Quarters and D-Type Quarters respectively. Amongst these, Trainee's Hostel was the one, which suffered most heavy damages, whereas D-type Quarters were amongst lightly damaged structure.

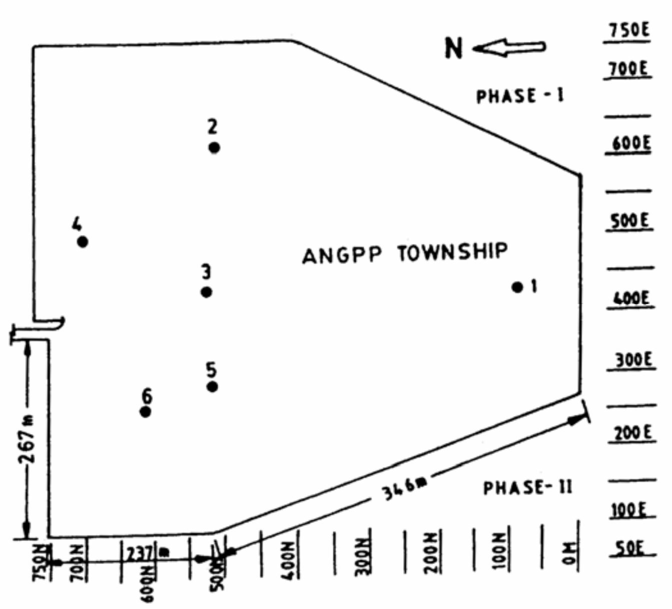

Fig. 1. Locations of boreholes for soil sampling.

At these locations, during September 1995 boreholes of 15 cm diameter were drilled to a maximum depth of 2.50 metre using auger. The exploratory depths of these bore holes were decided on the basis of generalised subsurface profile of the area, which is discussed in the subsequent section. Undisturbed soil samples were obtained from the depths of 0.75, 1.50, 2.25 and 2.50 metres below ground level (GL) in sampling tubes (around 10.5 cm internal diameter and 30 cm length). Representative soil samples in substantial quantity from various depths were also collected during augering operations.

SOIL CHARACTERISTICS

Generalised Subsurface Profile

Generalised subsurface profile of the area was prepared by synthesis and compilation of available data from the site investigation report and other reliable sources. Figure 2 illustrates such a generalised subsurface profile, which represents almost all the zones/areas where these (distressed) structures were constructed. The top soil stratum comprises of grey coloured silty clay varying in thickness from 1.75 m to 2.8 m. It is underlained by yellow coloured silty clay extending down to a depth from 1.75 m to around 9 m below ground level. Below this yellow silty clay, there is a layer of yellow soil, which exhibits presence of small size lime nodules. This yellow soil is underlain by disintegrated rock (shale) as shown in Fig. 2. The report also points out that both the grey soil forming the top layer and the yellow soil beneath are of swelling type. Based on this, for the present investigation boreholes were drilled to such a depth so as to penetrate into both these soil layers at each location.

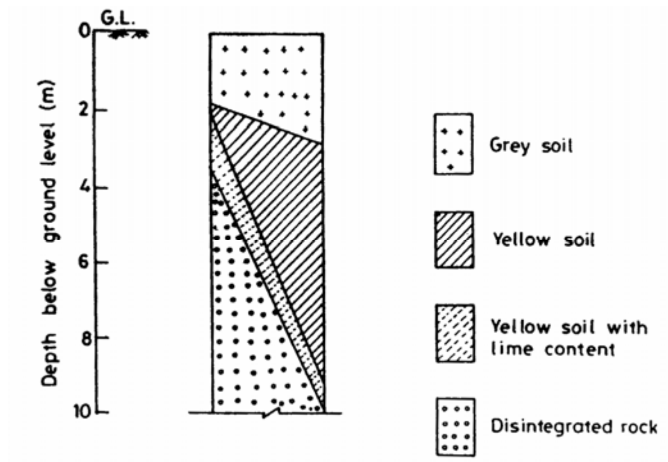

Fig. 2. Generalised subsurface profile representing the area.

