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INTRODUCTION

Underpinning work is usually carried out to increase the loading of a building or when there is excessive or uneven settlement of the foundation. It generally requires a comprehensive understanding of the problem involved and good planning and design for the safe and efficient execution of the construction. The general procedures for underpinning works include:

1. Preliminary investigation
2. Analysis and design of underpinning
3. Erection of preliminary supports
4. Actual underpinning work

Every phase is essential due to the interrelationship between the various stages. A working knowledge on the various areas of work involved in these stages is thus inevitable.

REASONS FOR UNDERPINNING

Underpinning design undergoes a procedure similar to structural and foundation design. Due to its difficult and costly nature, underpinning design requires greater detail and accuracy to ensure cost efficiency without compromising the quality of final product. Different reasons for underpinning will require different designs to cater to the needs and requirements. There are basically quite a number reasons for underpinning, which includes:

1. Conversion works
2. Protection works
3. Remedial works

Some other common causes for remedial underpinning are as follows:

i. Overloading the soil
ii. Improper soil exploration
iii. Placing the foundation eccentrically with the load
iv. Adjacent excavation causing settlement of structure
v. Pile driving vibration causing consolidation of loosely consolidated soil
vi. Disregarding the load placed on the ground floor of a building, thus causing the slab to settle
vii. Subsidence caused by trees which removes water from the ground near a structure
viii. Pumping of ground water
ix. Piles not driven to proper depth

x. Rotting of wood piles due to lowered groundwater
xi. Corrosion of steel piles due to chemical or electrolytic action
xii. Overdriven piles, thus resulting in wood piles broken by boulders
xiii. Negative friction caused by settling fill exerting a downward pull on the pile loading it more than its capacity

1. Conversion Works:

Alternation, improvement and renewal of old properties may be prompted by the need to preserve national assets of historical importance; to take commercial advantage where existing buildings are essentially suitable for change of uses; and often to minimize expenditure on housing provisions.

Thus the architect must ensure that the character of the building after the renovation and refurbishment conforms to the present setting or recognizes apparent changes in the local environment and avoids incongruity in the modern setting. The engineer must develop a proper understanding of the nature of the building and its relationship to the existing environment, particularly from the aspects of stability and the groundwater regime.

2. Protection Works:

Protection works to structures may be necessary in the following situations:

- ✓ Construction of new buildings in sufficiently close proximity to existing buildings to warrant the provision of underpinning works under the existing properties in order to limit ground movements and protect the existing building.
- ✓ The construction of additional higher floor levels to the existing buildings.
- ✓ The construction of new basements within existing buildings.
- ✓ The construction of new buried structures, such as services tunnels and pipelines in close proximity to existing buildings.
- ✓ The growth of trees in clay soils causing adverse ground displacements due to moisture movements.
- ✓ The construction of new manufacturing facilities that contain mechanical sources of harmful vibrations to the extent that the ground support beneath existing buildings will be affected.

3. Remedial Works:

Recent modern buildings, which should have continued to perform satisfactorily for some years, have often suddenly undergone movements and

displayed structural defects that required immediate attention. The determination of the reasons for the change of behavior, an assessment of the residual strength and stiffness of the building structure and the selection of suitable economical remedial measures can involve much time and expenditure, regardless of the relative importance of the building. The timing and extent of the remedial underpinning works to foundations are important aspects of the process of assessment and care must be taken that the problem has been clearly defined and appropriate remedial measures taken.

PRELIMINARY INVESTIGATION

The aim of preliminary investigation is to collect relevant information in connection with the planning and design of the underpinning work. Such information shall include important technical data of the site and of the subject, i.e.: the building itself.

The investigation shall cover the following aspects:

1. Soil condition
2. Ground water condition
3. Structural condition of the building
4. Historic uses of the building
5. Adjacent and neighbouring buildings and activities

1. Soil Condition:

The designer of the underpinning work must gain a good knowledge of the soil condition such as the nature and depth of each soil stratum as well as the mechanical properties of the soil. Technical data of the soil characteristics help to determine bearing capacity and consolidation behavior of the ground.

Soil investigation reports made from the site at the time of construction shall be referred in this aspect. As and when additional information is required, in-situ tests can be carried out. The 2 most commonly used tests are Cone Penetration Test (CPT) and self-boring or push-in pressuremeters. They are used to determine the un-drained strengths of clay soils to obviate the effects of sampling disturbance on laboratory tests.

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With regard to fine-grained non-cohesive soils, information on the in-situ condition of sand deposits can be obtained from the Standard Penetration Test (SPT).

However, good drilling and cleaning techniques and careful execution of the SPT are essential in order to ensure that typical values of penetration resistance are obtained from this form of testing. If the boring operation causes serious disturbance, it can completely misrepresent the state of compaction of the sand deposits. Sometimes rocks may be presented in the soil and in such cases point load test may be carried out on pieces of rock core. Point load tests permit strength measurements to be carried out on small portions of rock cores.

However in many cases, due to limited headroom, investigation works to be carried out below the structure will be inconvenient or even impossible. In such cases, borehole investigation shall be carried out in locations adjacent to the building.

2. Ground Water Condition:

Information on the ground water condition of the site is essential and must be emphasized. This is due to the sizeable impact that ground water condition has on the final design as well as the temporary works. For instance, if the possibility of large outflow of ground water over time is not considered in the design, structural damage due to excessive settlement may occurs.

Diversion of normal paths of groundwater flow caused by any artificial barriers created by underpinning could result in flooding of basement property formerly enjoying relatively dry conditions. Artificial lowering of the groundwater table to facilitate underpinning operations, or reductions in the water table derived from environment changed due to the construction of underpinning can cause significant increases in effective vertical soil stresses which may result in the settlement of adjoining buildings.

3. Structural Condition:

The existing structure to be underpinned must be properly inspected to reveal its condition. Inspection would involve examining faulty areas, e.g. cracking, sagging and to study the nature of such faults. This survey facilitates the analysis of the problems faced by the building, and to allow for more effective design. In many instances, tests may be carried out in order to reveal its actual condition.

4. Historic Uses of the Building:

Through time, a building may be subjected to changing uses. Previous uses may have adversely affected the structure and an analysis is necessary to evaluate such possible effects.

