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# Geotechnical investigations into the characteristics of cracking and damage analysis of low rise buildings due to shrink-swell potential of Expansive soils

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**Abstract**
Expansive soils which occur in arid and semi-arid climate regions of the world cause serious problems on Civil Engineering lightly loaded structures. In recent years, the focus of research lies in understanding the influence of Geotechnical characteristics of such problematic soils. Expansive soils cause damage to houses, other buildings, roads, pipelines, and other structures which is more than twice the damage from floods, hurricanes and earthquakes. Only a few studies have been described in the Indian context. Ten low rise buildings from different locations 1 to 10 are selected for Geotechnical investigations and analysis at Pondicherry region of East coast India. Three soil samples from each location under different ground conditions are collected and tested The characteristics studied are initial moisture Content, Dry Density, Liquid Limit and plasticity Index, shrinkage limit, free swell index, natural moisture content, compression index, liquidity index (LI), consistency index (Ic) activity, specific gravity, and cation exchange capacity. The ratio of Plastic Limit to Liquid Limit of the soil varied from 0.49 to 0.71indicating the characteristic of high plastic clay at depth varying from 1m to 3 m. The author attempts to describe criticality of physical defects in the building system using multi criteria decision analysis approach considering two case studies. The cracks are analysed with respect to crack width, crack orientation, and crack intensity into a relative physical condition with the building systems as alternatives. This technique could be used in monitoring the progression of cracks in the building elements. Preliminary investigation includes visual inspection of cracks, structural damages followed by a detailed assessment of damages along with Non-Destructive Test (NDT). Visual inspection and non-destructive tests indicate the distress found in the case studies can be categorized as partial and complete impairment due to soil behaviour and poor construction materials used in the buildings.

**Keywords:** Expansive soils, liquid limit and plasticity index, crack width, crack orientation, non-destructive test

## Introduction

Engineering problems due to ‘expansive soils’ have been reported all over the world. They cause damage to structures, affecting heavily on the economy of individuals and the Nation. Plastic clays termed as expansive soils exhibit volume change when exposed to moisture variations. The expansive soils swell if their moisture content increases and they shrink if their moisture content decreases. Clay minerals, such as smectite and montmorillonites absorb water exhibit swelling and shrinking behaviour. As a result, these materials swell, and thus increase in volume, when they get wet and shrink when they dry Engineering problems due to ‘expansive soils’ have been stated in many countries all over the world. They cause damage to structures, thus affecting heavily on the economy of individuals and the Nation. Expansive soil deposits commonly occur in the arid and semi-arid regions of the world such as: Africa, Australia, Indonesia, India, United States, Israel, Myanmar and some countries in Europe. In India, it is estimated that the area covered by expansive soils is 20% of the total area, which is substantial. Several studies have been carried out to understand swell-shrink behavior of expansive soils and their damages [14]. More recently, emphasis has been on understanding the influence of geotechnical characteristics of such soils on the distress of buildings founded over such soils [7]. In the Indian context [5] have investigated the influence of soil properties among other factors, to understand foundation failure of a residential building. However, such studies are rather scarce, in the Indian context. Expansive soils have been found in several locations in Pondicherry, India. Several buildings located in Pondicherry and founded on such expansive soils have been subjected to distress, in the form of cracks. It is necessary in the larger interests public at large and for civil engineers to understand the nature of causes, determine the cause/(s) and suggest remedial measures. In this context the present work assumes significance. Ten low rise buildings which are found to have cracks in them have been identified and based on the various test on soil samples collected from the site, an attempt has been made to understand the influence of the geotechnical characteristics of the soil and investigation into the characteristics of cracking and damage analysis due to shrink/swell potential of expansive soils. During wet and dry seasons soil volume varies and thereby causing serious functional and structural problems to buildings, highway pavements and other Engineering buildings. Collapsible soils are known to experience significant volume decrease due to the increase of soil moisture content, without an increase in the in-situ stress level [25]. The soils are subject to periods of wetting and drying, the formation of cracks in the soil leading up to the surface can drastically alter the landscape hydrology [20]. The incessant changes in volume of the soil can move buildings unevenly thus forming cracks on the building elements.

A general classification of cracks ranges from thin, medium and wide from the crack width less than 1 mm, 1 to 2 mm and more than 2 mm respectively. Initially, the observed cracking would have been due to drying shrinkage [6]. The differential settlement which is responsible for several visible cracks in building may be due to short consideration in the foundation design therefore it becomes a challenge for mitigation in the structures built on expansive soils. Evidently cracks are generally perpendicular in action to the route of force, and this action may be partial with the relative stiffness of the building elements [23]. Criticality ranking of defects in building systems can be estimated using analytic hierarchy process using physical condition as the predominant criteria in decision analysis tool with various system of the building as alternatives [2]. In order to understand the damage process from gradual cracking, to collapse, and further to strengthen the weakened parts from collapse, the stability of the structure becomes the basic factor necessary to understand by using the available software solutions [23].

**Statement of the problem**

The presence of the expansive soils, also known as shrink-swell or swelling soils in Puducherry where clayey soils are predominant has caught many builders unawares. Swelling or expansive clay soils are those that comprise swelling clay minerals such as montmorillonite and have high degree of shrink-swell reversibility with change in moisture content. A large number of structures especially lightweight structures found on these expansive soils have met with widespread problems associated with serviceability performance mainly in the form of cracks or permanent deformation. While very little work has been done to study the extent of expansive soils in Puducherry on one hand, on the other hand the damages in buildings founded on expansive soils have been very poorly documented.

**Objectives of the study**

The beneficial effects of this paper is, To study the engineering properties of the clay soils with their origin.

To study and understand the important soil properties for the soil swell/shrink potential.

To understand the influence of the geotechnical characteristics of the soil on the formations of cracks in the buildings.

To understand the nature of causes, determine the cause/(s) and suggest remedial measures.

The area of focus in respect of the above objectives is to develop an integrated approach to field observation measurement results and laboratory test results in order to make a forecast of the magnitude of cracks in the buildings. The end-result will serve as an essential tool to better understanding of the damages and the cost effective choices in treating damages in the future.

**Brief details of case study area**

The selected case study area is around Pondicherry nearing 20 Km from the center of the town. Apparently the soil condition of the study area was identified as clay soil of high compressibility. Two distressed building were taken for case study and Salient details of the selected buildings are given in Table 1. Pondicherry is the capital of the union tertiary (UT) of Pondicherry, located in the east cost of India. It is one of the four enclaves constituting the UT of Pondicherry. The temperature of the above town ranges from 28-36°C and north-east monsoon is the primary monsoon which contributes to 80% of the annual rainfall. The average annual rainfall is about 1200mm. Ground water is located at shallow depths within the old town area, where several heritage buildings are located. Low rise buildings (ten in number) were selected such that they are spread all over the Pondicherry region, recently developed areas located far from the old town. Salient details of the selected buildings are given in table 1.and Fig 16a, 16b, 16c and 16d

**Methodology**

The study was carried out in three stages; reconnaissance survey, building inspection and laboratory testing of soil samples collected from the study areas Fig 15. The reconnaissance survey was aimed at studying the immediate environment of the building in question, and building inspection was carried out to diagnose the distress i.e. Cracks in the buildings based on their location, width, depth, orientation and pattern table. All measurements for the above were based on standard method of building inspection. Soil sample were collected from ten different locations in the near vicinity of buildings at foundation depths ranging from 1-1.5m, and the locations are denoted as L1 to L10. Fig 16. Physical and engineering properties of soil sample were determined adopting relevant IS Codes. The above data is used to interpret the cause of cracks in the buildings.

The study was carried out in the subsequent stages like reconnaissance survey, building inspection and laboratory testing of soil samples collected from the study areas and finally the analysis using all the possible criteria are used in the building systems for evaluating the sources of cracks and their general progression consequences on the building [5]. The chronology importance for physical condition on the progression of cracks in buildings of case study L6 and L7 are tabulated in Table 4.5, 6 and 7 respectively. The reconnaissance survey was aimed at studying the close environment of the building in question, and building inspection was carried out to diagnose the distress i.e. Cracks in the buildings based on their location, width, depth, orientation and patterns are measured [10]. Soil samples were collected from three different locations in each case study buildings at depths ranging from 1m to 2m Case study of buildings from locations 1 to 10 denoted as L1 to L10. Physical and engineering properties of soil sample were determined adopting relevant IS Codes.

The criteria used to analyze are PC: Physical condition, and While the building systems considered as the alternatives are; FS = Floor System, WS = Wall System, DW = Doors / Windows, CS = Ceiling System, ES = Electrical system, DS = Drainage system, WF = Wall finishing [7]. The above data is used to interpret the cause of cracks in the buildings and to identify the importance of defects, intensity of defects and extends of defects.

## Result and Discussions

### Reconnaissance survey

The preliminary survey conducted indicates that some buildings was constructed on a water logged area and the formation is capped with thinly laminated silt and clay. Detailed Soil Investigation was very essential to reveal the variation of the Soil Strata across the Site [23]. There are few matured trees near the building which can influence the initiation of the cracks and all the drainage systems within the building area are not properly lined channels. Therefore, the cracks in the building may be caused by ingress of tree roots into the building and due to movement of water penetrating into the ground due to lack of proper drainage system. Soil samples from two buildings were collected for laboratory testing, which were selected for the study. The preliminary survey indicates that whether the building was constructed on water logged area. The Soil Strata across the Site was very essential for a detailed Soil Investigation [15] and the formation is identified to be covered with lightly layered silt and clay. No matured trees found near the building and the drainage systems are concrete lined channels within the building. Therefore the cracks do not originate either by ingress of tree roots or due to lack of proper drainage system in the building.

### Building Inspection

The building inspection was carried out to identify and diagnose the cracks about their location (L1 to L10), and orientation pattern. The source of the study begins in the measurement of the length and width of the cracks which were marked and monitored from time to time to find out whether there is any change in the length and width of the cracks for a period of time. In Case study of location L6 and Case Study of location L7 cracks progression were observed as horizontal, vertical and inclined over the alternatives of wall system and ceiling system with the physical condition as criteria used for inspection. In L6 horizontal cracks width 6mm was noticed above the door opening increasing in width and length towards the end of the wall and the vertical cracks extending from the door lintel to the roof slab were identified. In the case study of L7 diagonal cracks are emerging from the corners of the window opening progressing towards the wall joint. The physical condition (PC) scale of the building system is given in Table 3.

Severe cracks are observed throughout the wall at near the corner of the wall in the vertical direction and the cracks are seen to have been initially developed from the floor towards the height of the wall and also in case study of L7 vertical cracks are identified to separate column and walls. In L3, cracks have developed near the junction of columns and beams. Diagonal cracks have developed from the corner of window sill towards the wall end and vertical cracks have developed from the lintel towards the floor making the wooden frame distorted, in L6, L7, L8 and L9. Fig. 5 to Fig 14 shows the crack sizes and orientation in the buildings taken for inspection. Details of cracks like length, width and orientations in all the buildings are given in Table 9.

