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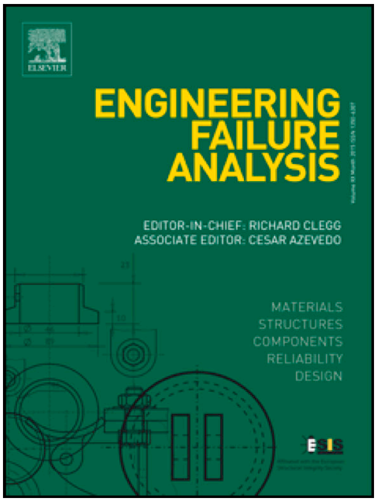

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PII: S1350-6307(23)00288-1
DOI: https://doi.org/10.1016/j.engfailanal.2023.107334
Reference: EFA 107334

To appear in: *Engineering Failure Analysis*

Received Date: 6 August 2022
Revised Date: 5 April 2023
Accepted Date: 11 May 2023

Please cite this article as: Igba, U.T., Igba, P.O., Adekunle, A.A, Labiran, J.O., Oyebisi, S.O., Cosmas, C.A., Strengthening and underpinning of a sinking two storey building in lagos state nigeria, *Engineering Failure Analysis* (2023), doi: https://doi.org/10.1016/j.engfailanal.2023.107334

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STRENGTHENING AND UNDERPINNING OF A SINKING TWO STOREY BUILDING IN LAGOS STATE NIGERIA

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ABSTRACT:

Many existing foundations, particularly those that are old and dilapidated, are no longer strong enough to support the pressures they bear or support new loads applied to them. In order to boost the load bearing capacity, a unique underpinning technique is required. Underpinning technique provides secure, efficient, and reliable solutions to foundation and geotechnical problems affecting the foundations of buildings. However, the practice of underpinning is not common in Nigeria. This paper presents a case study on the settlement failure of a two-storey residential building in Lagos, Nigeria. The residential building encountered excessive differential settlement due to the variation in the soil strata in in 06°26'12"N Long: 3°30'44"E area of Lagos state. Some portion of the building was laid on weak and loose clayey sand which showed signs of foundation distress and led to the eventual choice of an underpinning technique adopted to extend the foundation depth to a stable stratum, to salvage the failed areas of the foundation in order to strengthen the bearing capacity and to minimize settlement. Underpinning was done because the original raft foundation was inadequate for vertical and lateral loads. The procedure used for underpinning was summarized. The measured settlement points of the underpinned foundations after six-year service life were less than 0.333 mm. This result meant that every point (from points 1-10) measurements were below the settlement limit which guaranteed the bearing resistance of the building. The result showed that the underpinning technique salvaged the areas that initially settled and showed distress signs.

Keywords: Underpinning, Strengthening, Foundation, Construction.

1.0 INTRODUCTION

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The difference in soil compressibility leads to an excessive differential settlement in buildings [1]. A tried-and-true approach for foundation rehabilitation used over the years has been underpinning. Underpinning is the process of strengthening an existing foundation by adding supports to it in a bid to make it more rigid, avoid settling and collapsing of such buildings [2]. In Nigeria, there are many building failures and collapses, which are caused by inadequate monitoring and use of inferior and substandard materials [3]. When a building reaches the end of its service life, renovation work, such as foundation underpinning, is often done to salvage such buildings. Buildings deteriorate and collapse when there is a poor design and construction method, or when the hiring of quacks rather than professionals is encouraged [4]. The Early Winchester Cathedral was strengthened by submersible workers who made use of an underwater digging technology to reach the gravel layer after crossing peat and silt which was then filled with concrete to carry out the underpinning construction [5]. An active underpinning technology for underpinning structures in the province of Kyoto Metro Japan, was used to meet the requirements in the designs of pile settlement [6].

The technology employed in pile underpinning can effectively protect existing structures and also solve problems that may arise from urban transportation and construction of an underground space [7-11].

In the eighteenth century, the Swedish Imperial Palace's foundation inclined, which was as a result of the wood piling foundation and the uneven soil foundation thickness. It was salvaged by the use of pile foundation underpinning technique [12]. In history, there are very few cases of underpinning construction details and performance-based analysis [13-14]. A study was done on both pile and pile group characteristics beneath an existing building [15].

New structures are prevented from any unexpected settlement, it is of utmost importance that a proper field investigation must be performed, including test borings, test pits, laboratory soil tests. Old and dilapidated buildings on the other hand requires renovation work which can yield either visible or invisible changes [16]. Many researchers in the past have identified the problems of settlement and collapse of buildings and have found lasting solutions to these problems. Some of such researchers include [17-20].

Over the years, various methods of underpinning methods have been adopted [21-22]. In the early 1980s, the methods used included, the extension of the foundation by deepening and broadening, use of different types of pile work and soil nailing [23-24]. Micro-piles have been a common underpinning method since the 1980s [25-27]. The steel-structured micro-piles are installed by drilling, driving, jacking, or screwing, depending on the circumstances and the installation equipment available [28-30]. Micro-piles reduced soil pressure as a result of load transferred from the soil to the micro-piles after the connection of the micro-piles to the new foundation [31].

Most underpinning techniques are based on the level of construction experience with few experiences in the theoretical and experimental studies. This current work provides a lasting solution of a settling two-storey building in Lagos Nigeria. This paper studies a retrofitting case by adding a new reinforcement cage linked with beams and piles beneath an existing 2 storey raft building construction project, in Lagos Nigeria. Attention was given to the whole underpinning procedure to ensure that the settlement that occurred was stopped and within the minimum bearable range.

2.0. Engineering Description

The residential reinforced concrete building was built on a raft foundation located in Lagos, Nigeria. The initial raft foundation had a depth of 2 metres below the natural ground level with a floor plan of 19.79 metres by 16.675 metres.

The new underpinning foundation had about 10 pile points with pile width of 450 mm and depth of 15 metres with a basket reinforcement cage anchored to the new underpinning pile and the existing raft foundation.

The new dimension of the structure to be underpinned was 25.79 m by 22.675 m with an offset of 3 metres to the left and 3 metres to the right of the original building plan area. C40 concrete grade was used to cast with the

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use of 20 mm and 16 mm steel reinforcement diameter rods adopted for the connecting beams and pile underpinning foundation.

2.1 Methods of underpinning

There are two categories of underpinning techniques which are the temporary and permanent techniques. The temporary techniques can be sub-divided into Ground freezing and ground water control while, the permanent techniques can be sub-divided into Geometrical underpinning (deepening and enlarging the foundations), underpinning by grouting, and underpinning by piling [32].

2.2. Temporary underpinning methods

2.2.1 Ground freezing

For excavation below the ground water table, the ground freezing method has been used in tunnelling for many years. The primary goal of this underpinning method is to stop additional soil movement and settling by creating a mass of iced soil beneath or next to the current building [32].

2.2.2 Ground water control

Controlling ground water levels might be considered a foundational strategy that is preventive and quick to fix a ground water problem. A permanent underpinning should be done. However, in certain instances permanent ground water management is necessary. Numerous articles have cited the possibility of a major impact of ground water flow on the effectiveness of foundations [32].

2.3 Permanent underpinning methods

2.3.1 Geometrical underpinning

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Geometrical underpinning is the oldest type of underpinning. This type of underpinning often entails expanding (deepening) and/or broadening (strengthening) foundations. In other words, foundations are initially liberated from their loads using a variety of standard preliminary support techniques (such as shoring, Pynford stool, jacking, needle beam, etc.). In order to reduce the pressure beneath them, foundations are either broadened or deepened (and occasionally both are adopted) to achieve this reduction. Settlement will then be stopped or reduced. Moreover, deteriorating materials may occasionally be taken out and new materials, often concrete, substituted for them. The weight will subsequently be transferred to the reinforced foundation. As a result, the footings' geometry—that is, the breadth, depth, or both—will be altered. The traditional method of underpinning makes use of deeper, typically firmer soils; professional masons may be needed.