Made ground is the natural consequences of human activity. In large industrial cities, extensive areas of land surface are artificial and have resulted in the deposition of a wide variety of materials to elevate low-lying grounds and to backfill old stone quarry and clay pits. Fill materials often comprise boiler ash, steelwork slag, coarse discard from former mineral workings, chemical waste, demolition debris and excavation spoil consisting of mixtures of sand, slit and clay. Household refuse can also be found within landfill site. In historical cities, ancient watercourses may have been culverted and now exist as buried features. All such historical hidden features can remain unknown until exposed by the unwary.

Information on such historical usages of a building can be obtained from old newspapers, magazines, photographs, town and building control records.

5. Adjacent buildings and Neighbouring Activities:

A survey of the existing buildings and activities in the vicinity must be made. This is to allow for an analysis of the possible effects on such buildings and activities due to underpinning operation. Precautionary measures shall be undertaken where necessary to prevent any costly consequences.

SHORING

Where a building or structure is in poor condition due to settlement, and underpinning has to be carried out to limit or to arrest resulting movements, external shoring will probably be required. The main shoring members can be timber, steel or scaffolding. It is essential that regular checking be done during the underpinning operation so that adjustments and modifications can be carried out without delay, where necessary.

The most common forms of shores are
(1) raking shores
(2) flying shores, and
(3) needles and dead shores.

1. Raking Shores

These are used where a building or structure requires external support. Each raking shore consists of one or more members set an angle to the building. The angle should not be more than 75° to the horizontal and the top of each shore should terminate at a short needle set into the fabric of the building just below each floor level. The tendency for the shore to move upwards is resisted by a cleat fixed to a wall plate set immediately above the above the needle

The load from the shores is transferred to the ground by means of grillages on sole plates and, as in all form of temporary supports, the safe bearing capacity of the soil should be determined and a suitable sole plate designed so that this is not exceeded. Where possible the soleplates should be kept clear of the edge of the underpinning excavation work. The distance will depend on the nature of the soil, but should be equal to at least half the depth of the excavation. If, due to lack of room, this is not possible, the excavation supports should be designed to resist any additional surcharge load imposed by the shoring system.

Where raking shores are erected by scaffold tubings, the arrangement can be shown in *figure 1.* The use of scaffold tubings allows the support for higher buildings and offers greater rigidity and strength.

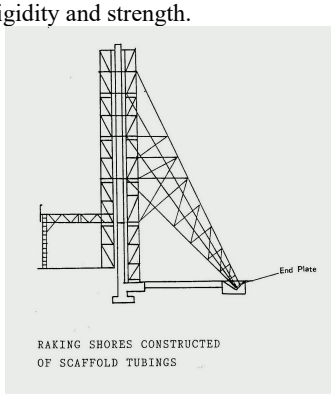


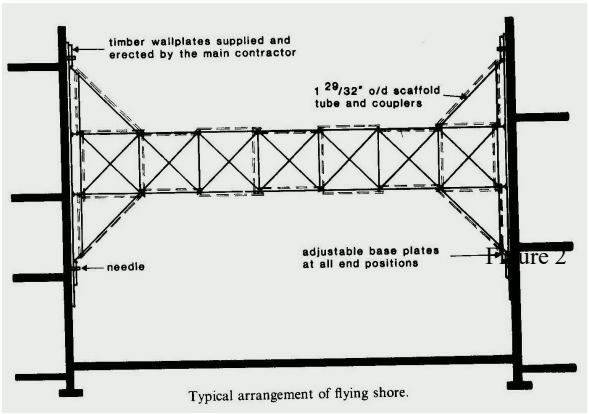
Figure 1

2. Flying Shore

Raking shores are external shores and are likely to cause obstruction to underpinning operation. Under these circumstances, flying shores can be used provided there is a conveniently placed wall or other structure to strut against, with the length of the flying shores can be used provided there is a conveniently placed wall or other structure to strut against, with the length of the flying shore not exceeding 10 metres.

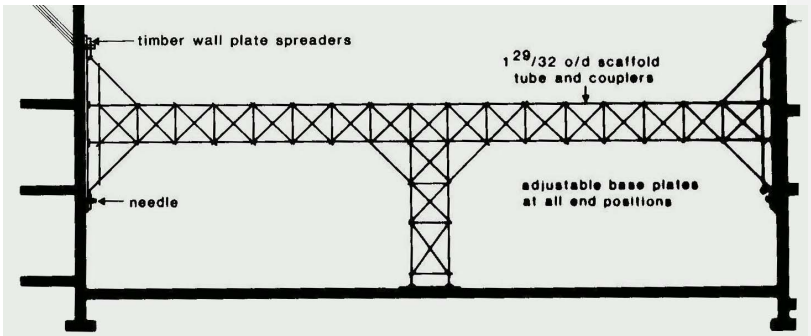
Flying shores should be needled in the same manner as explained earlier for raking shore, and the flying shores should be taken from the floor level of one building to that of the other if these are on the same horizontal plane. Where this is not so, a stiff vertical member should be introduced to distribute the load. *(refer figure 2)* Wedges are used to tighten up the whole system. The position of the raking shore and flying shore are located such that the thrust is transmitted to the whole building and avoid causing any bending on the walls.

Figure 2



Typical arrangement of flying shore.

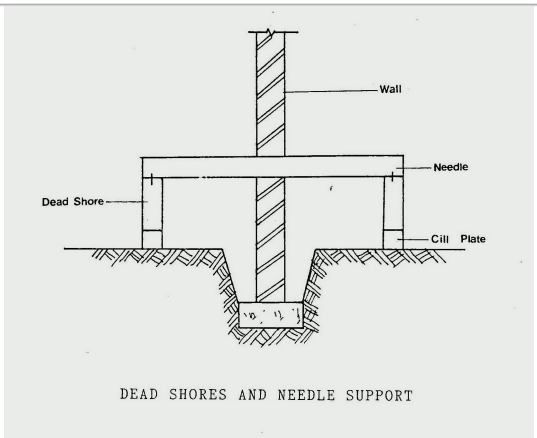
Alternatively, flying shores may be constructed of scaffold tubings and may not be carrying loads imposed by self-weight of wall and floors. *(refer diagram below)*



Arrangement of flying shore with centre support tower. Some bracing has been ommitted for clarity

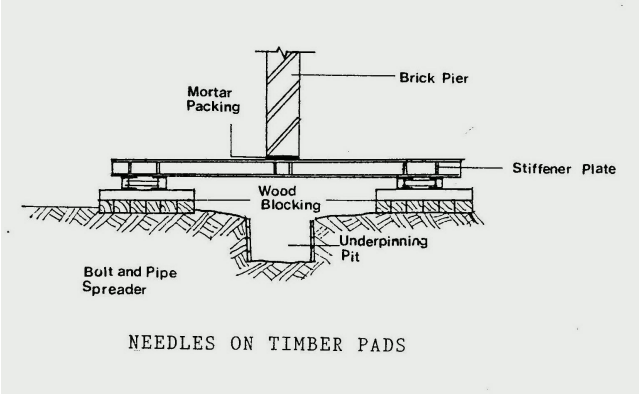
3. Needles and Dead shores

Needles and dead shores are generally used in combination. They serve to support walls and foundations and columns in underpinning operations. A typical arrangement is where the vertical member known as dead shores are placed on either side of the underpinning excavation. Dead shores in turn support horizontal members known as needles spanning between them.