Laboratory test results

Results of the tests conducted on the disturbed and undisturbed soil samples collected from case studies of buildings location 1 to 10 (L1 to L10) are summarized and given in Table8a and in Table 8b. It is seen that the liquid limit (LL) of soil samples in locations L1 to L10 except L4 is greater than 50 and hence they are classified as 'silt and clays of high compressibility' i.e. 'CH' soil as per IS code which was earlier suggested by [11]. From table 12 the soil samples from different locations have plasticity index (PI) greater than 17 and indicate that the soils are highly plastic in nature. The shrinkage limit (Sl) value of majority soil samples from different depths of locations L1 to L10 indicate 'high shrinkage'. Further, it is seen that the natural moisture content in is less than five times the liquid limit of the soil specimens in many locations among 10 case study locations. This shows that the clay layer has undergone substantially severe desiccation [12], which is responsible for causing distress in buildings in major building locations. The results of the laboratory samples for case study locations L1 to L10 are shown in Table 8a and 8b.

## Conclusion

### General Discussion

It is seen that the liquid limit (LL) of soil samples in L1 to L10 are greater than 50% except L4 which has LL 37% and hence they are classified as 'silt and clays of high compressibility' i.e. 'CH' soil as per Is code. As the LL of soil samples in L4 is in the range of 35-50, they are classified as silt and clays of medium/intermediate compressibility i.e. 'CI' soil.

The shrinkage limit (Sl) value of L2, L4, L6, L7 and L10 indicate 'high shrinkage', whereas L1, L3, L5, L8 and L9 are found to be low shrinkage.

Further, it is seen that the natural moisture content in locations 1 to 6 and 9 to 10 is less than half the liquid limit of the soil specimens in the locations. This shows that the clay layer has undergone significant desiccation, this responsible for causing distress in buildings in these locations. On the other hand, due to constant water logging the natural moisture content is on the higher side and that is reasonable for causing distress in the building in location-7 and 8.

The bulk densities ranged between 1.7 g/cm3 to 1.9 g/cm3 while the dry densities ranged between 1.32 g/cm3 and 1.82 g/cm3. The higher the unit weight the higher the hardness as well as the swelling potential (swell percent and swell pressure). The soils are mostly in greyish colour which is another indicator of the presence of expansive minerals. In addition to collecting information from visual inspections, field and laboratory investigations carried out offered very interesting results. All the tested samples satisfied the expansive soil criteria and have potential expansion rating from 'high' to 'very high'. The soils contain high clay content, high liquid limits (85.20% to 37%), plasticity index (18.6% to 43.23%).

Visual examination of the buildings in the study area revealed some interesting discovery. Damages in lightweight structures were mostly related to the absence of full structural design (non-engineered properties) triggered by the presence of expansive soils.

**Overall conclusions**

The existence of expansive soils could damage foundations of above-ground structures. It is not therefore surprising that the side effect of expansive soils is ignored in both design and construction of structures. This research project has helped identify the expansive soils and associated problems in the area. The positive outcomes of this research have the potential to improve the safety of the communities by assisting homeowners in promoting proper design, positive construction and maintenance altitudes. Most of the damages caused by expansive soils are due to the communities have insufficient knowledge about the features and behaviour of the expansive soils. Based on field data collected, and laboratory test results and visual observations of cracks in buildings in location 1 to 10, it can be concluded that:

i) The distress in buildings at locations L1 to L6 and L9 and L10 is attributed to the presence of CH/CI type of soil and have undergone significant desiccation.
ii) The distress in building at locations L7 and L81 is attributed to constant water logging over CH type of soil.
iii) The cracks found to be aesthetic cracks in the location L1, L2, L4, L9 and L10 and all other locations exhibit serviceability cracks in the structure at the moderated state.
iv) The impact of the geotechnical characteristics over the identified cracks denotes the effects from aesthetic to moderate attributed to serviceability of the cracks.
v) The relationship of Ll%, PI% and FSI% with depth of samples collected show great influence on the distress of the buildings. Fig 18 to Fig 21
vi) Soil investigations prior to construction are not carried out adequately, thus footings and slabs are placed directly on the expansive soils.
vii) The flooring system, terrace and the beams and columns are having high degree of chronology in the physical condition analysed from the cracks in the case study L6, as well the walling and flooring system in case study L7. Majority of cracks are moderate and come under serviceability conditions in both the cases

**Recommendations**

Many investigators [1, 5, 14, 18, 19] have suggested measures to mitigate potential problems associated with expansive soils. For the study at hand, the recommendations summarized here below have been single out based on the results of visual observations and field and laboratory investigations:

1. Control the shrink-swell behaviour through the following alternatives;
   a) Replace existing expansive soil with non-expansive soil.
   b) Maintain a constant moisture content.
   c) Improve the expansive soils by stabilization.
2. Tolerate the damage.
3. Underpinning the existing foundations.
4. Repair the cracked walls.
5. Enforcement of construction industry regulations.

**Fig 1:** Expansive soil with cracks

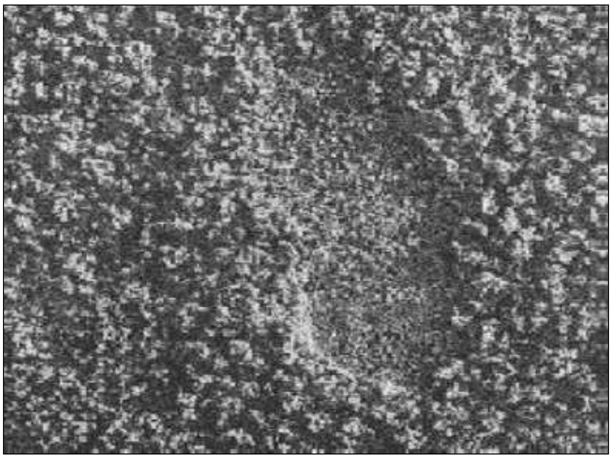


**Fig 2:** Expansive soil with popcorn texture

Identification of expansive soil from (Masoumeh Mokhtari, Masoud Dehghani. 2012 vol.17, Bund. R).

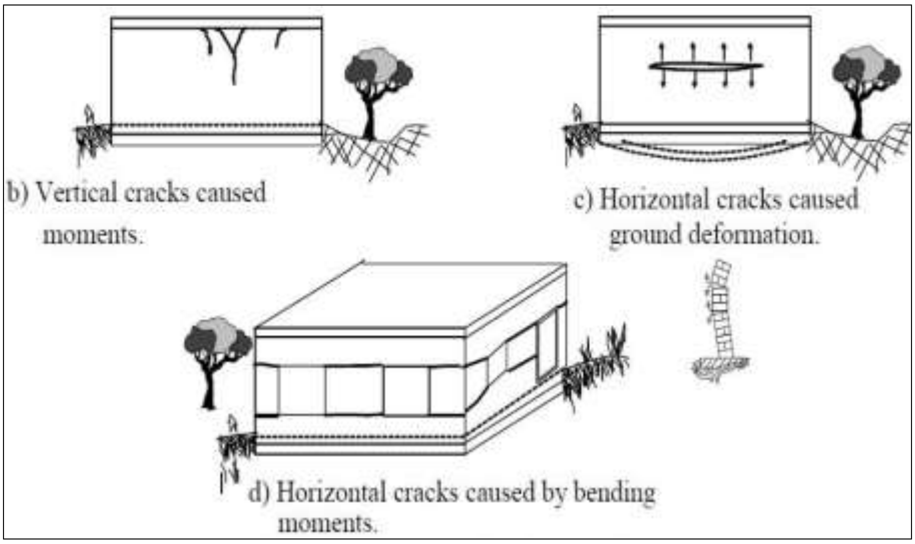



**Fig 3:** Damage mechanism of expansive soils (Hussein Elarabi,)

**Fig 4:** Typical excavation pit Building inspection


**Fig 5:** Cracks in walls, ceilng, pillar of the case study in location L1

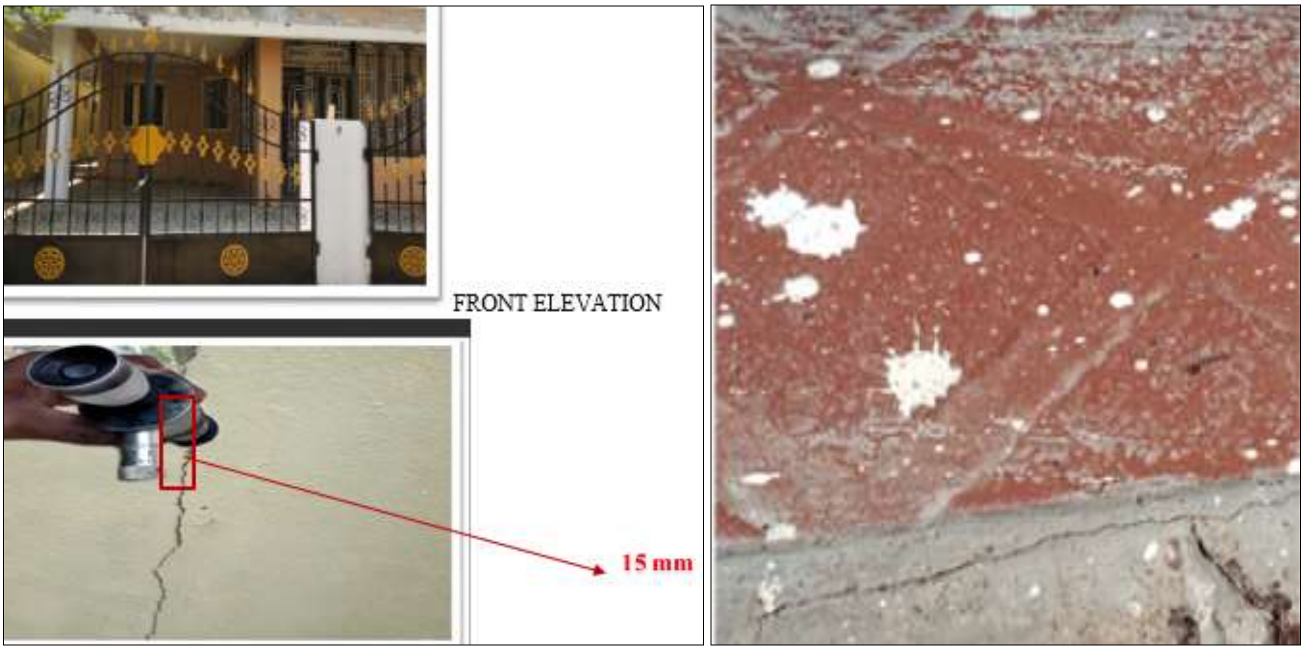
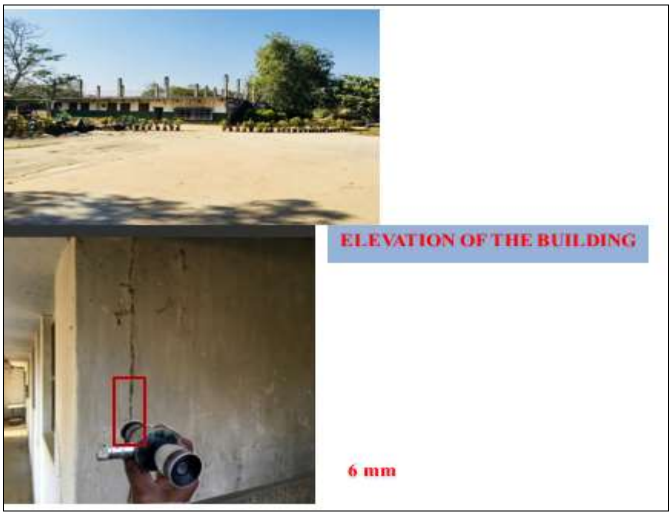