Geometrical underpinning can be sub-divided into:

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2.3.1.1. Continuous underpinning of strip foundations

This is the oldest and best-known method of wall underpinning, as described by several authors [33]. First, the intervals beneath the wall's strip foundation are dug to create rectangular pits (referred to as "legs" or "panels"). The average length of each pit is between one and two meters, as stated by several sources [33]. This length is controlled by the pit excavation's arching motion, and used in cases experiencing weak brickwork, it may be as short as 0.7 meters [34].

2.3.1.2 Needle beam underpinning (needling)

When using the prior technique, needle beams shown in **Fig. 1** are required to hold the wall if the excavation depth exceeds 1.2–1.5 m, or when the load distribution is uneven, there is a risk that the wall would collapse from lack of tensile strength. This approach is well-known and widely used, as it has been described by several writers. The positioning of the beams via holes in the wall is the method's fundamental idea. Typically, a collar or bracket is required to attach a column to a needle beam for support. Steel beams are often favoured; however, needle beams can also be composed of wood or reinforced concrete. Concrete blocks or spread footings are placed next to the foundation to support them on the ground [32].

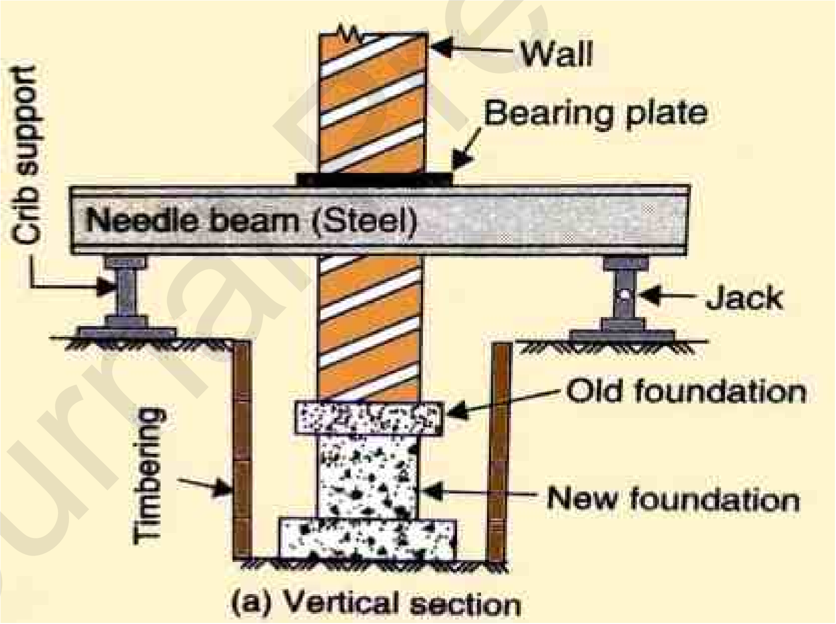

Fig. 1. Needle beam underpinning [35]

2.3.1.3 Shoring underpinning

The purpose of shoring is to release load from the walls to the foundation for underpinning to be achieved. In order to sustain the weight of the structure, shores are made up of inclined steel or timber bracing. This approach is advantageous for light masonry structures and are usually less costly. An extra vertical leg is placed when the framework is excessively frail or thin.

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2.3.1.4 The Pynford underpinning method

This technique shown in **Fig. 2** is said to be more economical than conventional continuous underpinning for underpinning masonry walls. Forham Pryke created the system in the middle of the 1940s, and he described it in [36]. This approach does not use needle beams; instead, it uses stool that are inserted into the holes at a distance of 0.9 meters from centre to centre to sustain the weights. A strong mortar made of 1:1 Portland cement and sharp sand is used to fill the spaces between the tops of the stools and the walls. Brickwork between the stool is cut once the mortar has dried, and beam reinforcement is then inserted through the stools, followed by the pouring of concrete to create a reinforced concrete beam that extends up to 50 mm below the underside of the wall. The hole is finally filled and secured.

Fig. 2. Pynford stool for underpinning [35]

2.3.1.5. Jacking

Jacking operations shown in **Fig. 3** are usually performed to re-align sections of existing structures that have defected, and such defects can be rectified by a jacking process. This technique is usually adopted to lift or lower an already existing structure. During the jacking process, the structural component in the foundation will be observed to check for stress and signs of distress, once any sign of stress is noticed, the jacking operation will be terminated [2].

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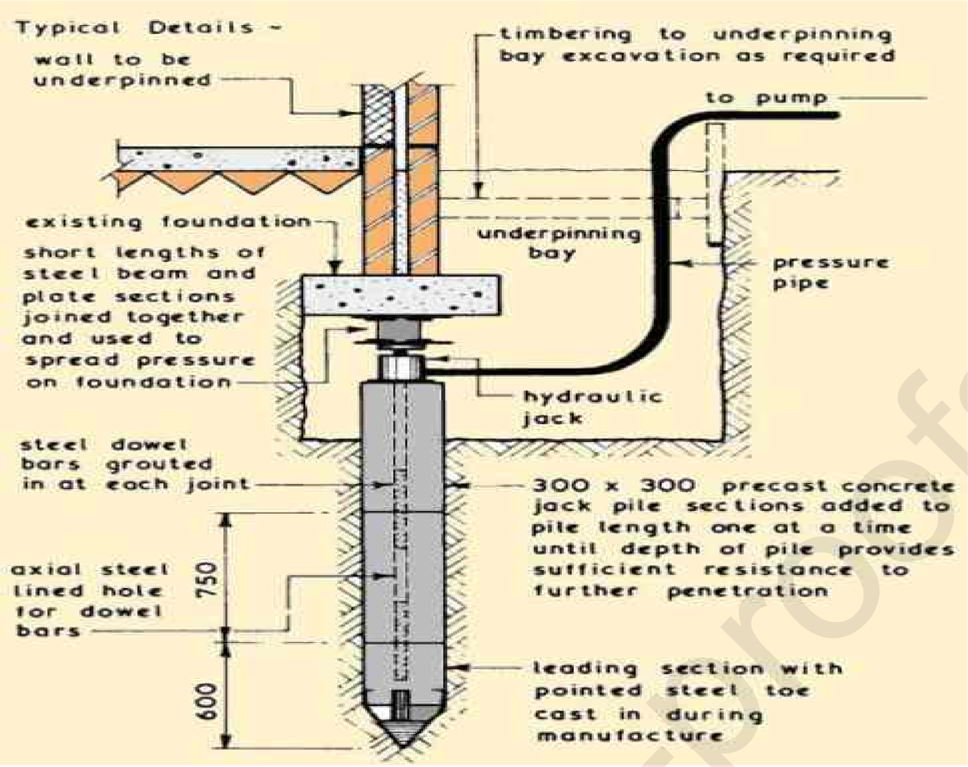

Fig. 3. Jacking underpinning [35].

2.3.1.6 Beam -and-Column Underpinning

The single beam underpinning is a common method of masonry structure housing. A beam is set at the top of the demolished wall, as shown in **Fig. 4** instead of the lower bearing wall to bear the upper load. Due to the change in the load transfer path, the concrete columns are set below both ends of the underpinning beam, and form combination columns with the original walls [32].

Fig. 4. Beam and Column underpinning [32].