DEAD SHORES AND NEEDLE SUPPORT

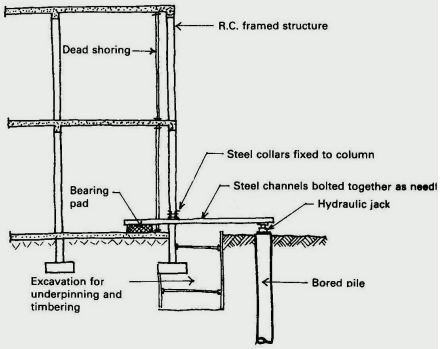
Needles may be used without dead shores by inserting the needles through foundation and walls and resting on timber pads. The timber pads serves to transfer the load of the wall onto the ground.



NEEDLES ON TIMBER PADS

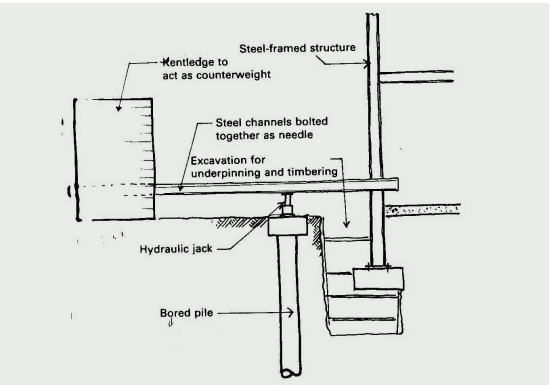
It will sometimes be necessary to construct king posts to support one end of the needle; for example the ground conditions make it imperative to carry the load to a deeper layer of soil. For sequence of operation of this method please refer to *(figure __ bb. pp5070.fig2.120).*

Another similar method rests the needle on a concrete bearing pad on a firm support and load is distributed to a safe stratum with a hydraulic jack on a precast pile or bored pile.



Pile and needle method of supporting column

There will be circumstances where it is not possible to gain access to the inside of a building or structure; for example where the building is still occupied or its content cannot be disturbed. On these occasions, a system of cantilevered needles could be constructed with the needles being supported on a fulcrum and the counterbalance being supplied by kentledge. A hydraulic jack could be placed between needles and the fulcrum enables the latter to be precompressed and any settlement taken up to prevent movement of the column.



Cantilever support to stanchions

Dead shores may also be used singly for purpose of propping up parts of the structure.

ANALYSIS & DESIGN OF UNDERPINNING

There are a variety of underpinning methods to choose from, the selection being determined by the considerations being discussed above. Some of the underpinning methods are as below:

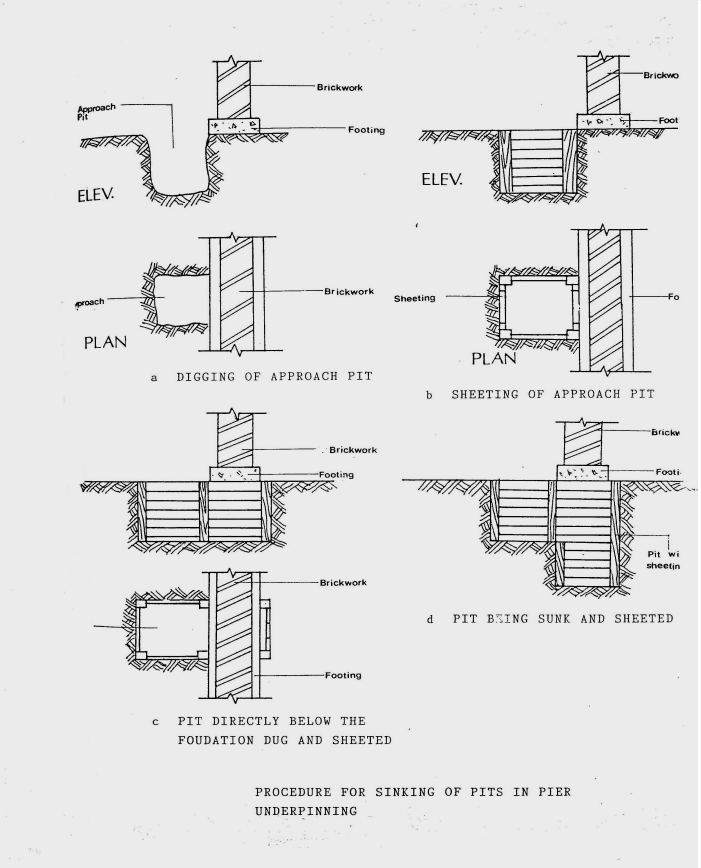
1. Underpinning by excavation
2. Underpinning by grouting
3. Underpinning by Piles

1. Underpinning by Excavation:

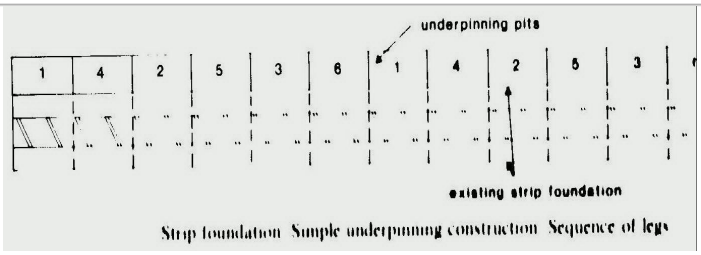
For underpinning by excavation we shall look into
A) traditional pier underpinning method and,
B) the patented Pynford method.