**Fig 6:** location 2, settlement of 20 mm was observed near the Main Gate of the residence and cracks in the wall



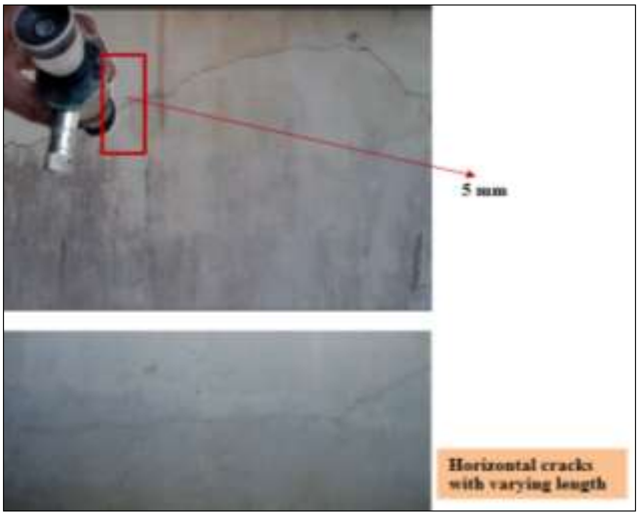




**Fig 7:** Location L 3, crack separates the wall and column Fig 8 location L 4, longitudinal cracks in the main wall

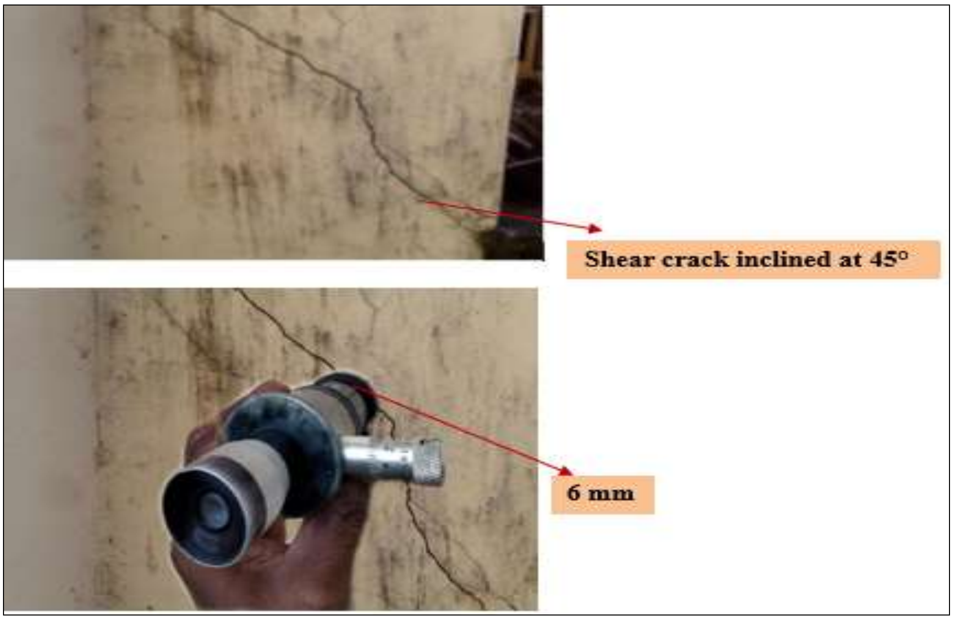



**Fig 8:** Location L 5, longitudinal Shear crack length >1000 mm, crack width= 6 mm.


**Fig 9:** location L 6, Wall separation 40 mm.from column


**Fig 10:** Location L 7, Crack width 70 mm


**Fig 11:** Location L 8, Crack width 25 mm and 1000 mm length

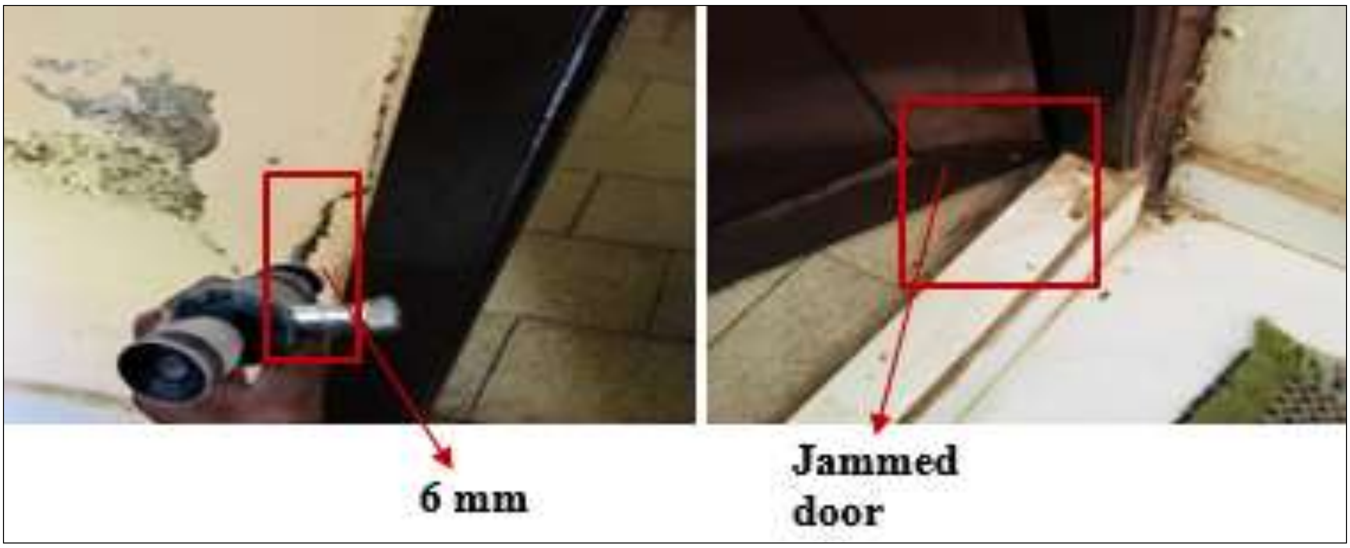



**Fig 12:** Location L 9, Crack width 6 mm near wall and the door is jammed.

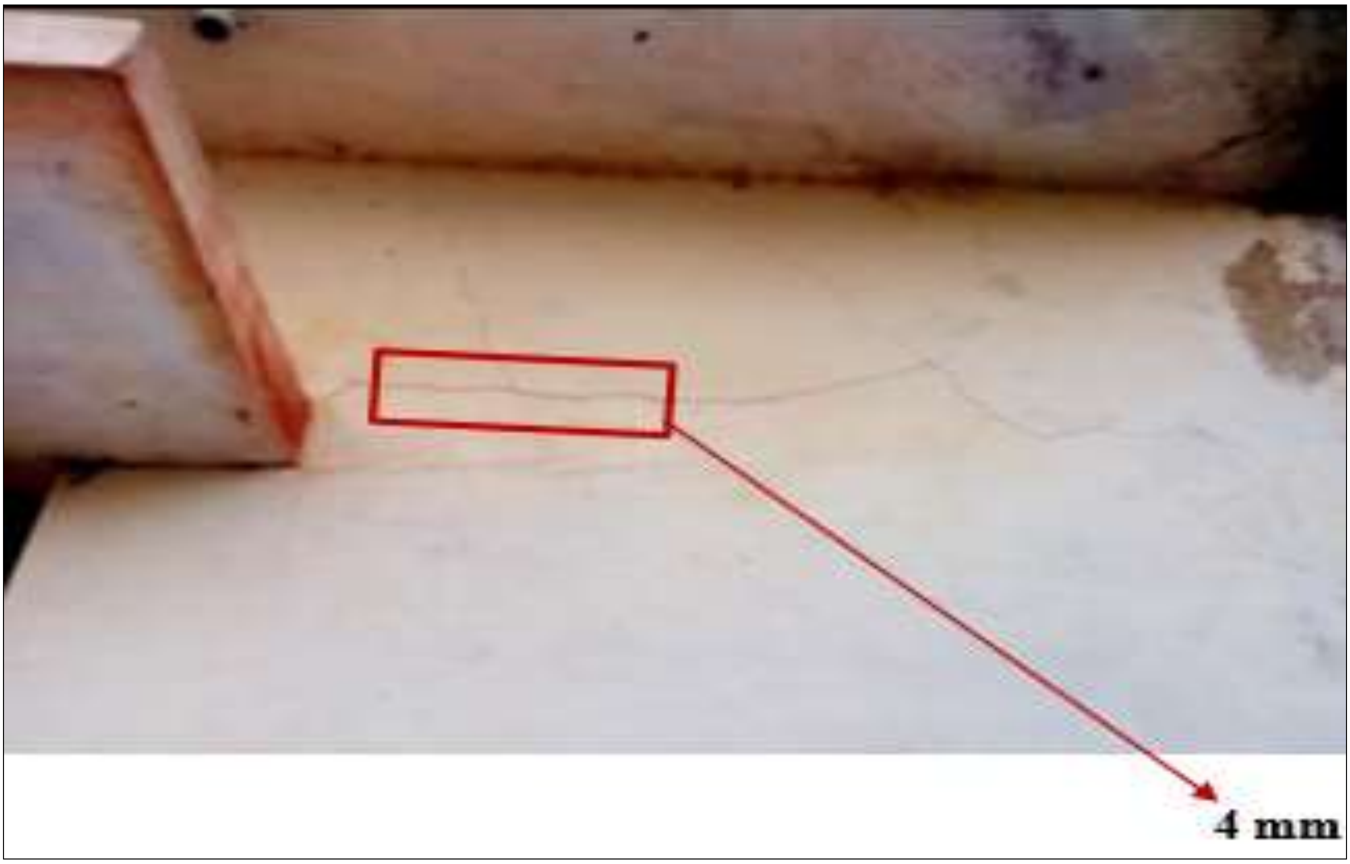



**Fig 13:** Location L 10 Horizontal crack 1800 mm length, crack width = 4mm

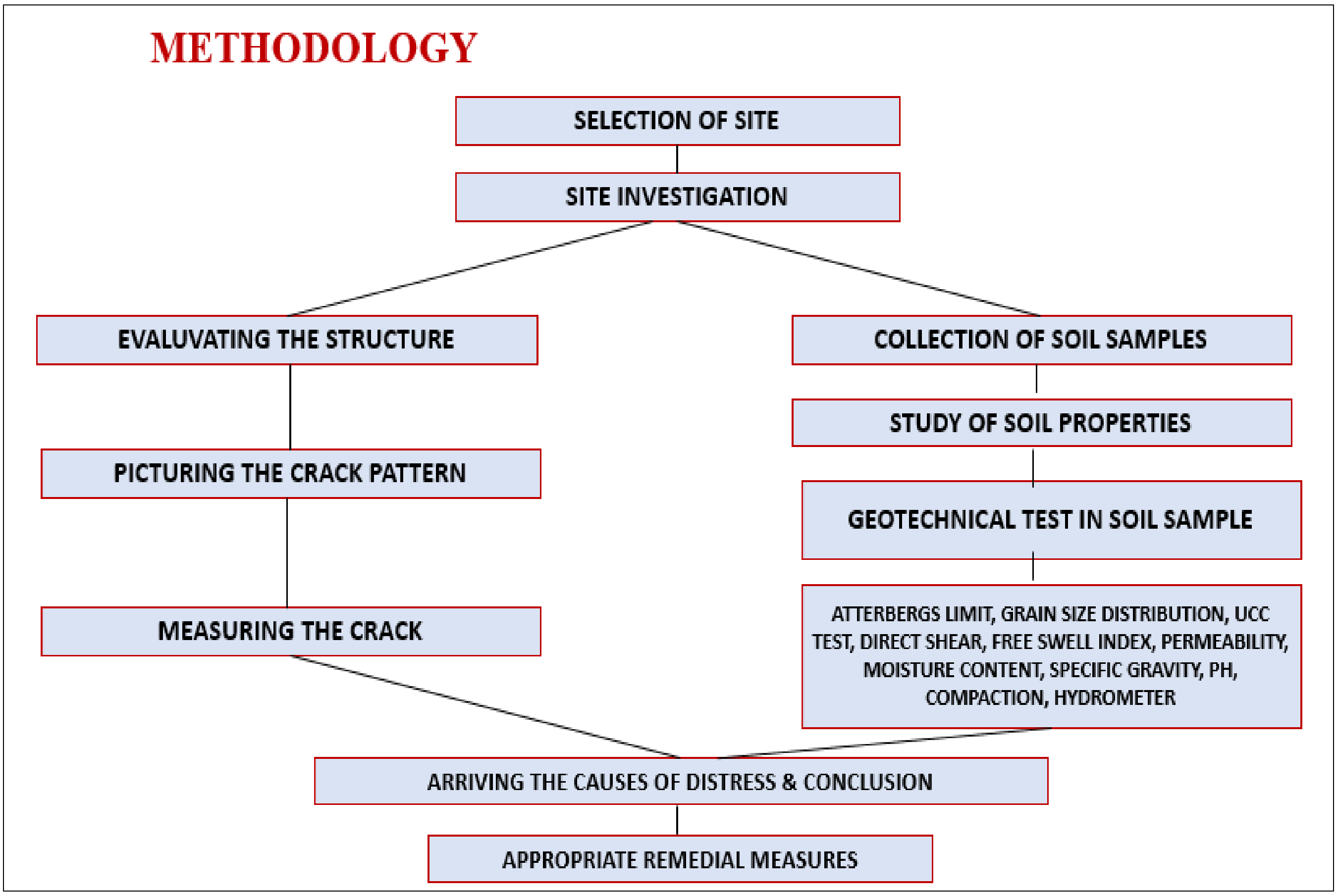



**Fig 14:** Methodology chart

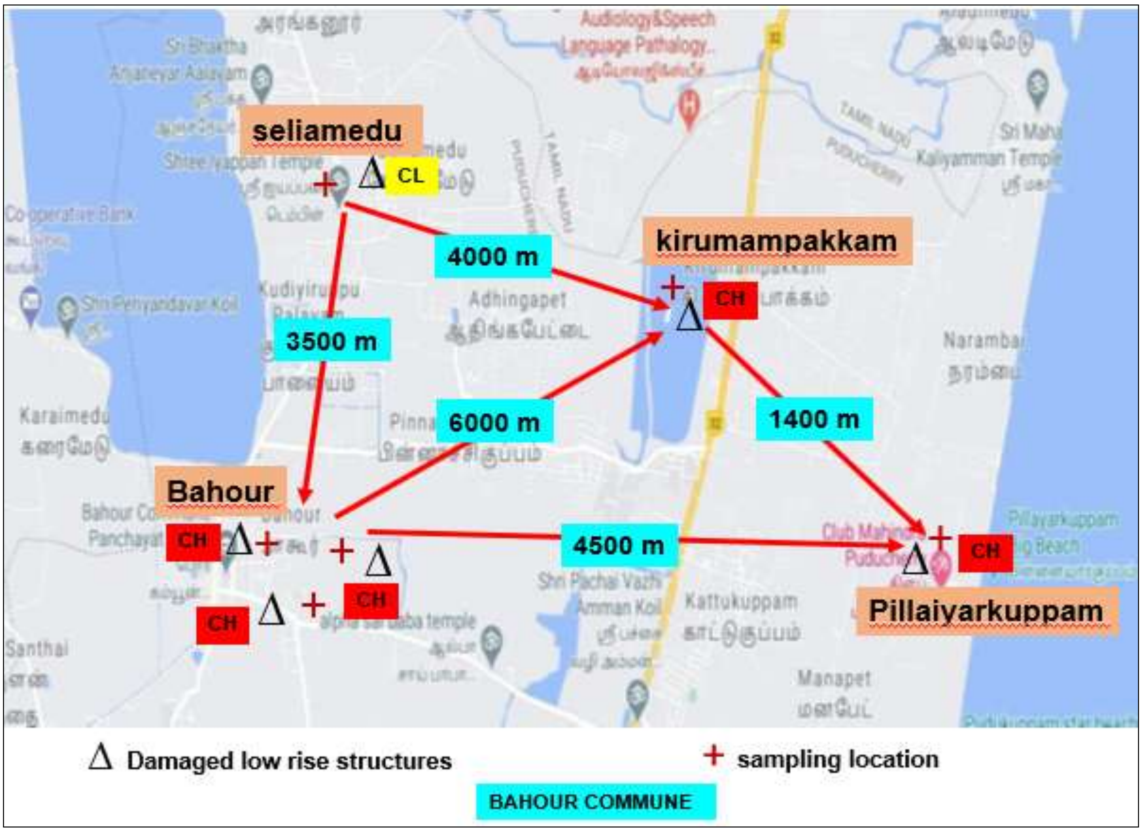



**Fig 15a:** Geographic locations of case study L1 to L3

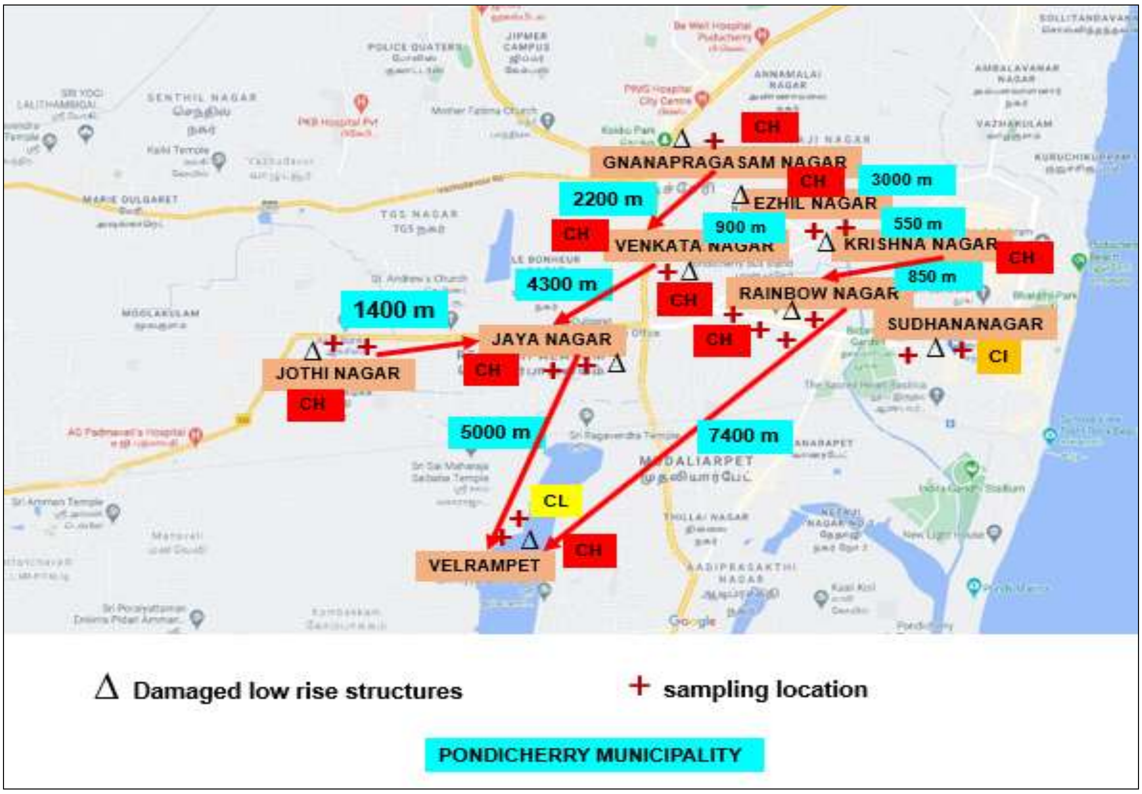



**Fig 15b:** Geographic locations of case study L7 to L10

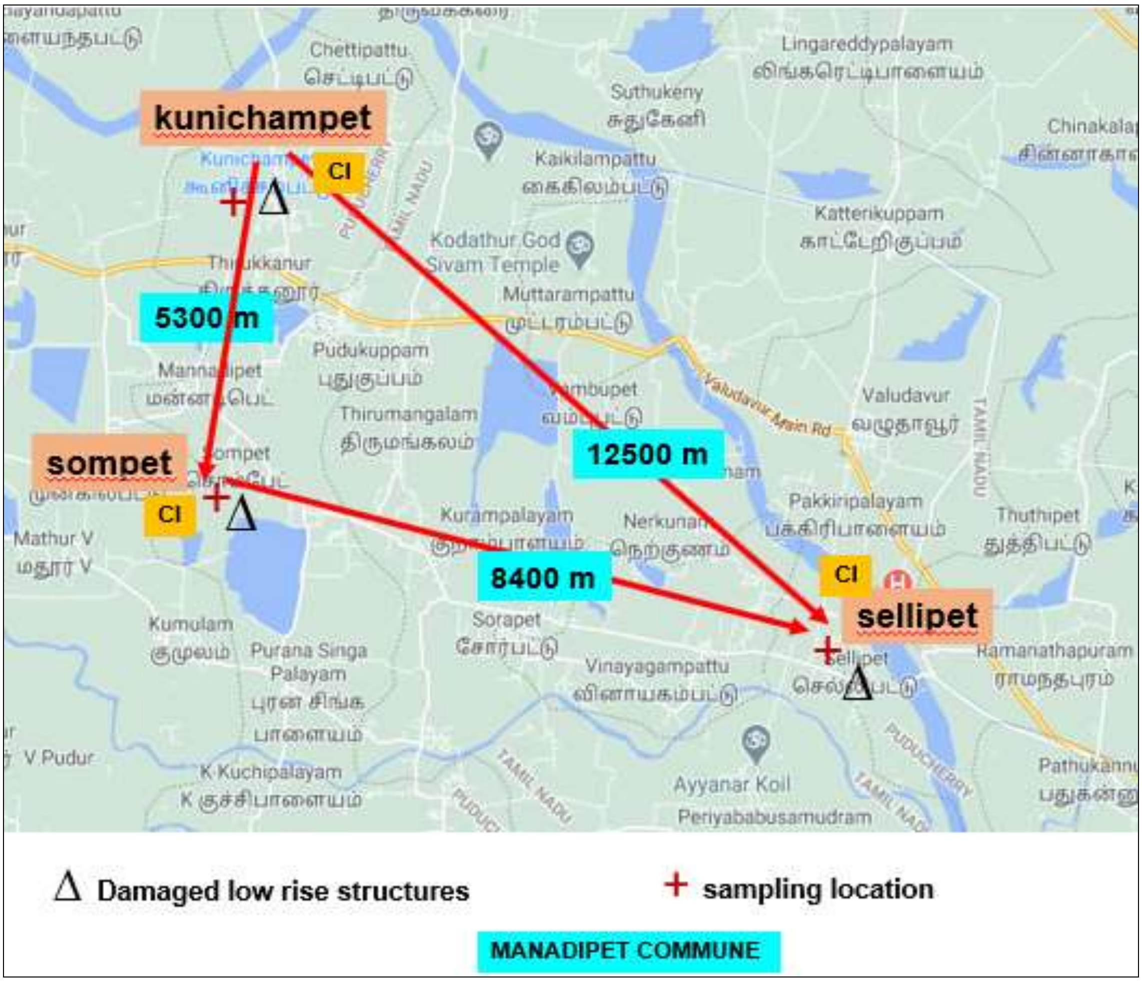



**Fig 15c:** Geographic locations of case study L4

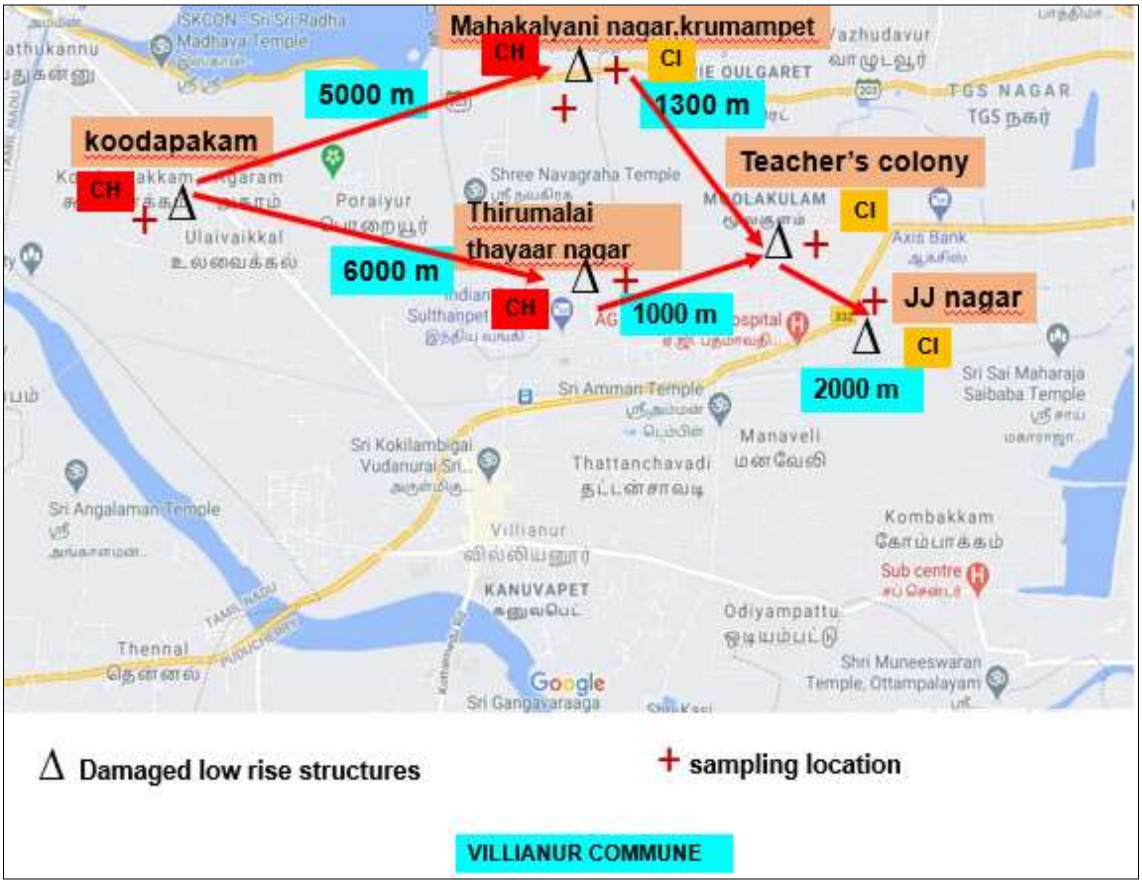



**Fig 15d:** Geographic locations of case study L5

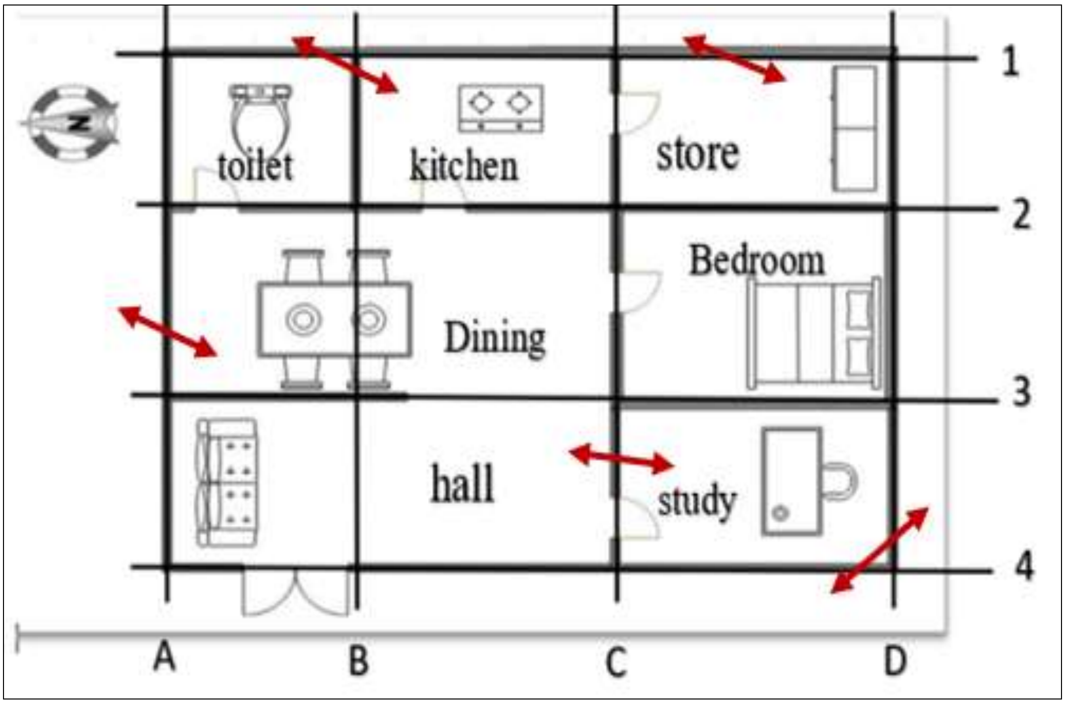



**Fig 16:** Plan with mark of distress in walls of Ground Floor in location L2

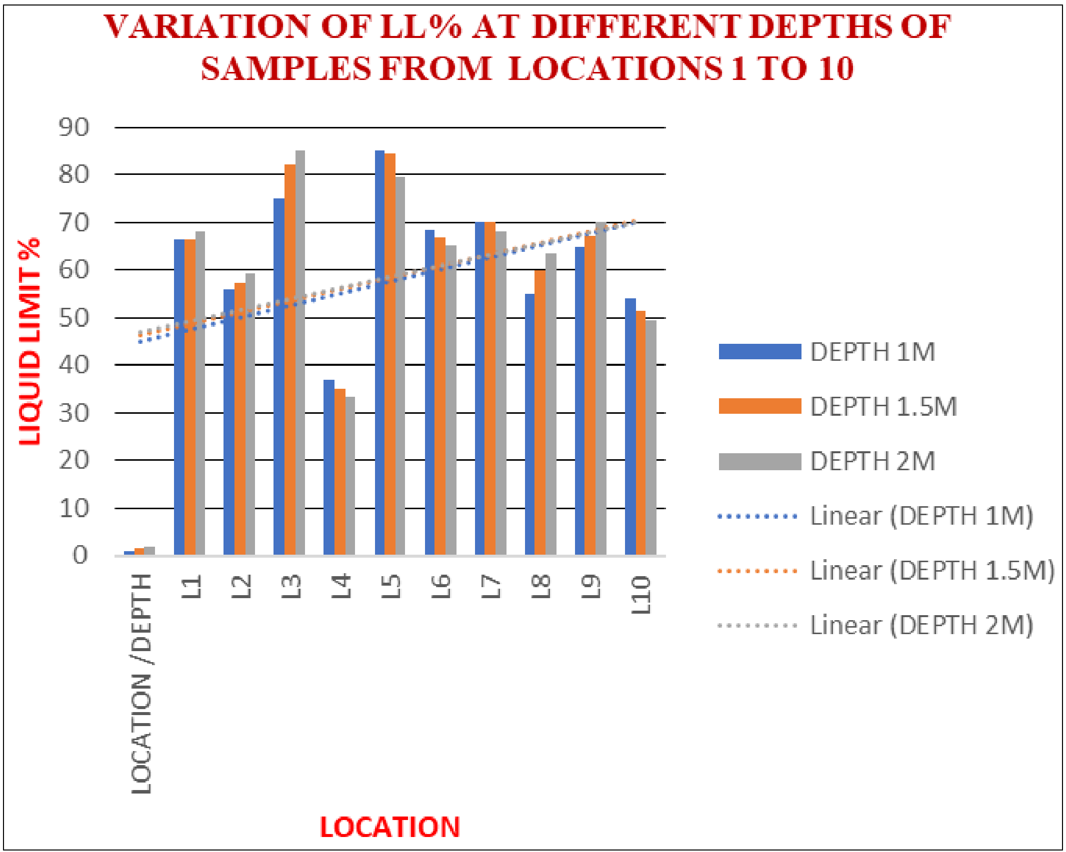



**Fig 17:** LL% of samples from locations L1 to L10

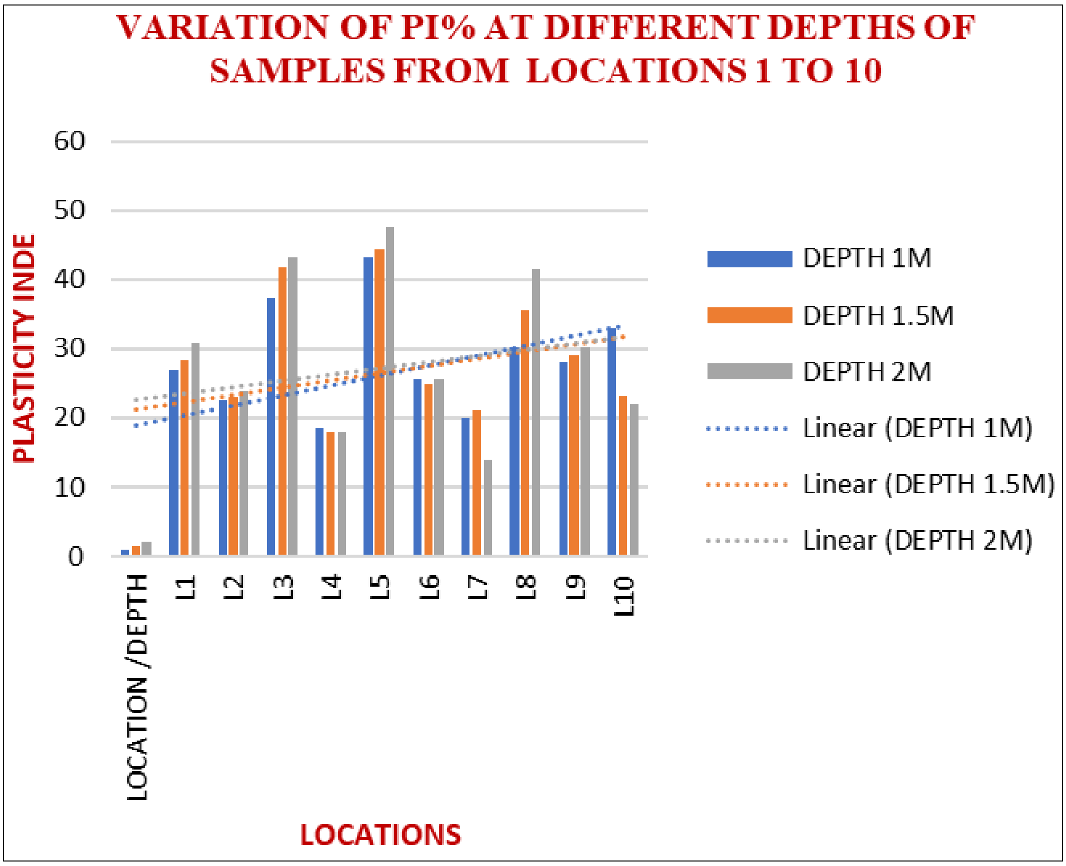



**Fig 18:** PI % of samples from locations L1 to L10

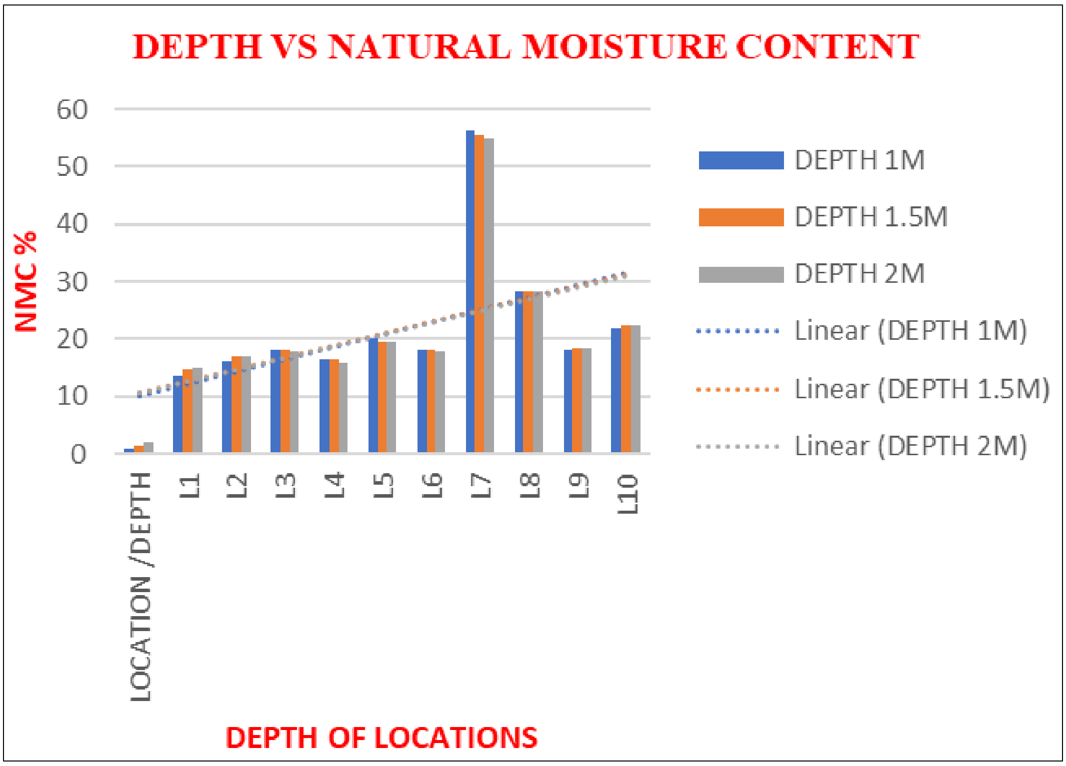



**Fig 19:** Variation of water content with depth.

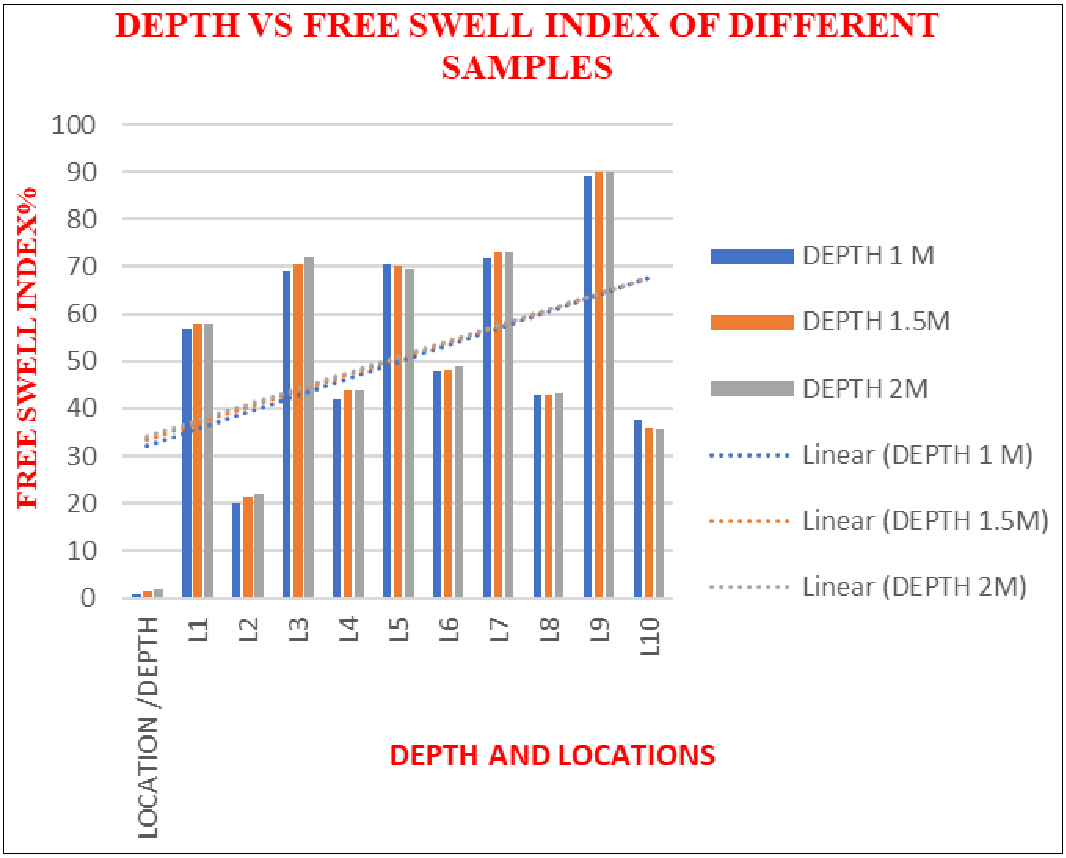



**Fig 20:** Percent Free swell versus depth for all soil specimens from different locations of various depth

**Table 1:** Salient details of selected building from case study

| S. No | Description | Bahour | Kirumampakkam | Pillayarkuppam | Sellipet | Koodapakkam | Thondamanatham | Ezhil nagar | Krishna nagar | Rainbow nagar | Venkata nagar |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Location | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 |