In-situ Properties

The results of tests conducted on soil samples (undisturbed as well as representative) collected during drilling of boreholes at selected locations (Fig.1) are presented in Table 1. The values of moisture content (w) observed during September in this area in general, range from a minimum of 17.6 % to a maximum of 24.1 %, which gives degree of saturation in the range of 92 % to 96 % indicating considerably wet soils. It is worth mentioning here that, in this particular zone of Rajasthan state there are frequent rains during September. The study of the available records of seasonal moisture changes in this area revealed that during summer (hot) season, the soils from ground level to a depth of around 2 metres become almost dry and shrinkage cracks are visible on the ground surface. All these observations clearly indicated that this area is prone to considerable seasonal moisture fluctuations.

As seen from Table 1, in-situ total unit weight (γ_t) range from 19.1 to 21.3 kN/m^3 in top grey soil stratum and from 20.4 to 21.5 kN/m^3 in the yellow soil layer. The in-situ dry unit weights (γ_d) range from 15.5 to 17.7 kN/m^3 in top grey soil stratum and from 17.3 to 18.3 kN/m^3 in the yellow soil layer beneath. In general, it is seen that, γ_d increases with depth at these locations.

Free Swell Index

In order to get preliminary idea about the swelling nature of these soils, Free Swell Index (FSI) tests were conducted on the soil samples thus collected from different depths. Free swell index (the ratio of change in volume of soil in swollen state in distilled water to its original volume in kerosene oil, expressed as a percentage of latter) of soil samples were determined by following the procedure as per Indian Standard (IS 2720, part 40, 1977, reaffirmed 1997).

Table 1. In-situ Properties and Free Swell Index of Soils

Sample Location			w (%)	Unit Weight (kN/m^3)		FSI (%)
Locality	No.	Depth below GL (m)		γ_t	γ_d	
ABB Colony	1 A	0.75	22.7	19.7	16.0	57
	1 B	1.50	23.6	20.0	16.2	45
	1 C	2.25	18.2	20.9	17.7	65
Central School	2 A	0.75	22.9	19.8	16.1	36
	2 B	1.50	23.4	20.3	16.5	44
	2 C	2.25	19.2	21.0	17.6	62
Quarter C-119	3 A	0.75	22.8	20.5	16.7	44
	3 B	1.50	22.5	20.2	16.5	33
	3 C	2.25	18.5	20.9	17.6	48
	3 D	2.50	17.6	21.5	18.3	54
Trainee's Hostel	4 A	0.75	24.1	19.5	15.7	35
	4 B	1.50	23.9	20.4	16.5	46
	4 C	2.25	18.0	20.4	17.3	70
C-Type Quarters	5 A	0.75	23.3	19.2	15.6	40
	5 B	1.50	24.0	19.9	16.0	57
	5 C	2.25	20.4	21.3	17.7	55
	5 D	2.50	20.7	20.8	17.2	60
D-Type Quarters	6 A	0.75	23.6	19.1	15.5	50
	6 B	1.50	23.4	20.4	16.5	50
	6 C	2.25	21.1	20.9	17.3	53

The values of FSI given in Table 1 range from 33% to 57% for top grey soil layer indicating in general, that this soil layer possesses moderate swelling potential. Yellow soil layer exhibits a range of FSI from 53% to 70% displaying moderate to high swelling potential. Interestingly, the nature of structural damages noticed at various locations corroborate well with the FSI values of soils at these locations e.g. the structural damages at Trainee's hostel were severe and the corresponding soil samples exhibit maximum value of FSI of 70%. Based on FSI, typical soil samples selected for detailed investigations were 1 A and 1 C from ABB colony and 4 C from Trainee's hostel locality. The soil sample 1 A represents the top grey soil layer with maximum FSI of 57% whereas, 1 C and 4 C represent yellow soil layer at two locality each with maximum FSI of 65% and 70% respectively.