A) Traditional Pier Underpinning

This technique involved in the traditional pier underpinning method, which requires extensive excavation works for the construction of a new foundation structure. Pier underpinning is the most common and oldest form of underpinning. It is also the simplest form of underpinning and it can be used where ground conditions are good. It consists of excavating for and constructing a series of columns or piers beneath the wall to be underpinned. The length of these piers is usually determined by the condition of the existing structure, its composition, and the nature of the ground supporting the underpinning.



It is good practice to construct the piers on a 'hit or miss' basis up to a maximum of six in a group, depending on the length of the wall to be underpinned. The sum of piers being constructed should not exceed one-quarter of the total length of the wall. Where structure shows some signs of distress, this should be reduced to one-fifth or one-sixth of the total length of the wall. Each group of piers should be completed before the next group is commenced.



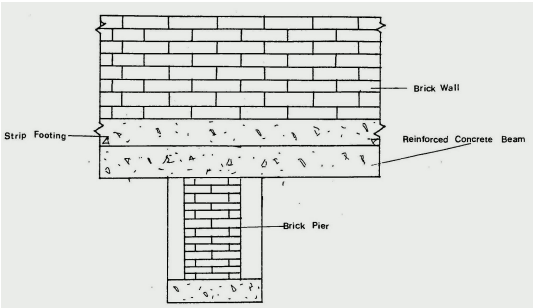
Strip foundation Simple underpinning construction Sequence of legs

Each pier should be constructed to within 75mm of the underside of the old foundation or wall, and the top should be carefully levelled off to receive the final pinning. The final pinning should be carried out using a fairly dry concrete mixture with a maximum aggregate size of 10mm, and this concrete should be well rammed into the gap between the new pier and the old foundation. The leading edge of each pier should incorporate a vertical groove or chase so that the adjacent pier when constructed can be keyed into it and the total length of underpinning can act as one unit. At all times during the construction of this type of underpinning, the sides and ends of the excavations should be supported by temporary timbering or sheeting as mentioned earlier.

Pier underpinning may be i) intermittent or ii) continuous.

i)Intermittent Underpinning:

Pier underpinning may be intermittent, which is used in support of isolated column footing in framed construction. In areas where a continuous wall is to be underpinned, it would be possible to utilize the piers as supports by constructing a reinforced concrete beam to transfer the building loads to the intermittent piers.



UNDERPINNING OF CONTINUOUS WALL WITH PIERS

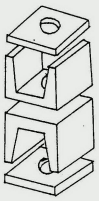
ii) Continuous Underpinning:

In continuous underpinning, the actual work consists of digging a series of pits, at spaced intervals against the bottom soffit of the brick wall footing. When the bottom of the foundation is reached, a new support is built up. Upon the successful construction of the new structure, in the first set of pits, adjoining intervening sections are then carried down successively until a continuous pier-wall structure is formed. The spacing of the pit is dependent on the strength of the structure, while the size must be large enough to provide adequate working space.

B) Pynford Method

When the superstructure and its foundation are in a weak condition, continuous beam support to the wall may be essential. The Pynford method demonstrates a convenient and efficient way of constructing a beam beneath a load-bearing wall for underpinning purposes.

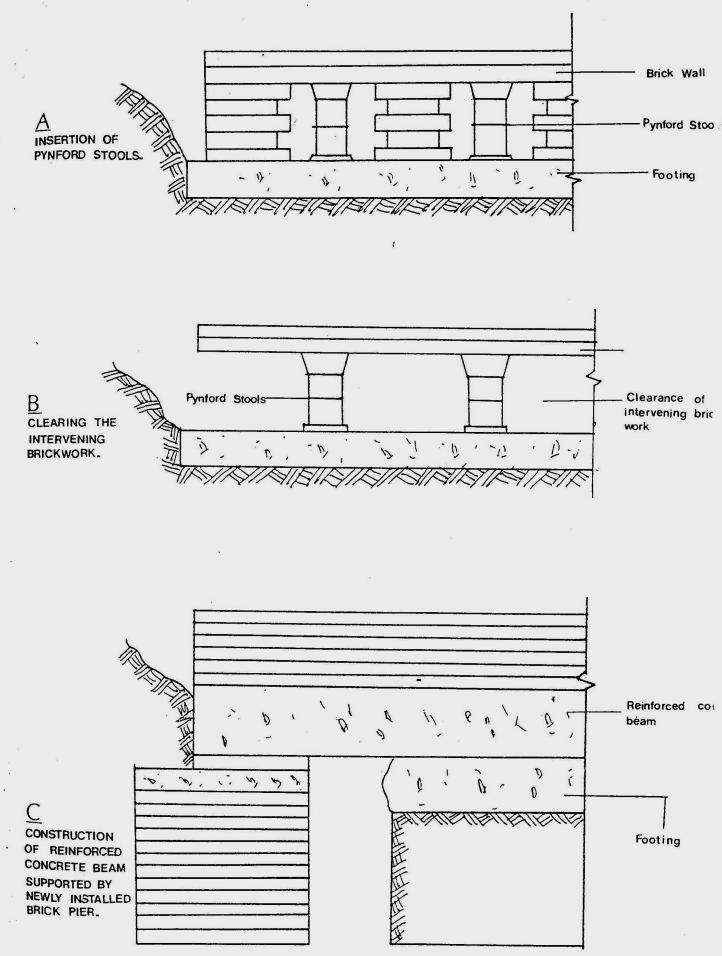
The procedure in the Pynford method involves cutting away potions of the brickwork above the existing foundation to enable precast concrete or steel stools to be inserted and pinned. These 'stools' acted as short struts bearing on the old foundation and they are inserted into the holes cut at the bottom of brick wall at about 900mm centres. The intervening brickwork can then be removed, leaving the structure entirely supported on the stools.



Pynford Stools

The reinforcements are threaded through the perforations in the stool to form the ring beam reinforcement. Once the reinforcement is in position, the beam is shuttered, and concrete is poured, leaving an interval at the top to be filled with well-rammed dry mortar mix on the final pinning up.

Piles and piers are then installed below the new reinforced concrete beam at specific points. These piles and piers serve to transfer the building load through the reinforced concrete beam to lower firm soil strata.