2.3.1.7 Mass concrete Underpinning.

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Traditional mass concrete underpinning shown in **Fig. 5** has the benefit of frequently reducing disruption to the walls' exteriors and is especially appropriate for heavy laden constructions. Mass Concrete Underpinning is the use of mass concrete blocks placed under the footings of sinking buildings at strategic locations to strengthen and stabilize an existing foundation. The process of mass concrete underpinning involves digging rectangular holes by hand underneath the existing foundation footing and pouring mass concrete at strategic locations in alternate bays [2].

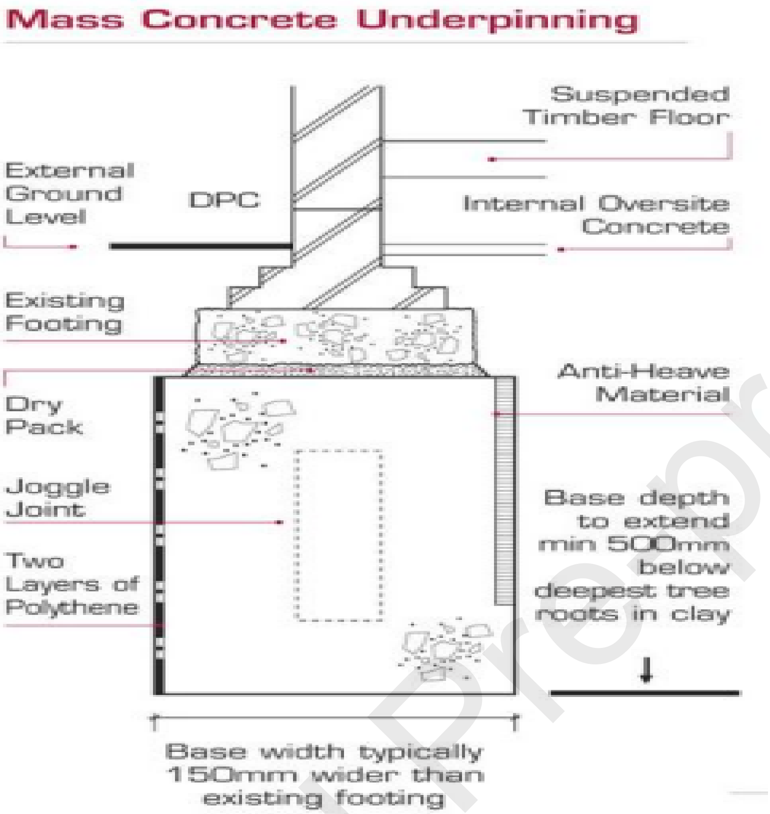

Fig. 5. Mass concrete underpinning [2].

2.3.2 Underpinning by grouting

2.3.2.1. Underpinning by cement grouting

For treated soils, cement grouting can serve the dual purpose of reducing permeability and reinforcing soils. It is excellent for sands and effective for soils with very coarse grain sizes when used just for its consolidating or compacting action by injection method at frequent intervals [37].

2.3.2.2 Underpinning by chemical grouting

The basis for chemical grouting in soil involves the process of injecting sodium silicate (also known as water glass), which when diluted with water undergoes chemical reactions that transform into a gel. It gives the soil mass a cohesive strength and hardens the soil to make foundation excavation and structural underpinning possible.

2.3.2.3 Underpinning by jet grouting

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It is also known as "Soilcrete." producing in-situ soil-cement columns. In order to reach the complete depth, the soil has to be stabilized and cemented, a hole is first bored using a rotary tool or water jet. When grout liquid (cement-bentonite) is combined in-situ with soil, a soil-cement column is generated to "solidify" the subsoil. The soil is then sliced by a specific high-pressure jet between 20-70 MPa and rotated horizontally (1-2 mm in diameter). The columns may be overlaid to create continuous walls.

2.3.2.4 Underpinning by Compaction grouting

It is used for underpinning foundations for anchoring, by raising and lifting foundations experiencing differential settling, this sort of grouting has been utilized by [32].

2.3.3 Underpinning by piling

When a stiffer layer of soil is available at an acceptable depth, loads are substantial, or standard. Underpinning techniques are impractical or impossible, piles are typically utilized. Different types of piles can be used, as discussed below.

2.3.3.1. Mini-Piling Underpinning

In cases when the depth of loose ground makes mass concrete or beam column approaches impractical, a mining piling system like that in **Fig. 6** is utilized. It has the advantage that it can be constructed into water bearing strata without the use of a pumping machine and allows the unhindered passage of ground water. There are varieties of mini piles, which include Augured/Bored piles, Driven piles, jacked in piles [2].

Fig. 6. Mini piling underpinning to support vertical loads [2].

2.3.3.2. Reinforced Concrete Underpinning (Piles and Beams)

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Reinforced concrete underpinning as shown in **Fig. 7** is the procedure of marking the holes to be dug in alternate bays of 1.0m to 1.5m intervals in serial orders of (1,2,3,4,5,6,7,8,9,10,11,etc.). This is the same as for mass concrete underpinning. The difference is that in the reinforced concrete underpinning, light reinforcement cages are fabricated and placed in each hole before concrete is poured and the concrete is fully vibrated with a poker vibrator. This light reinforcement is designed to resist all the tensile forces, which mass concrete cannot withstand [2].

Fig. 7. Piles and Beams to support vertical loads [2].

2.3.3.3 Driven piles

When there is enough area and headroom, driven piles can be used for underpinning from outside buildings. Despite being a rapid and affordable procedure, it has a significant drawback for underpinning projects since it causes vibration, soil displacements, and additional settling, particularly for older structures [38].

2.3.3.4 Bored piles

Although bored piles shown in **Fig. 8** produce little to no noise and vibration, they may be used for underpinning work. Additionally, they may be erected with little to no soil disturbance and little headroom (by employing tripod rigs), which are frequently crucial requirements for underpinning.

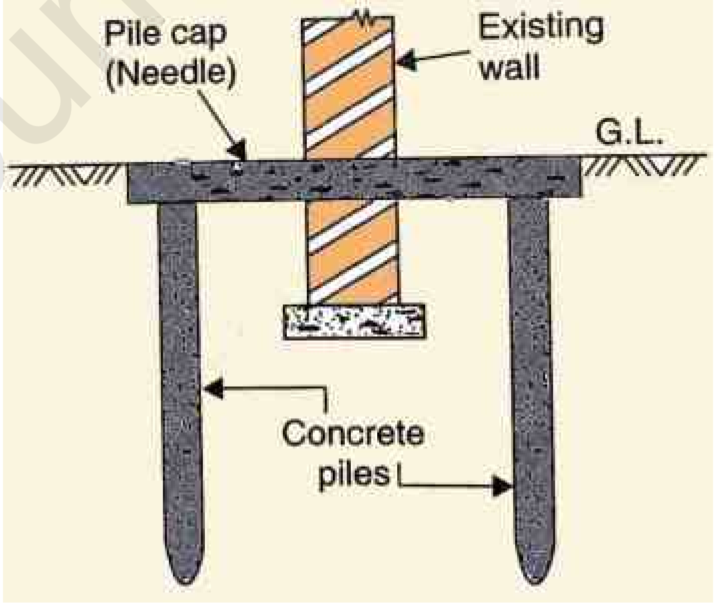

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Fig. 8. Pile method of underpinning [35]

2.3.3.5 Continuous flight auger piling

A continuous flight hollow-stem auger is used to create auger piles. Once the auger has been drilled into the earth to the desired depth, concrete or sand-cement grout is pumped into the hole from the auger tip while the auger is progressively withdrawn, forming the pile fully. Before the mortar hardens, a reinforcing cage, bar reinforcement, or high tensile bar is inserted into it if reinforcement is necessary. For unique reasons, auger piles can be built closely together to form a wall or an arch.