Engineering Properties and Shear Strength Parameters

The engineering properties and shear strength parameters of soils 1 A, 1 C and 4 C are provided in Table 2. Clay (< 0.002 mm) content, which plays a significant role in imparting swelling nature to soils are 39%, 44% and 48% whereas, the colloidal clay (< 0.001 mm) content are 27%, 29% and 33% for soils 1 A, 1 C and 4 C repectively. Soil 4 C exhibits highest values of liquid limit, followed by 1 C and the lowest by 1 A. Both the soils 1 C and 4 C have shrinkage limit of 9% whereas, it is 12% for soil 1 A. All the three soils are classified as CH i.e. Inorganic clays of high plasticity (fat clays) on A line chart. All the above properties are indicative of expansive nature of these soils and are consistent with respective free swell indices.

Table 2. Engineering Properties and Shear Strength Parameters of Soils

Property	Soils		
	1 A	1 C	4 C
Colour	Dark Grey	Grey	Yellow
Specific gravity	2.65	2.66	2.63
Grain size distribution			
(a) Clay			
(< 0.002 mm), %	39	44	48
(< 0.001 mm), %	27	29	33
(b) Silt (0.002 to 0.075 mm), %	49	43	41
(c) Sand (0.075 to 4.75 mm), %	9	11	9
(d) Gravel (> 4.75 mm), %	3	2	2
Atterberg Limits			
(a) Liquid limit (%)	55	64	66
(b) Plastic limit (%)	26	25	29
(c) Plasticity Index (%)	29	39	37
(d) Shirnkage limit (%)	12	9	9
Classification (A Line chart)	CH	CH	CH
Standard Proctor Test			
(a) MDD (kN/m^3)	16.8	16.7	16.4
(b) OMC (%)	17.0	17.5	18.0
Shear Parameters*			
(a) $^{+}c_u$ (kN/m^2)	65	72	75
(b) $^{**}c_{uu}$ (kN/m^2)	55	61	65
(c) $^{**}\phi_{uu}$ (degree)	7	5	6

*At in-situ γ_d and full saturation

+ From unconfined compression test

** From unconsolidated undrained triaxial test

The comparison of values of maximum dry density (MDD) and optimum moisture content (OMC) determined through Standard Proctor Compaction test with in-situ γ_d and w (Table 1) indicates that the deeper soils (1 C and 4 C) exhibit higher in–situ γ_d than MDD whereas, near surface soils exhibit lower γ_d than MDD. In-situ moisture content is significantly higher than their OMC for these soils.

The shear strength parameters of these soils were determined by remolding soil specimens at in-situ γ_d and full saturation. The values of undrained cohesion (c_u) obtained from unconfined compression test are 65, 72 and 75 kN/m^2 for soils 1 A, 1 C and 4 C respectively. The results of unconsolidated undrained triaxial shear test provided the values of cohesion (c_{uu}) and angle of internal friction (ϕ_{uu}) of the order of 55, 61 and 65 kN/m^2 and 7^0, 5^0 and 6^0 respectively by soils 1 A, 1 C and 4 C. Undrained cohesion values exhibited by these soils are very low in fully saturated condition.

SWELL AND SWELLING PRESSURE BEHAVIOR

The percent swell and swelling pressure tests were conducted on soils 1 A, 1 C and 4 C with and without lime additive under two different placement conditions. These are (i) undisturbed soil sample at in-situ γ_d and moisture content and (ii) soil sample remolded at initial compaction unit weight corresponding to in-situ γ_d and zero moisture content (completely dry). Later placement condition was chosen to understand the magnitude of swelling pressure under simulated seasonal moisture fluctuations in the field i.e. from completely dry during summer and at or near full saturation in rainy season. In view of possible use of lime for treatment of soils, study was conducted to assess its influence on the swelling and swelling pressure behavior of soils. The lime used was powdered good quality hydraulic lime with CaO of around 70%. The percentages of lime additive in remolded soil samples thus studied were 2%, 3% and 4%.

The percent swell and swelling pressure tests were conducted on soils/ soil lime mixes remolded at initial in-situ dry unit weight and zero moisture content by adopting oedometer method and procedure similar to that suggested in International TC-6 Standard (TC-6, 1993). These soils /mixes were remolded in oedometer ring of internal diameter and thickness of 60.5 mm and 20.5 mm respectively. These specimens were allowed to saturate fully under the applied external seating stress of 5 kPa during which observations of swell with time were recorded. The values of maximum percent swell for each soil and soil treated with various percentages of lime have been determined from the plots of swell with time.