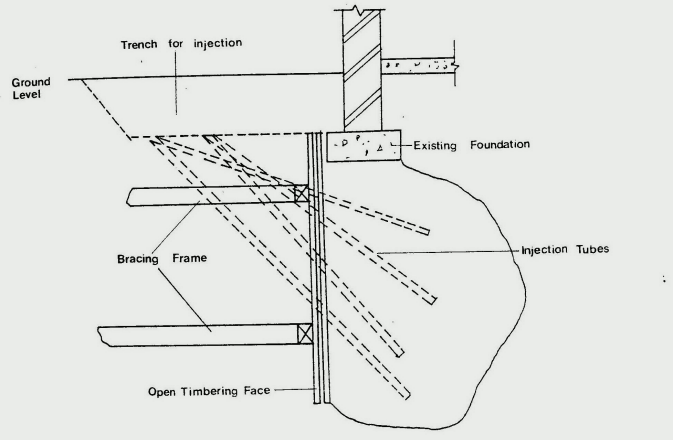


PROCEDURE OF PYNFORD METHOD

The Pynford method has been used effectively in only loadbearing structure. As the method is designed largely for mechanical construction, economies of scale and quick execution are achievable. It is noted that with this method minimal disturbances are caused to the structure. The only conceivable and significant source of disturbance is in breaking up the lower portions of the walls. However the breaking up process is unlikely to cause detriment to the wall structure.

2. Underpinning by Grouting:

The common grouting process involves the injection of chemical or cement mortar under pressure, passing through insertion tubes, into the ground. This has the effect of filling up the voids, and with time, solidification of the grout will serve to strengthen the ground. A typical example of using cement and chemical grouting is illustrated below.



CEMENT AND CHEMICAL GROUTING THROUTH TUBES INSERTED IN THE GROUND

A) Cement Grouting:

In this grouting method, the insertion tubes are placed in certain pattern, and pierced through an adequate depth to reach the required soil stratum. After injection

and upon hardening of the grout, the ground is reinforced and further settlement of the stratum is prevented. Grouting also prevents the entry of run-off water from the surroundings, which avoids disturbance to the adjacent soil's bearing capacity. However, indications by specialists have noted that stability is generally short term, and some settlement usually continues.

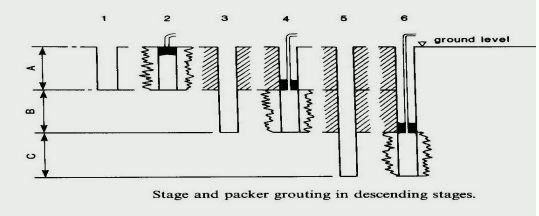
B) Chemical grouting:

It evolved logically from cement grouting practices where direct injection of neat cement into fine fissures or small pores was only partially successful. Injection technique varies from the choice of a wide range of chemicals available. While most of the recent developments in chemical grouting technology have been in the field of single-fluid low viscosity systems capable of penetrating fine-grained materials, soil and rock formation vary significantly in terms of permeability and porosity, the former being particularly sensitive to small changes in void sizes. The selection of the most suitable chemical grouts is therefore largely a matter of judgement on the part of an experienced engineer, and he should also be aware of the range of grout suspensions available, since considerable economies can result from the use of these cheaper grouts in advance of the more costly and penetrative chemical. The techniques employed is dependent on the chemical grout used, which is in turn chosen after careful consideration given to the various factors, namely:

i) Extent and quality of ground investigations with particular reference to permeability and porosity.
ii) Optimum injection method and hole pattern.
iii) Availability of grout materials.
iv) Viscosity – time development of grouting including sensitivity to temperature, dilution and mix proportioning errors.
v) Stability of grout in-situ.
vi) Degree of saturation of ground during service, including risk and effect of grout desiccation.
vii) Chemical composition of groundwater.
viii) Permanence of grout in-situ.
ix) Toxicity of grout and chemical components and working environment.
x) Aggressivity of grout and chemical components towards plant and equipment.
xi) Residual permeability or strength of grouted ground.
xii) Degree of site supervision required including sophistication of systems.

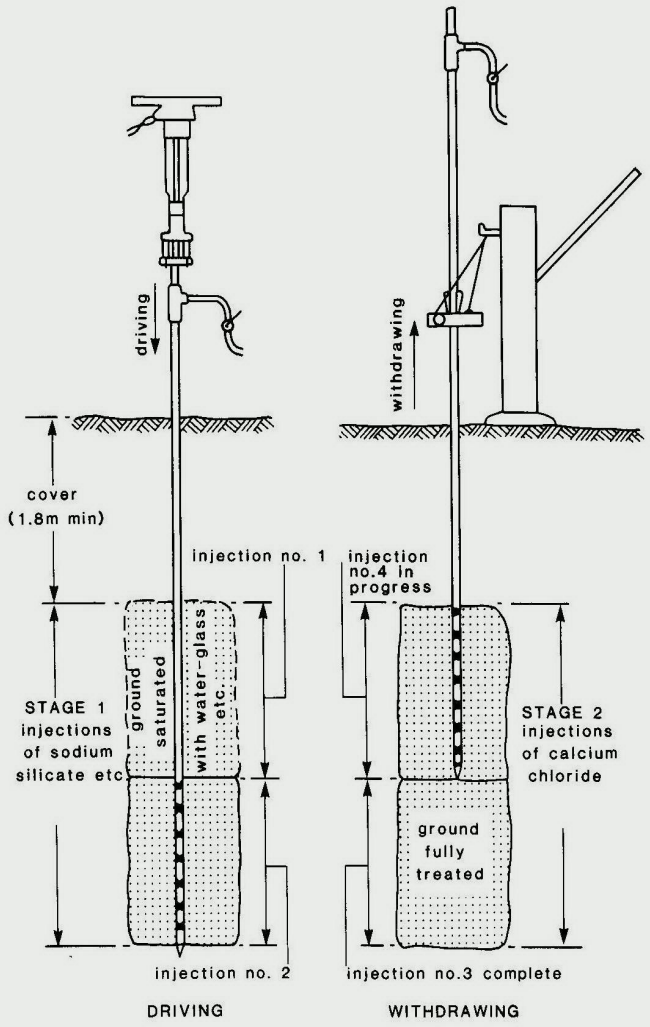
Grout is normally introduced into the ground in one of the four methods, choice being dictated by ground conditions and the degree of control required for grout placement into different horizons:

i) Through an injection pipe held in place in the hole or casing by a packer



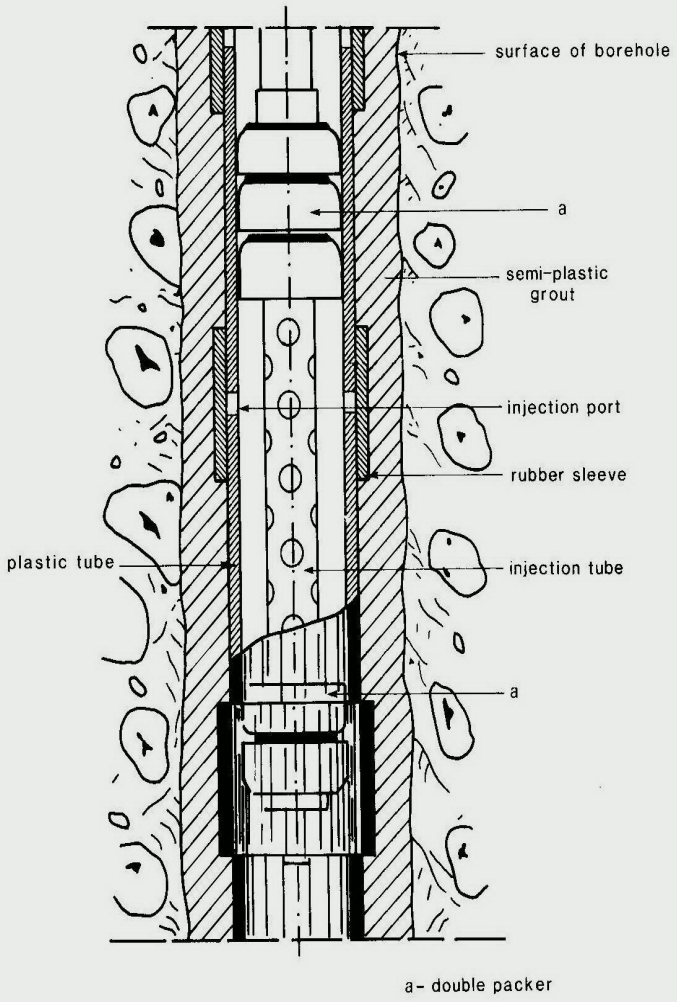
Stage and packer grouting in descending stages.

ii) From a pipe driven into the ground and withdrawn as injection proceeds.



Joosten process (after Glossop[1]).

iii) Through a pipe left in place in the ground, as with a tube à manchette.



Ischy's tube à manchette.

iv) Into an open hole in self supporting ground through pipes caulked at the surface.

Strength and stability of the soil is eventually achieved by chemical grouting when the chemicals form a gel in the soil.

C) Jet grouting:

This technique was developed in Japan and has been found to be satisfactory substitute to chemical grouting. The general basis for jet grouting is a special high-speed jet acting under a nozzle pressure, which may range, according to the type of equipment, up to 70Mpa. The soil may be mixed in place with a suitable grout or alternatively removed (to a certain extent depending on grain size and consistency) by air-water jetting and simultaneously replaced by grout jetting.

The process initially requires the boring of a hole approximate diameter of 150mm. A monitor comprising a triple phase fluid drill pipe, conveying the three process elements of air, water and grouting is then inserted into the hole. At the base of the monitor is two nozzles, the lower pressing the grout while the upper emitting water at high pressure. The latter will convey a cutting action equivalent to the excavation and creation of a void, which will subsequently filled by grout.

Jet grouting technique is available in three forms, namely:

i) Column jet grouting *(figure__ d.pp33.fig.4.2)*
Achieved by rotating the monitor as it is being raised. By overlapping the columns, a solidified ground can be created at depths.

ii) Panel jet grouting *(figure__ d.pp33.fig.4.3)*
Consists of adjacent panels, which are linked to create continuous ground barriers or wall of very low permeability. The panels are then formed by jetting while raising the monitor vertically.

iii) Wing jetting
This form of jetting is a specialized process that seals a leaking underground structure. Two nozzles are used, and as the monitor is raised without rotation, a fan-shaped mass is formed.

Analysis of Grouting Methods:

Cement and chemical grouting are economical methods and allow for easy operations. They possess the added advantage of emitting little noise and vibration. However, as far as underpinning applications are concerned, these methods have not been proved to be effective adequately.

Cement grouting would be effective only in dry loose soil. The extent of reinforcement provided to the soil is limited and thus full arrest of building settlement through this method is difficult.

Chemical grouting, despite the availability of a large range of chemicals, is generally ineffective in underpinning works. It serves mainly to reduce permeability and has thus found useful applications in tunneling works. The porosity of the soil must be high for the method to be operative.

3. Underpinning by Piles

A) Pali radice (root piles)

A typical scheme of an underpinning by means of pali radice (root piles) is shown in figure 4.1. The foundation reinforcement is formed by a double series of small-diameter piles, rotary drilled through the existing masonry and taken to an adequate depth in the subsoil below. When concreted, the pile is automatically bonded with the upper structure: there is no need of complementary connecting structures, no risky cuts in the walls, and no disturbance to the building's activities.

The construction to the piles, spaced out along the foot of the walls, does not present any risk to the stability of existing structures. No vibration is involved. The construction of the piles does not introduce any particular stress in the wall or the soil: this is of vital importance in buildings, especially ancient monuments, in which the conservation of the existing, however precarious, equilibrium is of paramount importance. Pali radice can be drilled in any soil, no matter what boulders, old foundations or other obstructions it may contain.

The technology of a palo radice:

Figure 4.2 shows the construction sequence of a palo radice.

(i) The drilling is performed by a rotating casing progressively introduced into the subsoil; the spoil is removed by flushing water or bentonite mud introduced from the top through a rotating swivel.
(ii) Once the drilling has been taken to a convenient depth, the reinforcement is placed: a single bar for smaller diameters, (10cm); a cage or a tube for larger diameters (up to 25-30cm). In underpinning, the smaller diameters are generally to be preferred.
(iii) The grout is then placed by tremie pipe, the mix comprising 600 to 800 kg of cement per m^3 of sieved sand. It is, therefore, a high-strength grout.