3.0 Methodology

3.1. Description of the Problem (Underpinning of a building in an Estate in Lagos, Nigeria).

3.1.1 The problem with the site

The building was one of the six duplex buildings in an estate located in Lagos State Nigeria. Originally, each duplex building had its own boy's quarter attached to the main building as a bungalow with its roof leaning to the back wall of the duplex as stand-alone building. The building was later changed and re-designed so that the Boys Quarters (B.Q's) were decked together with the main building. However, one of the six duplex buildings had been built to roofing level, having a raft foundation of 2 m depth, which was the closest to a nearby bridge, which in turn accommodated vibrations from the bridge.

3.2. Description of work

The residential structure was constructed on a raft foundation. A critical look showed that the depth of the foundation was not well interpreted from the borehole log, meaning the depth was shallower than what was required. The desired depth and bearing stratum, was not attained after looking critically at the borehole log.

The total Settlement of a normal building is supposed to be in the region of 400 mm for a lifespan of 100 years.

The new piling depth adopted was 15 metres which was in a strata of whitish-brown fine medium dense coarse silty soil.

3.3. Nature of Failure

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During the construction process, severe cracks began to appear on the wall of the building, which prompted the building committee to seek professional advice to solve the lingering problem. Severe horizontal and vertical cracks began to appear on the walls and on the floors. Looking at the cracks, it clearly showed that it was as a result of the foundation settlement. This was because from the history of the site, the building was previously used as a refuse dump site, which was not considered in the design process of the foundation. Some portion of the land was previously used as an old fish pond which was constructed years ago which led to the organic matter in the soil. The borehole log was wrongly interpreted as the raft terminated at 2 metres below the natural ground level which was in a strata of dark brownish soft compressible organic PEAT and Light Dark brown fine medium silty SAND with organic intrusion.

A large settlement can occur without showing any sign of 'failure', provided all the part of the structure move at the same rate. This has occasionally occurred in areas of mining subsidence [39]. The angular distortion, which is the difference in total settlement of two positions divided by the distance between them, should not exceed 1 in 300 or 1/300 if cracking of finishes and cladding are to be avoided [40].

3.4. Reason for Underpinning

The main reason for underpinning was to increase the depth of the existing foundations because the weak peaty-soil was not strong enough to withstand the weight of the structure due to the fact that the original foundation wasn't strong enough to support the existing 2 storey building structure that existed two floors.

Reinforced concrete (Beam and pile) underpinning was adopted to stabilize the foundation of the existing structure that was tilting, as well as to effectively strengthen and repair, the existing foundation that was subjected to very high differential settlement resulting in several cracked structural members.

4.0. Results

4.1. Borehole details:

Table 1 showed the result of 4 number (No) Penetration tests which was carried out using 2½-Ton machine. **Table 2** shown below has two borehole logs which were obtained from the field work that involved the use of a percussion drilling powered rig used to drill two (2) number of Boreholes (BH) to 30.0m depth.

Table 1: ESTIMATION OF BEARING PRESSURES USING CONE PENETRATION TEST (CPT) RESULTS

Depth	Cone Resistance kg/cm^2	Average Cone Resistance	Allowable Bearing Pressure	Submerged Bearing	Remarks

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	P1	**P2**	**P3**	**P4**	**kg/cm^2**	**KN/m^2**	**Pressure KN/m^2**	
0.25	10	10	2	5	7	43	22	Low Bearing Pressure, foundation submerged
0.50	10	2	2	2	4	25	12	= Ditto =
0.75	5	2	2	2	3	19	10	= Ditto =
1.00	5	10	5	5	6	37	19	= Ditto =
1.25	2	15	10	2	7	43	22	= Ditto =
1.50	2	15	10	2	11	68	34	= Ditto =
1.75	2	15	15	10	12	74	37	= Ditto =
2.00	2	15	15	15	12	74	37	= Ditto =
2.25	3	25	20	20	17	105	53	= Ditto =
2.50	3	40	25	20	22	136	68	= Ditto =
2.75	3	40	25	25	23	143	72	= Ditto =
3.00	20	40	40	35	34	211	106	Good Bearing Pressure, foundation submerged
3.25	20	40	40	30	33	205	103	= Ditto =
3.50	20	45	40	30	34	211	106	= Ditto =
3.75	20	45	45	30	35	217	108	= Ditto =
4.00	20	45	45	35	36	223	111	= Ditto =
4.25	25	45	45	40	39	242	121	= Ditto =

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4.50	25	45	45	50	41	254	127	= Ditto =
4.75	30	50	50	50	45	279	140	= Ditto =
5.00	30	50	50	55	46	285	143	= Ditto =
5.25	40	80	-	60	60	372	186	= Ditto =
5.50	50	80	-	70	63	391	196	= Ditto =
5.75	55	85	-	70	67	415	208	= Ditto =
6.00	60	85	-	80	75	465	233	= Ditto =
6.25	65	90	-	80	78	484	242	= Ditto =
6.50	65	90	-	85	80	496	248	= Ditto =
6.75	75	95	-	90	86	533	267	= Ditto =
7.00	85	105	-	105	98	608	304	= Ditto =

Engineering analysis of the field tests derived from the conducted investigations indicated that the shallow foundation cannot support the settling structure because of the occurrence of an unsuitable soil material which was a dark brownish soft organic fibrous PEAT shown in **Table 2** predominantly within the first 3 metres depth across the two boreholes obtained from site. Ground water was found to be 1.0 metre below the existing ground level. However, deep pile foundation was best to support the settling building. Such piles can be found within the sandy stratum at varying depths in the borehole profile.

The allowable bearing pressures estimated for shallow foundations was considered low and inadequate to support the proposed structure on this site, it was however recommended that a deep foundation in form of pile underpinning was the most feasible means of supporting the proposed structure on this site.

The proposed piles for underpinning the 2-storey building were expected to pass through layers of soft to firm deposit as indicated in the stratigraphic profile revealed by the borehole drillings below.

Table 2: Summary of sub-soil field test results

Borehole	Depth	Water	Materials

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No	**(m)**	**Level (m)**	**Encountered**
BH1	30.0	1.00	Top fill – Reddish lateritic CLAY (**0.0m – 0.15m**), Dark brownish soft organic fibrous PEAT (**0.15m – 1.0m**), Light Dark brown fine medium silty SAND with organic intrusion (**1.0m – 2.25m**), Whitish-grey firm sandy CLAY becoming sandy at depth (**2.25m – 4.50m**), Reddish fine medium coarse silty SAND (**4.50-m – 7.50m**), Reddish brown firm mottled lateritic silty sandy CLAY with whitish patches (**7.50m – 12.0m**), whitish brown fine medium dense coarse silty SAND (**12.0m – 17.25m**), Whitish firm silty sandy CLAY (**17.25m – 18.0m**), Whitish fine medium dense coarse silty SAND (**18.0m – 30.0m**)
BH2	30.0	1.00	Top fill – Reddish lateritic CLAY (**0.0m – 0.15m**), Dark brownish soft compressible organic PEAT (**0.15m – 3.0m**), Whitish-grey chalky like firm silty CLAY (**3.0m – 6.0m**), Reddish brown mottled lateritic silty sandy CLAY with patches (**6.0m – 14.25m**), Whitish brown to whitish fine medium dense coarse silty SAND becoming dense at depth **14.25m – 30.0m**).