| 2 | Site condition | Dry | Dry | Dry | Dry | wet | Wet and dry | Wet and dry | Wet and dry | Wet and dry | dry |
| 3 | Soil type | Clay soil | Clay soil | Clay soil | Silty clay | High plastic clay soil | High Plastic clay soil | Clayey soil | Clayey soil | Clayey soil | Clayey soil |
| 4 | Type of property | Private | Private | Private | private | private | Public school building | private | private | private | private |
| 5 | Age of property | 29 years | 8 years | 28 years | 15 years | 20 years | 23 years | 25 years | 20 years | 12 years | 10 years |
| 6 | Construction date | 1988 | 2012 | 1990 | 2006 | 2000 | 1995 | 1993 | 2000 | 2007 | 2005 |
| 7 | Use of structure | Residential | Residential | Commercial | Residential | Residential | Public | Residential | Residential | Residential | Residential |
| 8 | Type of structure | Masonry | Framed | Framed | Framed | Framed | Framed | Framed | framed | Framed | Framed |
| 9 | Surrounding activates especially the hazardous one | Sewer line in front of the house | Waterlogged area due to its low lying profile. Large, deep rooted trees were also observed in the vicinity | Horizontal crack and vertical crack below the lintel and skill levels. building has no plinth beam soil present were highly plastic | Movement of water penetrating into the ground due to lack of proper drainage system. | Moderate to severe degree of visible damages cracks were originating from floor towards the roof lack of adequate soil investigation | Uneven settlements of floor jammed doors and grill twisted placed in the wall | Water get stagnated around the building. high swell and shrink behaviour | Diagonal Cracks with a stair-step pattern in external walls. | Cracks moderately affect the serviceability | Horizontal cracks developed between the ground slab and the external substructure wall |
| 10 | Any major repair carried out | Cracks have been cover with mortar | Cracks have been covered with mortar | Cracks have been plastered | Cracks everywhere in external walls of varying length plastered | Building undergone significant settlement. major repair works carried out | Flooring newly done with plastering work and some portion of walls were demolished and constructed | Settlement cracks found in foundation walls are being plastered | For every two years cracks are being plastered | Diagonal cracks in windows are plastered | For every two years cracks are being plastered |