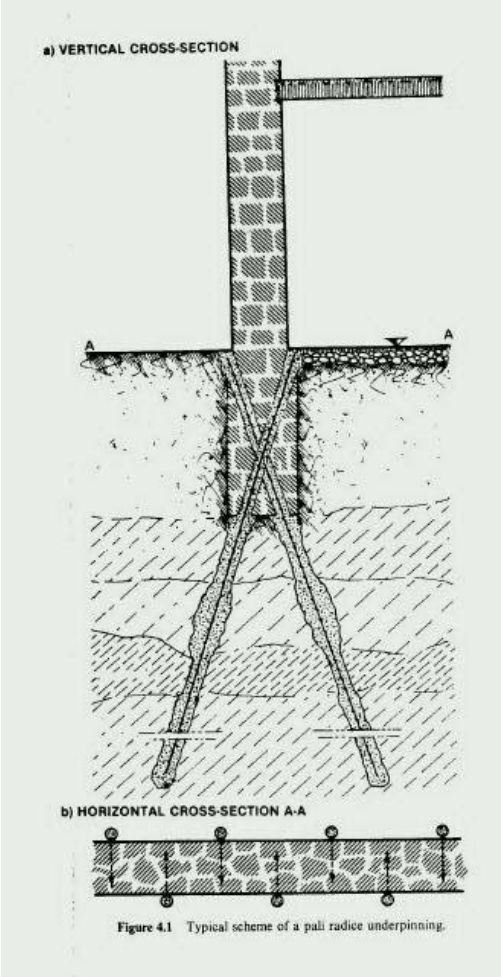


Figure 4.1 Typical scheme of a pali radice underpinning.

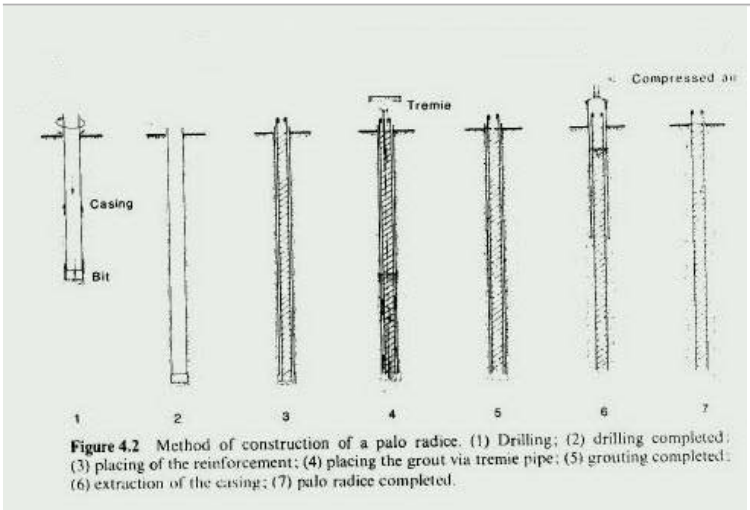


Figure 4.2 Method of construction of a palo radice. (1) Drilling; (2) drilling completed; (3) placing of the reinforcement; (4) placing the grout via tremie pipe; (5) grouting completed; (6) extraction of the casing; (7) palo radice completed.

Once the casing has been filled, it is gradually extracted. At the same time, compressed air introduced from the top pushes the mix outside the pipe against the borehole. The pressure of the air is limited to 6 to 8 bars, in order to avoid ruptures of the soil ('claquages'), while being sufficient to obtain a very rough outer surface to the pile. This gives the marked adherence to the soil that is an essential characteristic of the palo radice.

The quick response supplied by pali radice:

The most significant feature of the pali radice used in underpinning work is the quick response to any movement, however slight, of the structure. This essential feature is due to the technology of its construction in which a palo radice is essentially a friction pile. Pali radice underpinning does not supersede the existing foundation. From the start its function is complementary and only when necessary does it contribute to the foundation. The building continues to rest on its old foundation soil. It will call on the piles to assist only if it settles. This is the most important aspect which has made the palo radice so popular in underpinning works.

To clarify further, pali radice underpinning can be considered practically inactive at the moment of its construction. If the building has subsequent, albeit minimal, settlement the piling responds immediately, absorbing part of the load and reducing the stress on the soil. If the building continues to settle, the piles continue to take the load until, finally, the entire building load is supported by them. In even the most extreme case the settlements would be limited to a maximum of a few millimeters.

The working load of a palo radice:

The working load of a conventional foundation pile for a new building is generally a fraction of the ultimate load. In its assessment many factors have to be considered, including the desired safety factor and, above all, the extent of the acceptable settlement for the new building. For instance, while it may be acceptable to allow high settlements for the piers of a simply supported bridge, the same is not possible for a continuous structure. This consideration, which is fundamental for a pile foundation, is even more important for underpinning and so cannot be neglected.

For instance, should x (see figure 4.4) be the maximum settlement acceptable for the structure to be underpinned, (the value would be in millimeters or fractions of millimeters), the corresponding load to be supplied by the pile would be P. The fact that the ultimate load for the pile is much greater than P is of little importance. It must be stressed that the matter of importance is the acceptable settlement.

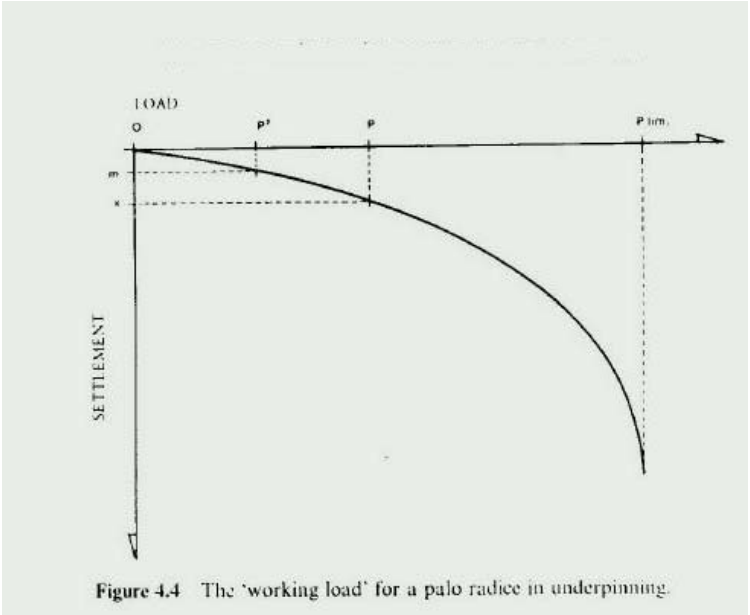


Figure 4.4 The 'working load' for a palo radice in underpinning.

From this point of view it can be seen that a palo radice used in underpinning is not completely utilized, compared to its full bearing capacity: it could always bear

much more than the assigned load. The pile, when its installation has been completed, has no immediate work to do; possibly it will never be completely utilized. As figure 4.4 makes clear, for each intermediate settlement (m) part of the load (P') is transferred to the pile, while the remaining part (P – P') continues to be supported by the soil.