The Standard Penetration tests (S.P.T) at intervals during the course of drilling with disturbed and undisturbed samples taken from cohesionless and cohesive strata as they were encountered. Drilling commenced with 450 mm diameter steel casing up to 30 metres depth. Clay cutter, shell and auger were dropped through a mechanical system from the rig to cut through the soil. Samples were taken sequentially at every 0.75 metre interval to know the different types of strata of soil taken. Disturbed samples were kept in sealed polythene bags for laboratory tests. Standard penetration test (SPT) blows were taken at every 1.50 metres depth interval especially in cohesionless strata such as sand. U-100 undisturbed samples were taken in cohesive strata such as clay with cutting and were kept in U-100 tubes sealed with wax to prevent loss of moisture. These operations were repeated until the 30m depth was achieved for the boreholes.

Table 3: Settlement measurements of underpinned building

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

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Settlement Measurement Points										
Reduced Level at 05/10/2012 (Before underpinning)	10.722	10.462	10.243	10.446	10.087	10.596	10.630	10.533	10.677	10.678
Reduced Level as at 03/12/2018 (After underpinning)	10.687	10.414	10.194	10.390	10.048	10.575	10.617	10.528	10.677	10.659
Total Settlement (mm) from 05/10/2018 to 03/12/2018	35	48	49	56	39	21	13	5	0	19

The reduced levels were taken with an automatic Leica Sprinter 250 metres Digital Levelling instrument. **Table 3** showed the reduced levels spot-heights from points 1 to 10 at the left-hand side of **Fig. 9** (weakened and settled portion) of the 19.79 metres by 16.675 metres underpinning plan of the settling 2 storey building in Lagos Nigeria. The period of check for the total settlement was six years (2012 and 2018). The maximum total settlement was noticed in position 4 with a settlement of 56 mm which was where the noticeable cracks occurred in the building.

Table 4: Settlement Analysis

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Two Consecutive Settlement Measurement points	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 – 10	10 - 11
Differential Settlement between Two Consecutive Points (mm) as at 03/12/2018	13	1	7	17	18	8	8	5	19	16
The distance between two consecutive points (mm)	7440	7200	6700	9150	9270	6970	6530	7400	10570	7300
Angular Distortion between Two Consecutive Points as at 03/12/2018	$^{1}/_{572}$	$^{1}/_{7200}$	$^{1}/_{957}$	$^{1}/_{538}$	$^{1}/_{515}$	$^{1}/_{871}$	$^{1}/_{816}$	$^{1}/_{1480}$	$^{1}/_{556}$	$^{1}/_{456}$
Remarks (ok if angular distortion is less than $^{1}/_{300}$)	ok	Ok	ok	ok	ok	Ok	Ok	ok	Ok	ok

Settlement Analysis shown in **Table 4** comprised of differential Settlement shown in **Fig. 9** between two consecutive points (mm), the distance between two points, Angular distortion between two points and their remarks once angular distortion was less than 1/300 or not.

The differential settlement was calculated in terms of the angular distortion which was the relative settlement between the two points divided by the horizontal distance between the two points.

Table 3 gave the settlement analysis. From this analysis, it was evident that all angular distortions were fewer than 1/300 (tolerable differential settlement for buildings in mm). Therefore, the observed differential settlements cannot cause cracks in any part of the building after completion of the underpinning process.

Note that as 1/3 (=0.3333) is greater than ¼ (= 0.25), so is 1/300 (= 0.00333) greater than 1/400 (= 0.0025); it is also greater than 1/500 or 1/600 or 1/700 etc.

Table 3 showed the total settlements (mm) observed from the surveyor's reduced levels from 05/10/2012 to 03/12/2012. The angular distortions were calculated for the underpinned structure as given in **Table 4** as well as the settlement analysis. From this analysis, it was obvious that ALL the Angular Distortions were fewer than 1/300. Therefore, the observed differential settlements CANNOT cause any cracks in any part of the building.

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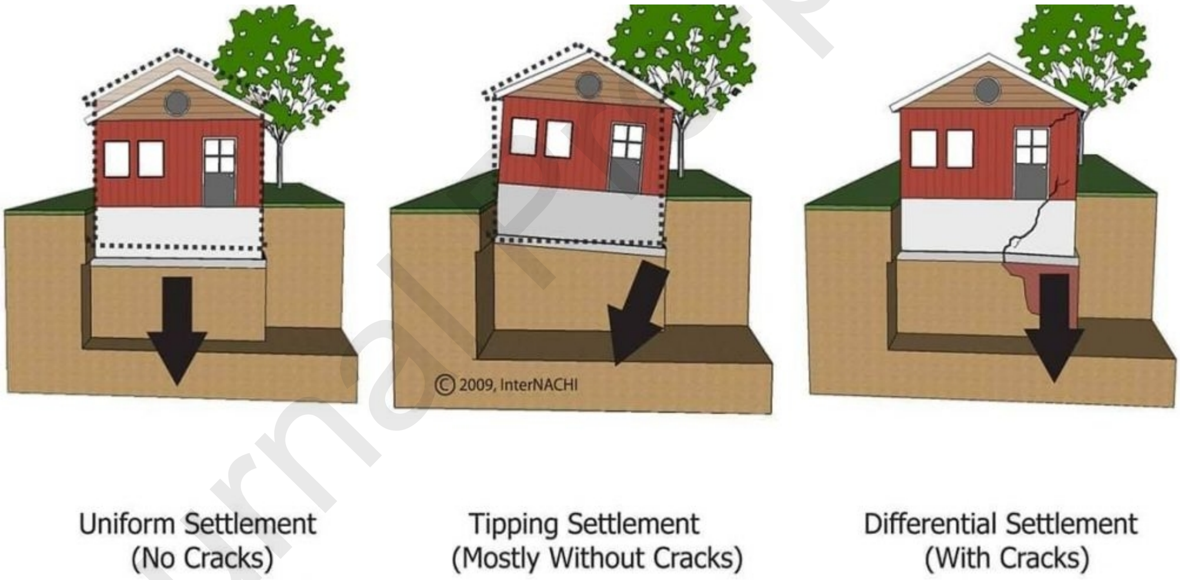
4.2. Solution to an existing problem

A new sub soil test was done, piling work was done as shown in **Table 2**, with the use of Auger drilling machine to a depth of 30 meters, mud pit was prepared and drilling chemicals, including bags of Antisol and Bentonite were used to prevent sand from caving into the drilled holes. 0.65 mm gauge steel sheets 1.05 metres by 2.44 metres steel pile casings were used as a template to fabricate the steel casing, which was formed by welding before it was lowered into the bored pile holes and left permanently in the pile hole after pouring concrete. A pile cap with ground beam formwork anchored to the existing raft foundation was prepared and completed. The opening of holes in the floor slabs was done to aid lowering of the pumpable concrete hose to pour concrete. This was done and completed before reinforcement cages were placed in position, then the concrete pump poured the concrete into the underpinning positions.

The provision of 20 mm diameter high yield steel in piles and pile cap ground beams, 16 mm diameter high yield steel for underpinning slabs in (2 layers) and 10 mm diameter high yield steel for links.

Lafarge transit movable pumpable concrete was used to pour concrete having a concrete grade strength of 40 MPa on the desired building floor with small hole openings. All cracked walls were screeded with 75 mm thick screeding ratio of 1:1 (one head pan of cement to one head pan of sand); the top surface of the screeding was made “rough” so that it bonded well with the screeding for floor tiles or marble.