| 11 | Depth of foundation | 1.5 m from EGL | 1.2 m from EGL | 1.5m from EGL | 1.20 m from EGL | 1.20 m from EGL | 1.5m from EGL | 1.5 m from EGL | 3.0 m from EGL | 1.50 m | 1.20 m |
| 12 | Type of footing | Masonry wall footing | Isolatedcolumn footing | Isolatedcolumn footing | Isolated column footing | Isolated column footing | Isolated and combined column footing | Isolated column footing | Pile foundation | Isolated column footing | Isolated column footing |
| 13 | No. of storeys | Single storey (GF) | Single storey (GF) | Single storey (GF) | Single storey (GF) | GF+1 storey | GF+1 storey | GF+1 storey | Single storey (GF) | Single storey (GF) | GF+1 storey |

**Table 2:** Categorisation and classification based on width of cracks

| Crack width (mm) | Category | Classification |
|---|---|---|
| Less than 2 mm | Very slight | Aesthetic |
| 2 mm to 5 mm | Slight | Aesthetic |
| 5 mm to 15 mm | Moderate | Serviceability |
| 15 mm to 25 mm | Severe | Serviceability |
| Over 25 mm | Very severe | Stability |

Based on width of cracks identified from the case study, the categorisation and classification of visible damages can be stated based on the literature support, by Burland *et al*. (1997) [11].

**Table 3:** Physical condition (pc) scale of the building system

| Sl. No. | Chronology Value | Physical condition |
|---|---|---|
| 1 | Repair is not needed | structural element is free from any visible defects |
| 2 | Repair is needed within the period of 1-2 years | Structural element is structurally functional but need minor repair |
| 3 | Repair is needed within the period of 6-12 months | Structural element is functionally sound but require urgent repair |
| 4 | Repair is needed within the period of 1-6 moths | Serious defect, structural element can function but not to an acceptable standard |
| 5 | Repair is required immediately | Structural member is not functioning at all. |