In order to determine swelling pressure, the following procedure was adopted. The test specimen saturated at seating stress of 5 kPa was allowed to compress under a number of successive stress increments, each stress increment being maintained constant until the compression virtually ceases (generally, 24 hours). The maximum swell under each applied stress was obtained by deducing corresponding compression from the maximum swell recorded at 5 kPa seating stress. The process of loading the specimen with stress increments continued until it showed net compression instead of swell. The swelling pressure at constant volume (which corresponds to magnitude of applied stress at zero percent swell) was determined from the plot of maximum percent swell versus applied stress (on log 10 scale).

The values of maximum percentage swell and swelling pressure of soils thus determined without and with lime additive are presented in Table 3.

Table 3. Maximum percent Swell and Swelling pressure of soils without and with lime additive

Soil	Item	Placement Condition				
		UD+	Remolded*			
1 A	Lime (%)	-	-	2.0	3.0	-
	Swelling Pressure (kN/m^2)	65	210	130	23	-
	Swell (%)	1.5	5.1	2.1	0.65	-
1 C	Lime (%)	-	-	2.0	3.0	4.0
	Swelling Pressure (kN/m^2)	80	270	156	52	6.3
	Swell (%)	1.9	7.6	3.1	0.97	0.03
4 C	Lime (%)	-	-	2.0	3.0	4.0
	Swelling Pressure (kN/m^2)	85	290	170	65	13
	Swell (%)	2.1	9.2	3.7	1.2	0.05

+Undisturbed sample at in-situ γ_d and w.

* Compacted at in-situ γ_d and dry (w = 0 %).

The remolded soil samples as compared to undisturbed samples exhibit considerably higher values of both the expansive characteristics demonstrating mostly the influence of initial moisture content on percentage swell and swelling pressure. It may be noted that the degree of saturations corresponding to initial moisture contents are > 92 % and 0 % for undisturbed and remolded samples respectively. It is seen that both maximum percent swell and swelling pressure are in increasing order of soils 1 A, 1 C and 4 C. Addition of lime significantly reduces expansive characteristics of these soils.

With increase in percentage of lime additive, the swelling pressure of soils decreases. Addition of 4 % of lime to soil 4 C brings down swelling pressure from high value of 290 kN/m^2 to a negligible 13 kN/m^2 . Thus, these results are supportive of use of lime for treating these soils to reduce their deleterious effect considerably.

REMEDIAL MEASURES

On the basis of study conducted and discussed in earlier sections, the remedial/corrective measures recommended to salvage/rectify the distressed structures were two stage operations. The first stage comprised of application of lime slurry pressure injection and second stage was construction of precast concrete (PCC) plinth protection apron with LDPE black film embedded beneath and curtain wall.

Classification of Damages

In order to adopt suitable pattern of injection holes for LSPI application, the damaged buildings depending upon the seriousness of their distress have been broadly categorized as A,B,C and D with the following descriptions.

Category A – Lightly damaged: Minor cracks on the walls extending to short lengths with no visible damage to the floors.

Category B – Moderately damaged: Fairly wide cracks on the walls extending to considerable lengths, with or without visible/minor damage to the floors. One side of the building exhibiting light damage whereas, other side showing moderate to heavy damage.

Category C – Heavily damaged: Very wide cracks in the walls everywhere extending to considerable lengths and heights with visible damages and distortions in the floors.

Category D – Extensively damaged: The distress is widespread throughout the building as evidenced through severe horizontal, vertical and diagonal cracks in the walls extending from floor to ceiling level, heavy crackings in joints of structural members, sinking and considerable distortions in the floors.

Slurry Injection Holes

Auger holes of 50 mm dia. spaced between 0.5 m to 1.0 m were drilled all around the damaged structures following a pattern based on their shape, size and extent of damages. These holes were drilled to substantial depth ensuring penetration down into constant volume zone or at least to a depth of 1 m below the base of existing footing/under-ream bulb. The preliminary estimate indicated the depth of constant volume zone to be around 1.7 m within yellow soil below its surface. The line of such holes was kept as close to the outer edge of footing/under-ream bulb as practicable. This arrangement of drilling exterior injection holes all around the structure was common for all the four categories of damages. The schematic arrangement of such injection holes are illustrated in Fig. 3 (a to d) for structures with different degree of distress.