Uniform Settlement (No Cracks)

Tipping Settlement (Mostly Without Cracks)

Differential Settlement (With Cracks)

Fig. 9. Type of settlement [41]

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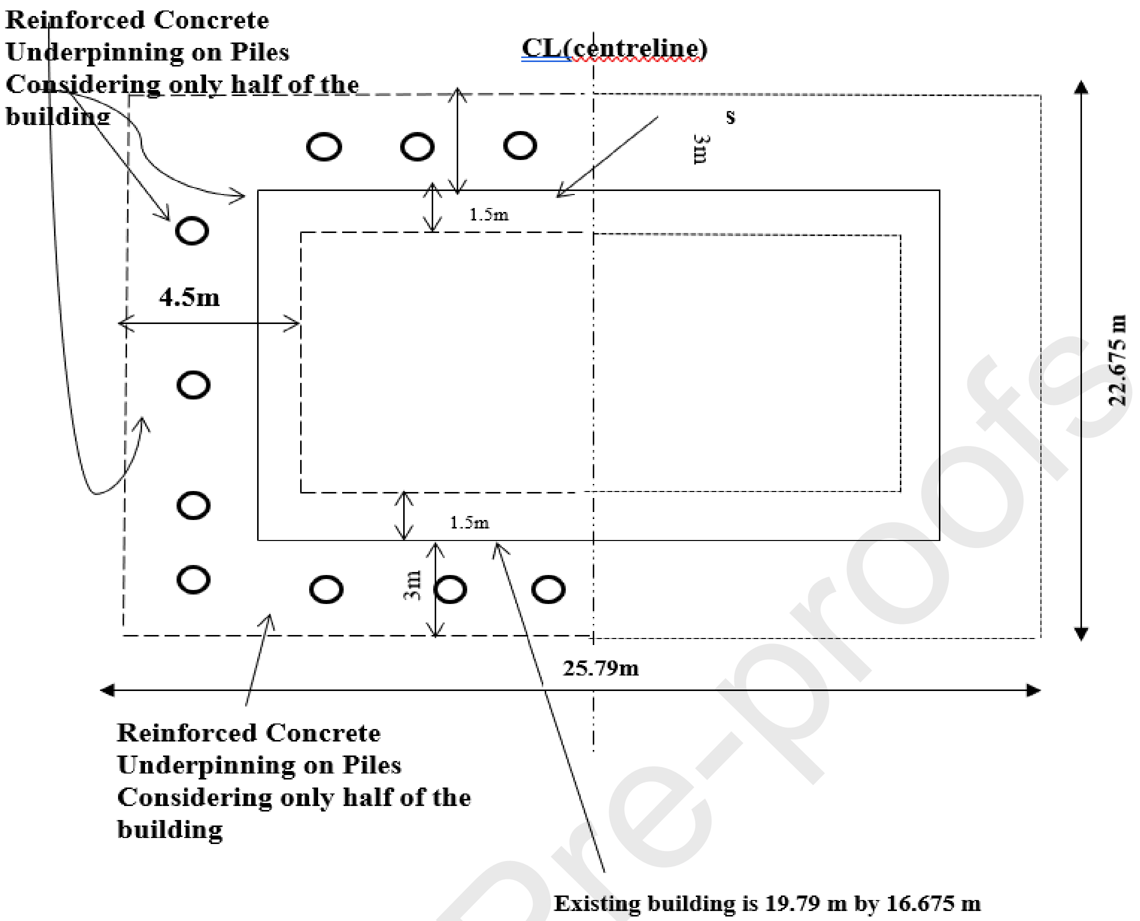

Fig. 10. Underpinning plan of a two-storey building showing the reduced scope of work.

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Fig. 11. Distressed building in 2012

Fig. 12. Cracks noticed on walls

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Fig. 19. Pile cap with ground beams

Fig. 20. Shuttering work

Fig. 21. Use of Poker vibrator

Fig. 22. Completed underpinning work.

Fig. 23. Completed underpinning work.

Fig. 24. Completed building in 2018

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5. CONCLUSION

From the research findings, the following conclusions were made:

- The result showed that a deep foundation underpinning was adopted because the bearing pressure using CPT tests was very low as a result the shallow raft foundation could not support the settling structure because of the dark brownish soft organic fibrous peat was found within the first 3m depth across the two boreholes.
- The results from the investigation of the cause of the foundation settlement and cracks on the walls confirmed that the settlement was as a result of poor workmanship, wrong interpretation of initial subsoil test, quackery in the construction methods adopted and the variation of the soil, which rested on a low bearing capacity as the area was formerly used as a dumping ground for refuse and fish pond, which led to the differential settlement that occurred on the building.
- After underpinning the sinking structure, it was observed that the angular distortions was less than 1/300. Therefore, the observed differential settlement didn't cause any cracks on any part of the building which, guaranteed the stability of the underpinned building.
- The pile foundation underpinned structure met the load-bearing capacity requirements of the structure after the completion of the distressed foundation underpinning process.
- The underpinning technique was found to be a successful method in solving problems related to distressed and failed structures.
- The technique of underpinning presented in this paper can be applied to distressed buildings on weak and peaty soils.

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FIGURES

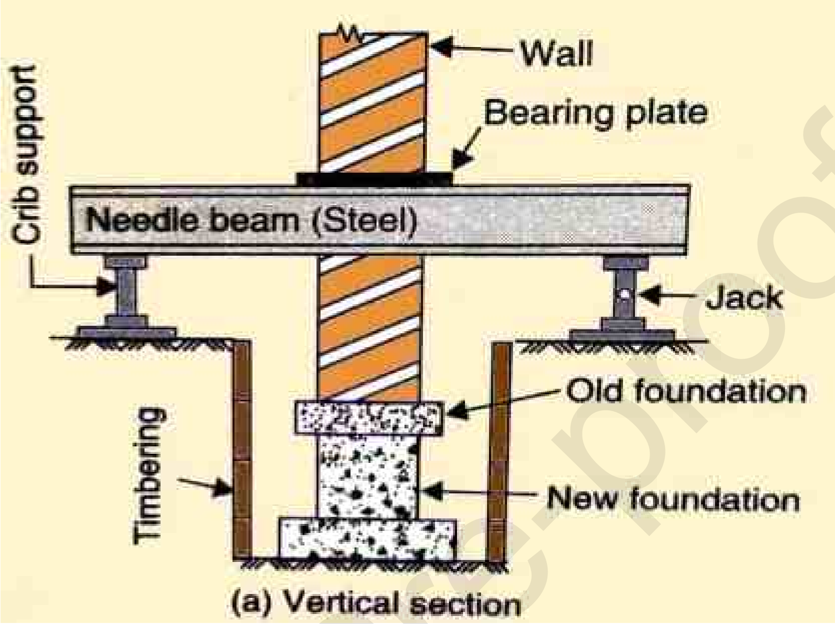

Fig. 1. Needle beam underpinning [35].

Fig. 2. Pynford stool for underpinning [35].