The physical condition (pc) scale of the building system is based on the literature support, by Dabo Baba Hammad *et al*. (2014) [4].

**Table 4:** Progression details of cracks in buildings in case study of l6

| Location of crack | Short term inspection (3 months) in progression of cracks-case study of l6 | | | | | | | Approximate length of cracks (MM) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 day (mm) | 15 days (mm) | 30 days (mm) | 45 days (mm) | 60 days (mm) | 75 days (mm) | 90 days (mm) | 1 day (mm) | 45 days (mm) | 90 days (mm) |
| Walling system | 50 | 52 | 56 | 60 | 64 | 66 | 72 | 3600 | 3608 | 3614 |
| Doors and windows | 16 | 20 | 24 | 28 | 30 | 32 | 35 | 950 | 958 | 962 |
| Beams and column | 40 | 41 | 45 | 48 | 50 | 52 | 60 | 700 | 705 | 712 |
| Floor system | 20 | 29 | 30 | 36 | 39 | 40 | 45 | 2700 | 2742 | 2780 |

**Table 5:** Chronology importance for physical condition on the progression of l6

| Physical condition criteria | Location of cracks in the critical location of alternate building system (l6) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Floor system | Walling system | Doors and windows | Ceiling system | Electrical system | Terrace | Beams and column |
| Approximate width of cracks (mm) | 45 | 72 | 32 | 17 | 5 | 25 | 60 |
| Activity of crack | active progression | Passive with slight progression | active | passive | passive | Passive with slight progression | Passive with slight progression |
| Physical condition (PC) | Structural member is not functioning at all. | Functionally sound but require urgent repair | functionally sound but require urgent repair | Serious defect, can function but not to an acceptable standard | structurally functional but need minor repair | Serious defect, can function but not to an acceptable standard | Serious defect, can function but not to an acceptable standard. |
| Chronology importance | Repair is required immediately | Repair is needed within the period of 6-12 months | Repair is needed within the period of 6-12 months | Repair is needed within the period of 1-6 months | Repair is needed within the period of 1-2 years | Repair is needed within the period of 1-6 months | Repair is needed within the period of 1-6 months |