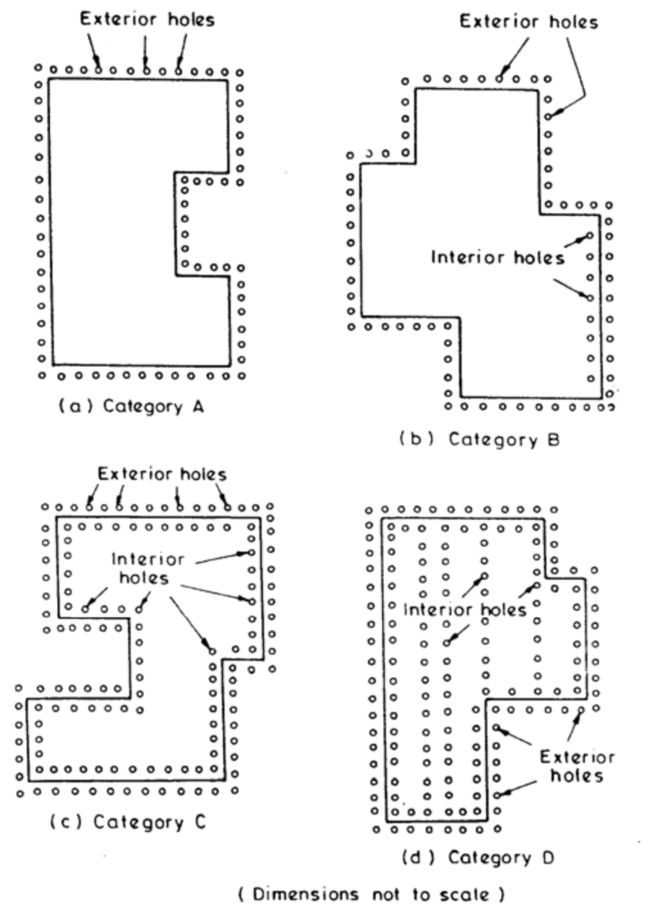

Fig. 3. Schematic arrangement of injection holes for various category of damages.

The side(s) of building which exhibit(s) more damage in case of Category B, additional holes were drilled inside the building on damaged side by removing floor slab and the line of such holes kept as close as possible to the inner edge of the footing/under-ream bulb (Fig. 3,b). Similar lines of interior holes were drilled inside the entire building for both the category C and D buildings (Fig. 3, c and d). In addition, for category D, such injection holes were drilled in the central portion encompassing the damaged floor area (Fig. 3,d).

Lime Slurry Injection

The lime slurry was prepared fresh using good quality unslaked hydraulic lime with water to lime ratio of 8:1 by weight. This slurry was injected into pre-drilled holes by adopting initially a pressure of around 50 kN/m^2 per metre of soil overburden. It may be noted that, the injection pressure required in expansive soils is considerably higher than for ordinary clays under similar conditions. Depending upon requirement, pressure was further increased taking into consideration volume of slurry intake and effectiveness of injection/grouting operation established through certain field trials. For higher pressures continuous monitoring of ground upheaval was done and care was taken to see that in no case it exceeds 5 mm.

The injection of lime slurry was carried out as full depth grouting starting from the bottom of injection hole (using packer or suitable placement method) and working upwards until refusal. For the present grout hole geometry and soil conditions, the effective radial (lateral zone of influence) outward penetration of lime slurry required was around 30 cm (for 50 cm spacing) and 55 cm (for 1 metre spacing) for each grout hole so as to ensure overlap.

The sequence of grouting adopted was such that sufficient time was allowed for lime slurry to permeate into the surrounding soil, diffuse and set/react before the adjacent holes are grouted. In order to achieve this, after grouting a particular hole the distant hole was grouted next by skipping the adjacent/intermittent holes and the process was repeated until all the holes were grouted. After completing the injection process, the holes were filled up with the lime slurry and plugged with soil.