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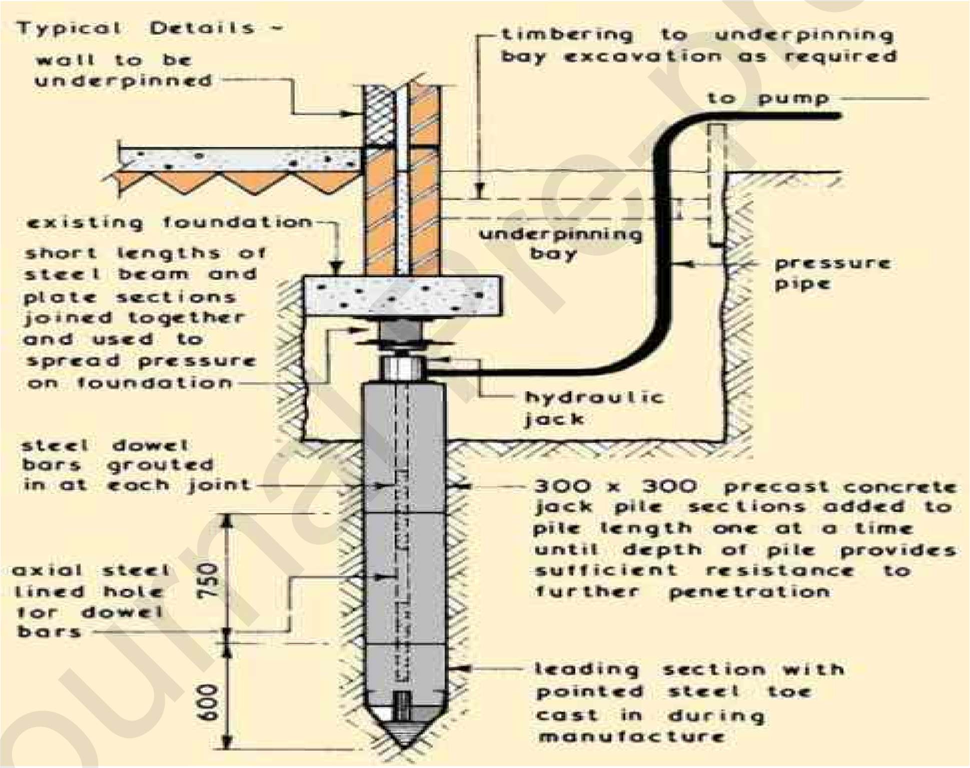

Fig. 3. Jacking underpinning [35].

Fig. 4. Beam and Column underpinning [32].

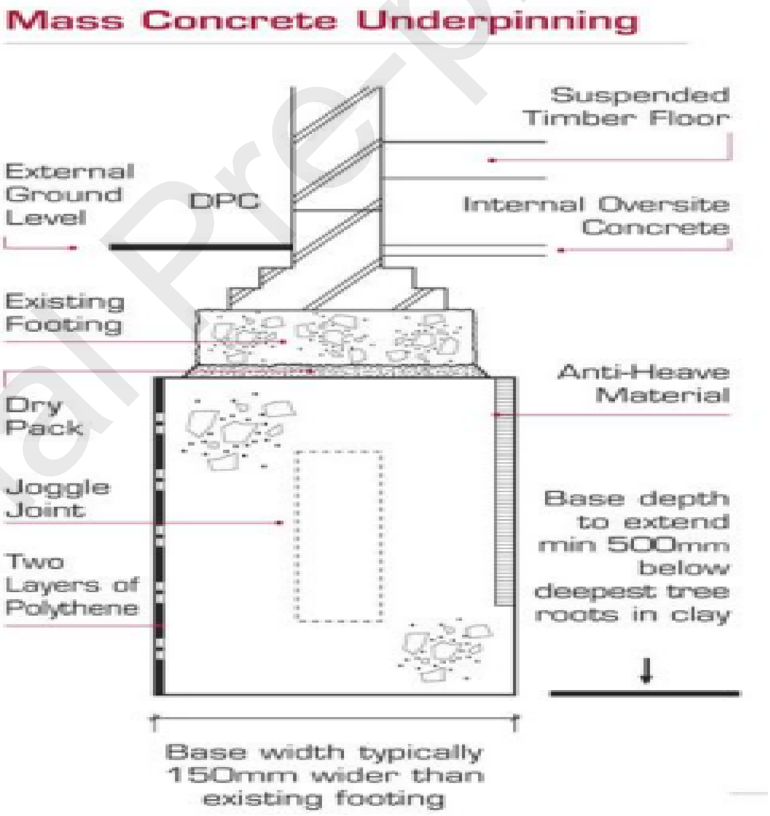

Fig. 5. Mass concrete underpinning [2].

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Fig. 6. Mini piling underpinning to support vertical loads [2].

Fig. 7 Piles and Beams to support vertical loads [2].

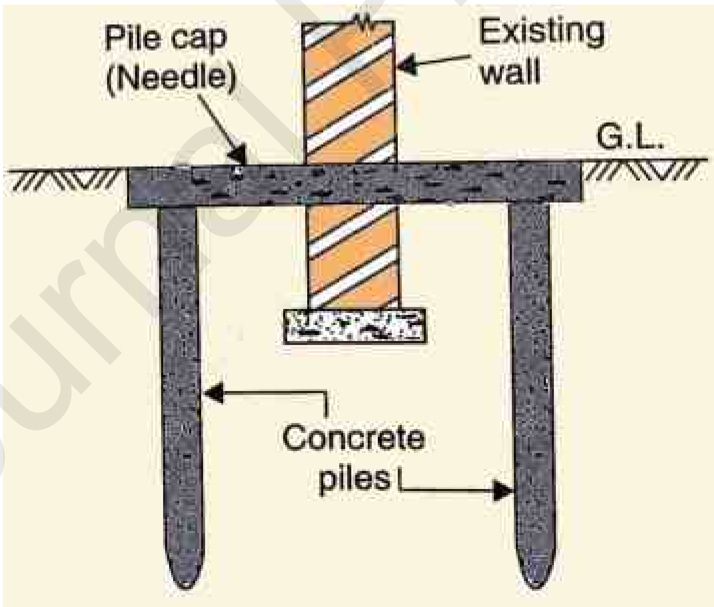

Fig. 8. Pile method of underpinning [35]

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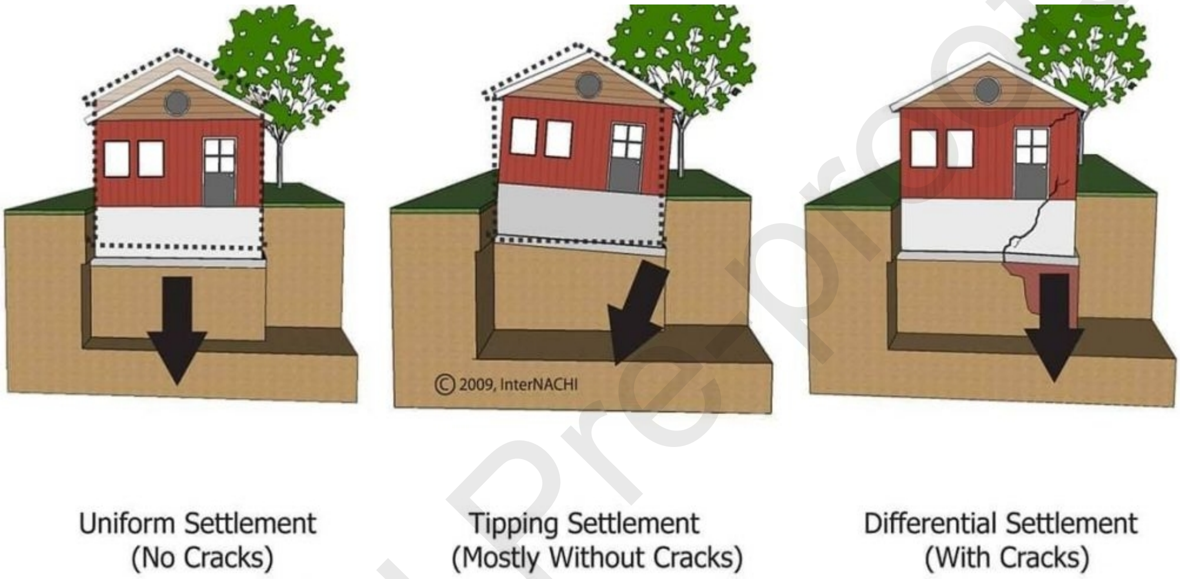

Fig. 9. Type of settlement [41]