**Table 6:** Progression details of cracks in buildings in case study of l7

| Location of crack | Short term inspection (3 months) in progression of cracks-case study of l7 | | | | | | | Approximate length of cracks (MM) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 day (mm) | 15 days (mm) | 30 days (mm) | 45 days (mm) | 60 days (mm) | 75 days mm) | 90 days (mm) | 1 day (mm) | 45 days (mm) | 90 days (mm) |
| Walling system | 70 | 75 | 80 | 84 | 88 | 90 | 95 | 2600 | 2608 | 2618 |
| Doors and windows | 7 | 8 | 8 | 10 | 11 | 11 | 12 | 1050 | 1058 | 1072 |
| Beams and column | 30 | 35 | 36 | 36 | 40 | 40 | 41 | 600 | 615 | 618 |
| Floor system | 15 | 18 | 18 | 20 | 22 | 25 | 30 | 2700 | 2750 | 2755 |

**Table 7:** Chronology importance for physical condition on the progression of cracks in buildings of case study of l7

| Physical Condition Criteria | Location of cracks in the critical location of alternate building system (l6) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Floor system | Walling system | Doors and windows | Ceiling system | Electrical system | Terrace | Beams and column |
| Approximate width of cracks (mm) | 30 | 95 | 12 | 15 | 5 | 25 | 41 |
| Activity of crack | Active progression | Active | Active | Passive | Passive | Passive with slight | Passive with slight progression |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | progression | |
| Physical condition (PC) | Functionally sound but require urgent repair. | Functionally sound but require urgent repair | Functionally not sound but require urgent repair | Serious defect, can function but not to an acceptable standard | Structurally functional but need minor repair | Serious defect, can function but not to an acceptable standard | Serious defect, can function but not to an acceptable standard |
| Chronology importance | Repair is needed within the period of 6-12 months | Repair is needed within the period of 6-12 months | Repair is needed within the period of 6-12 months | Repair is needed within the period of 1-6 months | Repair is needed within the period of 1-2 years | Repair is needed within the period of 1-6 months | Repair is needed within the period of 1-6 months |