Plinth Protection Apron and Curtain Wall

The precast concrete plinth protection apron of at least 2 m width alongwith 300 micron thick low density polyethylene (LDPE) black film (impervious geomembrane) laid beneath was constructed all around the building. At the periphery of apron, concrete curtain wall of 15 cm width extending down to at least 1.75 m below plinth level was constructed. Figure 4 illustrates typical arrangement of plinth protection apron, LDPE black film and curtain wall alongwith the footing.

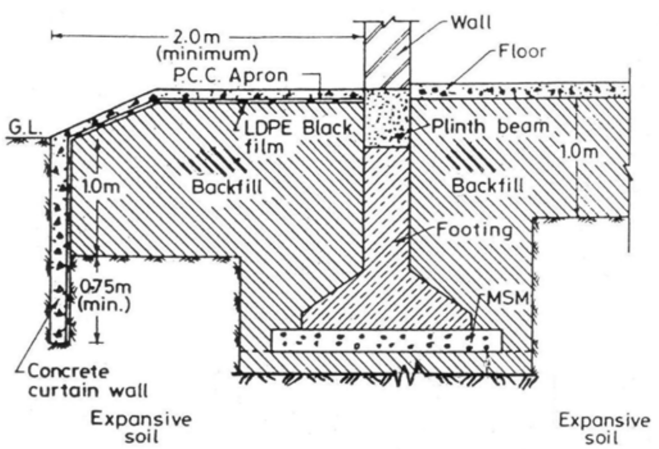

Fig. 4. Typical arrangement of apron, LDPE film and curtain wall alongwith footing.

The LDPE black film was suitably embedded into the ground beneath apron and extended down along with concrete curtain wall to its full depth. The curtain wall, which serves as lateral moisture barrier preventing direct entry of outside moisture within influence zone in the vicinity of footing. It is desirable to extend the curtain wall as deep as practicable. The plinth protection apron, LDPE black film together with concrete curtain wall maintains equilibrium moisture contents in expansive soils within influence zone beneath the building. The LDPE black film not only helps in controlling the moisture migration but also prevent the underneath soil from drying by not allowing the penetration of ultra-violet rays. Proper sealing between apron, LDPE black film and curtain wall is required to prevent any leakage of water.

POST TREATMENT PERFORMANCE OF STRUCTURES

After completing treatment and other operations (LSPI, plinth protection apron, etc.) for all the damaged buildings, the cracks on the walls were suitably patched up/plugged/repaired in the usual way for face lift/new look purpose. This was done for all the buildings except for typical four, each one representing category A,B,C and D damages, which were left as it is for monitoring the post treatment performance. The floor slabs were repaired wherever possible or completely replaced by new one especially for extensively damaged structures.

The movement (settlement/heave) of structures, cracks (their sizes and patterns) and certain other features relevant to damages were under observations (through instrumentation, direct measurements, sketches of patterns and visual inspection) for two complete cycles of seasonal moisture variations i.e. during winter, summer, rainy season and repeat cycle. The observations of structural movements recorded during first cycle of seasonal moisture variations showed almost no movement by category A structure. Whereas, heave in the range of 3 to 7 mm was shown by category B,C & D structures with D category showing the maximum heave. During second cycle, the magnitude of heave reduced to 1 to 3 mm. None of the structures exhibited any settlement during this period. In general, it was noticed during this period that the cracks remained stable without any further deterioration. Interestingly, in some cases even the closing of cracks and vanishing were also recorded. All these rectified/renovated structures are under observations since last eleven years and until this date are exhibiting satisfactory performance.

CONCLUDING REMARKS

In the present case study, the treatment of expansive soils underneath the damaged structures for their rectification was carried out as two stage operations to ensure complete safety and has eventually proved to be successful. The first stage operation, LSPI process resulted into converting expansive soils within the zone of influence into a stable material to significant depth. The second stage operation involving construction of plinth protection apron, laying down LDPE black film and curtain walls all together controlled moisture migration and helped maintaining equilibrium moisture in soils beneath the structures. Both these operations were equally important and formed most essential components for remedial measures, and to prevent damages to the structure on long term considerations.

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