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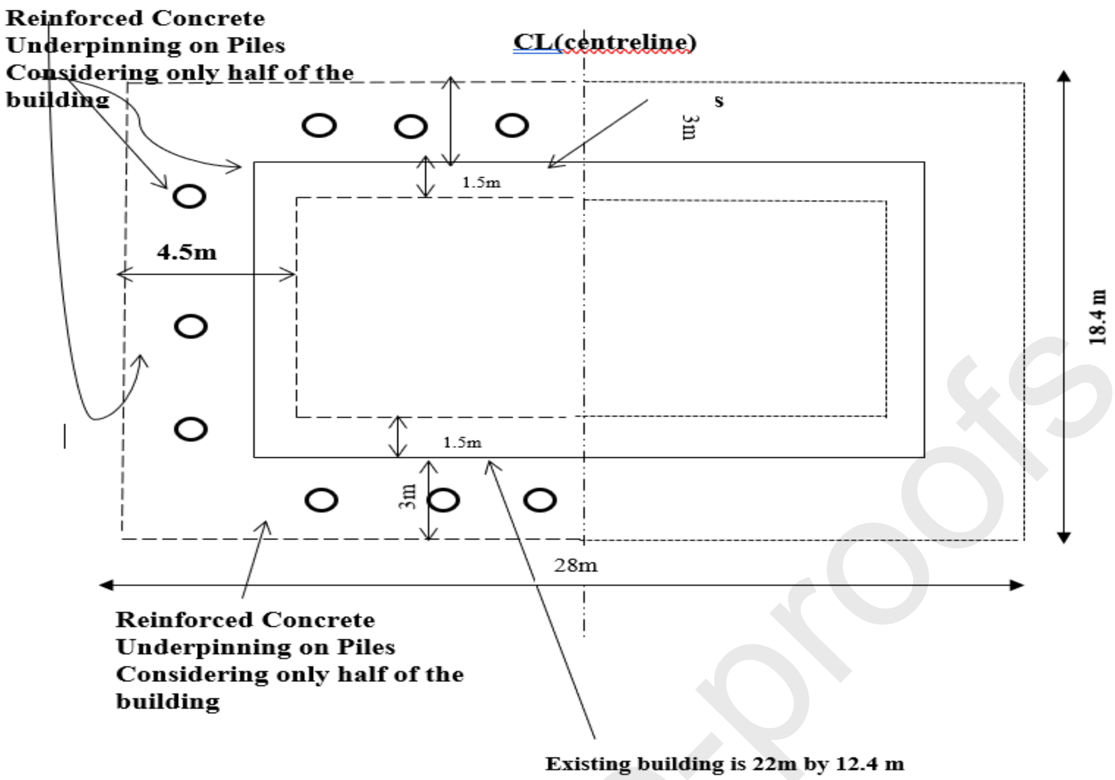

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Table 1: ESTIMATION OF BEARING PRESSURES USING CONE PENETRATION TEST (CPT) RESULTS

Depth	**Cone Resistance kg/cm^2**				**Average Cone Resistance kg/cm^2**	**Allowable Bearing Pressure KN/m^2**	**Submerged Bearing Pressure KN/m^2**	**Remarks**
	P1	**P2**	**P3**	**P4**				
0.25	10	10	2	5	7	43	22	Low Bearing Pressure, foundation submerged
0.50	10	2	2	2	4	25	12	= Ditto =
0.75	5	2	2	2	3	19	10	= Ditto =
1.00	5	10	5	5	6	37	19	= Ditto =
1.25	2	15	10	2	7	43	22	= Ditto =
1.50	2	15	10	2	11	68	34	= Ditto =
1.75	2	15	15	10	12	74	37	= Ditto =
2.00	2	15	15	15	12	74	37	= Ditto =
2.25	3	25	20	20	17	105	53	= Ditto =
2.50	3	40	25	20	22	136	68	= Ditto =
2.75	3	40	25	25	23	143	72	= Ditto =
3.00	20	40	40	35	34	211	106	Good Bearing Pressure, foundation submerged
3.25	20	40	40	30	33	205	103	= Ditto =

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3.50	20	45	40	30	34	211	106	= Ditto =
3.75	20	45	45	30	35	217	108	= Ditto =
4.00	20	45	45	35	36	223	111	= Ditto =
4.25	25	45	45	40	39	242	121	= Ditto =
4.50	25	45	45	50	41	254	127	= Ditto =
4.75	30	50	50	50	45	279	140	= Ditto =
5.00	30	50	50	55	46	285	143	= Ditto =
5.25	40	80	-	60	60	372	186	= Ditto =
5.50	50	80	-	70	63	391	196	= Ditto =
5.75	55	85	-	70	67	415	208	= Ditto =
6.00	60	85	-	80	75	465	233	= Ditto =
6.25	65	90	-	80	78	484	242	= Ditto =
6.50	65	90	-	85	80	496	248	= Ditto =
6.75	75	95	-	90	86	533	267	= Ditto =
7.00	85	105	-	105	98	608	304	= Ditto =

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Table 2: Summary of sub-soil field test results

Borehole No	**Depth (m)**	**Water Level (m)**	**Materials Encountered**
BH1	30.0	1.00	Top fill – Reddish lateritic CLAY (**0.0m – 0.15m**), Dark brownish soft organic fibrous PEAT (**0.15m – 1.0m**), Light Dark brown fine medium silty SAND with organic intrusion (**1.0m – 2.25m**), Whitish-grey firm sandy CLAY becoming sandy at depth (**2.25m – 4.50m**), Reddish fine medium coarse silty SAND (**4.50-m – 7.50m**), Reddish brown firm mottled lateritic silty sandy CLAY with whitish patches (**7.50m – 12.0m**), whitish brown fine medium dense coarse silty SAND (**12.0m – 17.25m**), Whitish firm silty sandy CLAY (**17.25m – 18.0m**), Whitish fine medium dense coarse silty SAND (**18.0m – 30.0m**)
BH2	30.0	1.00	Top fill – Reddish lateritic CLAY (**0.0m – 0.15m**), Dark brownish soft compressible organic PEAT (**0.15m – 3.0m**), Whitish-grey chalky like firm silty CLAY (**3.0m – 6.0m**), Reddish brown mottled lateritic silty sandy CLAY with patches (**6.0m – 14.25m**), Whitish brown to whitish fine medium dense coarse silty SAND becoming dense at depth **14.25m – 30.0m**).

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Table 3: Settlement measurements of underpinned building

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Settlement Measurement										

Points										
Reduced Level at 05/10/2012 (Before underpinning)	10.722	10.462	10.243	10.446	10.087	10.596	10.630	10.533	10.677	10.678
Reduced Level as at 03/12/2018 (After underpinning)	10.687	10.414	10.194	10.390	10.048	10.575	10.617	10.528	10.677	10.659
Total Settlement (mm) from 05/10/2018 to 03/12/2018	35	48	49	56	39	21	13	5	0	19

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Table 4: Settlement Analysis

Two Consecutive Settlement Measurement points	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 1
Differential Settlement between Two Consecutive Points (mm) as at 03/12/2018	13	1	7	17	18	8	8	5	19	16
The distance between two consecutive points (mm)	7440	7200	6700	9150	9270	6970	6530	7400	10570	7300
Angular Distortion between Two Consecutive Points as at 03/12/2018	$^1/_{572}$	$^1/_{7200}$	$^1/_{957}$	$^1/_{538}$	$^1/_{515}$	$^1/_{871}$	$^1/_{816}$	$^1/_{1480}$	$^1/_{556}$	$^1/_{456}$

Remarks (ok if angular distortion is less than $^{1}/_{300}$)	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok

HIGHLIGHTS

- Nature of building failure and description of the problem.

- Type of settlement encountered.
- Method of underpinning adopted.
- Settlement measurements of underpinned building

- Settlement Analysis and solution to the existing problem.
- Panorama of distressed and underpinned building.

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