**Table 8a:** Results of the laboratory test on soil samples from different study locations from l1 to l10

| Location/Samples | Depth (m) | LL % | PL % | PI % | SL % | Clay % | pH | G | MDD KN/m³ | OMC% | NMC% | Soil classification |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L1 S1-Bahour | 1.00 | 66.50 | 39.50 | 27.00 | 4.80 | 65.50 | 7.35 | 2.66 | 18.39 | 15.14 | 13.51 | CH |
| L1 S2 | 1.50 | 66.40 | 38.00 | 28.40 | 3.90 | 66.50 | 7.35 | 2.52 | 18.20 | 15.10 | 14.75 | |
| L1 S3 | 2.00 | 68.00 | 37.00 | 31.00 | 3.90 | 67.00 | 7.40 | 2.60 | 17.90 | 14.90 | 14.90 | |
| L2 S1-Kirumampakkam | 1.00 | 56.00 | 33.41 | 22.60 | 25.70 | 64.78 | 7.15 | 2.60 | 17.73 | 18.19 | 16.25 | CH |
| L2 S2 | 1.50 | 57.25 | 34.20 | 23.05 | 27.10 | 66.40 | 7.00 | 2.55 | 17.80 | 17.90 | 17.00 | |
| L2 S3 | 2.00 | 59.25 | 35.25 | 24.00 | 27.10 | 68.00 | 7.15 | 2.62 | 18.00 | 18.00 | 17.00 | |
| L3 S1-Pillayarkuppam | 1.00 | 75.00 | 37.50 | 37.50 | 8.40 | 72.43 | 7.20 | 2.62 | 13.10 | 32.00 | 18.20 | CH |
| L3S2 | 1.50 | 82.30 | 40.50 | 41.80 | 8.25 | 73.00 | 7.40 | 2.55 | 12.89 | 31.25 | 18.20 | |
| L3S3 | 2.00 | 85.20 | 41.97 | 43.23 | 8.13 | 73.52 | 7.40 | 2.6 | 13.19 | 32.30 | 18.00 | |
| L4 S1-Sellipet | 1.00 | 37.00 | 18.40 | 18.60 | 15.20 | 70.30 | 7.15 | 2.33 | 17.35 | 16.70 | 16.50 | CI |
| L4 S2 | 1.50 | 35.00 | 17.20 | 17.80 | 15.85 | 68.50 | 7.10 | 2.40 | 17.20 | 16.40 | 16.50 | |
| L4 S3 | 2.00 | 33.50 | 15.50 | 18.00 | 16.50 | 65.80 | 6.85 | 2.38 | 16.85 | 15.25 | 16.00 | |
| L5 S1-Koodapakkam | 1.00 | 85.20 | 42.00 | 43.20 | 8.10 | 73.52 | 7.00 | 2.20 | 13.19 | 32.30 | 20.15 | CH |
| L5 S2 | 1.50 | 84.50 | 40.20 | 44.30 | 8.00 | 70.80 | 7.15 | 2.35 | 13.10 | 31.85 | 19.50 | |
| L5 S3 | 2.00 | 79.50 | 31.80 | 47.70 | 7.95 | 66.20 | 7.05 | 2.30 | 12.89 | 31.60 | 19.50 | |
| L6 S1-Thondamanatham | 1.00 | 68.35 | 42.72 | 25.63 | 12.80 | 74.30 | 7.25 | 2.60 | 14.20 | 22.15 | 18.10 | CH |
| L6 S2 | 1.50 | 66.80 | 42.00 | 24.80 | 12.55 | 72.50 | 7.10 | 2.62 | 14.10 | 22.05 | 18.10 | |
| L6 S3 | 2.00 | 65.20 | 39.70 | 25.50 | 12.28 | 70.90 | 7.15 | 2.55 | 13.89 | 21.45 | 17.90 | |
| L7 S1-Ezhil Nagar | 1.00 | 70.00 | 49.50 | 20.50 | 15.40 | 65.20 | 7.31 | 2.58 | 15.94 | 24.25 | 56.20 | CH |
| L7 S2 | 1.50 | 70.00 | 48.90 | 21.10 | 13.50 | 64.81 | 7.25 | 2.64 | 15.94 | 24.20 | 55.50 | |
| L7 S3 | 2.00 | 68.00 | 54.00 | 14.00 | 10.01 | 64.81 | 7.33 | 2.66 | 15.85 | 23.40 | 55.00 | |
| L8 S1-Krishna Nagar | 1.00 | 55.00 | 24.90 | 30.10 | 8.70 | 72.00 | 7.10 | 2.22 | 14.23 | 35.80 | 28.20 | CH |
| L8 S2 | 1.50 | 59.80 | 24.25 | 35.55 | 8.10 | 74.50 | 7.05 | 2.22 | 14.85 | 35.80 | 28.20 | |
| L8 S3 | 2.00 | 63.50 | 22.00 | 41.50 | 7.80 | 78.50 | 7.10 | 2.30 | 15.05 | 36.15 | 28.35 | |
| L9 S1-Rainbow Nagar | 1.00 | 65.00 | 37.00 | 28.00 | 4.25 | 72.00 | 6.95 | 2.70 | 15.10 | 17.50 | 18.20 | CH |
| L9 S2 | 1.50 | 67.25 | 38.10 | 29.15 | 3.10 | 76.30 | 7.02 | 2.68 | 15.24 | 17.25 | 18.50 | |
| L9 S3 | 2.00 | 70.00 | 39.86 | 30.14 | 2.00 | 80.24 | 6.95 | 2.71 | 15.59 | 17.68 | 18.50 | |
| L10 S1-Venkatanagar | 1.00 | 54.00 | 20.92 | 33.08 | 10.00 | 70.35 | 7.20 | 2.61 | 15.80 | 23.40 | 21.85 | CH |
| L10 S2 | 1.50 | 51.40 | 28.15 | 23.25 | 9.70 | 66.80 | 7.10 | 2.59 | 15.40 | 23.10 | 22.30 | |
| L10 S3 | 2.00 | 49.50 | 27.50 | 22.00 | 9.20 | 64.50 | 7.20 | 2.62 | 15.24 | 22.95 | 22.30 | |

**Table 8b:** Results of the laboratory test of free swell index of soil samples from different study locations from l1 to l10

| Depth/locations | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 m | 57 | 20 | 69 | 42 | 70.6 | 47.8 | 71.8 | 42.9 | 89 | 37.5 |
| 1.5m | 58 | 21.5 | 70.6 | 44 | 70 | 48.2 | 73 | 43 | 90 | 36 |
| 2.0 m | 58 | 22 | 72 | 44 | 69.5 | 49 | 73 | 43.4 | 90 | 35.8 |

**Table 9:** Classification details of cracks in case study buildings from l1 to l10

| Location | Most affected building elements | Approximate length of cracks and details | Approximate width of cracks (mm) | Category | Classification |
|---|---|---|---|---|---|
| L1 | Floor, walls, lintels | 800 mm | 5 | Slight | Aesthetic |
| L2 | Walls and floors | 1200 mm | 3 | Slight | Aesthetic |
| L3 | Walls., floors, column separating from wall, terrace | From the bottom towards the roof (External walls) 1800 mm in length | 15 | Moderate | Serviceability |
| L4 | Walls. Floors | . 850 mm | 5 | Slight | Aesthetic |
| L5 | Walls., floors, column separating from wall, terrace | .800 mm | 6.5 | moderate | Serviceability |
| L6 | Walls, floor, lintels grill work bend in opening | Diagonal cracks of length 2000 mm | 25 | Severe | Serviceability |
| L7 | External walls, lintel and sunshade, window edges, corner of the wall is affected, roof get exposed reinforcement | Diagonal cracks of length 800 mm | 12 | Moderate | Serviceability |
| L8 | Floor, window edges, external walls | From the bottom | 6 | Moderate | Serviceability |

| | | | | | |
|---|---|---|---|---|---|
| | | towards the roof 720 mm | | | |
| L9 | External walls | Numerous cracks of 740 mm length | 5 | Slight | Aesthetic |
| L10 | External walls, cracks from lintel to roof | 600 mm | 5 | Slight | Aesthetic |

**Table 10:** IS Classification based on liquid limit (IS 1498)

| Liquid limit | Description |
|---|---|
| Less than 35% | Low compressibility |
| 35% -50% | Medium compressibility |
| Greater than 50% | High compressibility |

**Table 11:** IS Classification based on the plasticity index (IS 1498)

| Plasticity index | Soil description |
|---|---|
| 0 | Non plastic |
| Less than 7 | Low plastic |
| 7-17 | Medium plastic |
| Greater than 17 | Highly plastic |

**Table 12:** IS Classification based on liquidity and consistency index (IS 1498)

| Consistency index | Liquidity index | Description |
|---|---|---|
| Less than 0 | Greater than 1 | Liquid |
| 0-0.25 | 0.75-1.0 | Very soft |
| 0.25-0.5 | 0.5-0.75 | Soft |
| 0.5-0.75 | 0.25-0.5 | Medium soft |
| 0.75-1.0 | 0-0.25 | Stiff |
| Greater than 1 | Less than 0 | Very stiff or hard |

**Table 13:** Soil expansivity prediction by liquid limit (IS 1498)

| Degree of expansion | Liquid limit (%) |
|---|---|
| Low | 20-35 |
| Medium | 35-50 |
| High | 50-70 |
| Very high | 70-90 |

**Table 14:** Soil expansivity prediction by plasticity index (IS 1498)

| Degree of expansion | Plasticity index (%) |
|---|---|
| Low | Less than 12 |
| Medium | 12-23 |
| High | 23-45 |
| Very high | Greater than 32 |

**Table 15:** Typical values of unconfined compressive strength IS (1498)

| Consistency of clay | UCC (kN/m2) |
|---|---|
| Very soft | Less than 25 |
| Soft | 25-50 |
| Medium | 50-100 |
| Stiff | 100-200 |
| Very stiff | 200-400 |
| Hard | Greater than 400 |

**Table 16:** Comparison of compressive strength to the difference of Crack Width within 3 months of inspection and monitoring at location L2

| No. | location | Crack width difference (mm) | Compressive strength of concrete(MPa) | |
|---|---|---|---|---|
| | | | Inspection (July 2018) | Monitored (October 2018) |
| 1. | Grid along B1-kitchen and toilet wall | 2 | 30 | 29 |
| 2. | Grid along 11-store wall | 3 | 32 | 31 |
| 3. | Grid along AA external wall in dining | 5 | 34 | 32 |
| 4. | Grid along CC-wall between hall and study | 7 | 34 | 33 |
| 5. | Grid along D4-study wall | 4 | 32 | 29 |

**Table 17:** Swelling potential prediction in soils [3]

| Parameter | Reference | Degree of expansion | | | |
|---|---|---|---|---|---|
| | | Low | Medium | High | Very high |
| LL% | Chen, 1975 | <30 | 30-40 | 40-60 | >60 |
| PI% | Chen, 1975 | 0-15 | 10-35 | 20-55 | >55 |
| | Holtz and Gibbs, 1956 | <20 | 12-34 | 23-45 | >45 |
| Clay content% | Holtz and Gibbs, 1956 | <17 | 12-27 | 18-37 | >27 |
| Clay content% | Holtz, 1959 | - | 13-23 | 20-31 | >28 |
| Swell percent% | Thomas *et al.*, 2000 | <3.0 | 3.0-6.0 | 6.0-9.0 | >9.0 |
| Swell pressure (kPa) | Thomas *et al.*, 2000 | <81 | 81-153 | 153-225 | >225 |
| Activity | Skempton, 1953 | <0.75 | - | 0.75-1.25 | >1.25 |

**Table 18:** Expansive soil classification based on FSI (IS 1498)

| Locations | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| FSI % | 58.00 | 19.80 | 70.60 | 42.50 | 60.00 | 50.25 | 73.00 | 61.00 | 90.00 | 34.40 |
| Swell Potential | M | M | M | L | M | M | L | M | M | L |

**Table 19:** Soil expansivity prediction by LL

| Locations | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| LL % | 68.00 | 59.25 | 85.20 | 33.50 | 79.50 | 65.20 | 68.00 | 63.50 | 70.00 | 49.50 |
| Degree of Expansion | | | | | | | | | | |
| IS 1498 | H | H | VH | M | VH | H | H | H | H | M |
| Chen | VH | H | VH | M | VH | VH | VH | VH | VH | M |
| Holtz and Gibbs, 1956 | H | H | VH | H | VH | H | H | H | H | H |

**Table 20:** Soil expansivity prediction by PI

| Locations | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| PI % | 31.00 | 24.00 | 43.23 | 18.00 | 47.70 | 25.50 | 14.00 | 41.50 | 30.14 | 22.00 |
| Degree of Expansion | | | | | | | | | | |
| IS 1498 | H | H | VH | M | VH | H | M | H | H | M |
| Chen | VH | H | VH | M | VH | VH | VH | VH | VH | M |
| Holtz and Gibbs, 1956 | H | M | VH | M | VH | H | M | VH | H | M |

M= Medium, H= High, VH= Very High

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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