The design of a pali radice underpinning: the ultimate load of a palo radice

Where the range of case histories, in different soils, do not immediately supply sufficient data about the length and bearing capacity for the various pile diameters, the design problems can be solved by direct load tests. The cost of a load test on a palo radice is without any doubt less than that of burdensome subsoil investigations; sampling analysis of the mechanical characteristics of the soil and other data, that involve extensive documentations and are, in this instance, of very little use.

After the many load tests that have been carried out, some purely orientative empirical data can be given, simply expressed.

(i) With the exclusion of particularly soft soils, a palo radice develops its maximum bearing capacity (to the crushing limit of the grout in the cross-section) over lengths of not more than 30m.
(ii) For soils having an average consistency, 20m is generally sufficient.
(iii) For very stiff soils, lengths of 10-15m are sufficient.
(iv) For compact sands and gravels, the limit varies from 6 to 10m.
(v) For clay, the lengths can vary from 10 to 15m depending on the compactness of the formation.

Considering the above, a simple empirical formula can be put forward, for the ultimate load P_{ult} (kg) of a palo radice:

$P_{ult} = \pi DLKI$

Where

D is the nominal diameter (in cm) of the pile, i.e. the drilling diameter;

L is the length of the pile (in cm);

K is a coefficient that represents, in kg/cm^2, the average interaction between the pile and the soil for the whole length. (From the physical point of view, it can represent the pile/soil adherence, or the shear stress induced in the soil by the pile, or the cohesion of the soil, etc.)

I is a non-dimensional coefficient of form, that depend on the nominal diameter of the pile.

Reticulated pali radice structures:

A reticulated root pile structure is a three-dimensional lattice soil/pile structure built directly in the soil in situ according to a pre-determined plan, with many pali

radice forming a special resisting network. The piles are all connected at the top by an RC capping beam. In the resistant complex, the piles are the lines of force, while the soil encompassed supplies the weight, rather like a gravity wall. The whole is intended to resist compressive as well as tensile and shear forces.

The basic element of the reticulated pali radice structure is the palo radice, whose main characteristic is exceptional adherence to the soil. It is worth noting that the system does not rely on an intergranular improvement of the soil obtained by penetration of the grout used for the construction of the piles, since in permeable soils, this effect would be non-existent. On the contrary, the system is based on the interaction between pile and soil: in fact, if a pile takes its bearing capacity from the soil, it is logical to presume that the soil, in its turn, is in a position to transfer a stress to a pile.

Provided they are not too far apart, the piles can therefore be relied upon to provide a kind of 'knot' effect. The network of piles encompasses and so supports the soil, but at the same time the piles are supported by the soil. The piles' primary purpose is that of introducing reinforcing elements into the soil.

Different applications of reticulated pali radice:

1) Strengthening of the subsoil in urban areas
2) Protection of buildings close to excavations for underground roads or railways
3) Protection of buildings directly above construction site of shallow tunnels
4) Protection against the risk of landslide
5) Act as a reinforced soil basement
6) For consolidation of damaged tunnels

B) Micropiling

Pali radice made a name for itself in Italy and abroad, although in the USA there were some difficulties, as cast-in-places piles are not very popular in that country. After about twenty years (in the 70s), with the expiry of the first patents of pali radice, other similar piles were proposed. They were generically called 'micropiles'. Some of them in practice conform to the characteristics of pali radice, while others have been characterized as steel piles, cemented into the soil.

It has been said before that the high bearing capacity of pali radice, compared with their small diameter, is their most favourable characteristic. But in a palo radice, as in any concrete pile, the bearing capacity has its limit in the crushing resistance of the cross-section of the shaft.

The tendency therefore arose to increase the steel reinforcement to obtain more resistant sections. Finally micropiling, consisting substantially of very heavy metal pipes (or structural beams), which could bear considerably higher loads were proposed. They are securely cemented into the subsoil.

One such micropile ('Tubfix') is illustrated in figure 5.1, where the phases of construction are depicted.

(1) The drilling is carried out with any system suitable for the particular soil, including flushing of the spoil with bentonite mud.
(2) Once the fixed depth is reached, a steel pipe (reinforcement) is introduced. At its lower end, the pipe is provided with a series of holes protected by rubber sleeves (valves).
(3) Through these valves a cement mix is injected to fill the annular space between the hole and the pipe.
(4) Before the complete hardening of the mix, the lower valves are pressure grouted in order to form a kind of bulb. These special valves allow for some regrouting, if necessary.

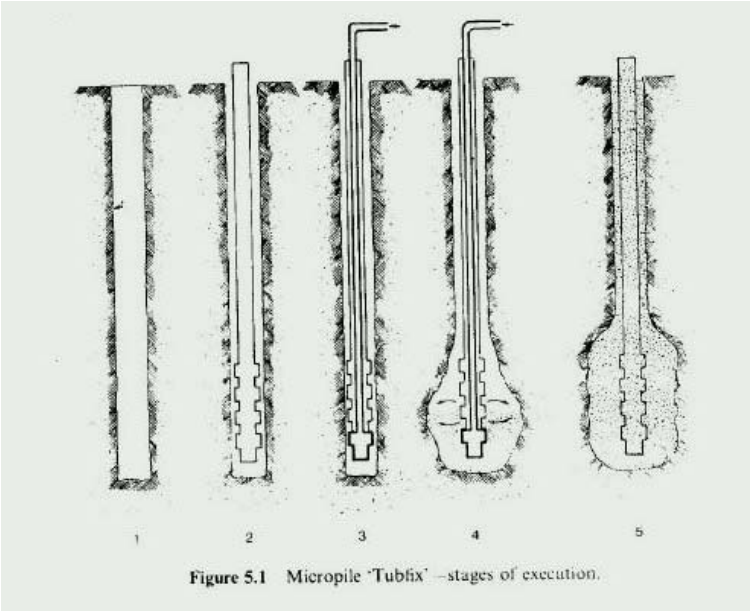


Figure 5.1 Micropile 'Tubfix' –stages of execution.

The high strength of the steel offers an increased loadbearing capacity. On the other hand some other points must be considered.

(a) The adhesion between the pipe and the soil, in metal piles, is obtained by means of fluid cement grout, injected through the pipe. Obviously, the thin cement grout crust so obtained cannot ensure a very effective adhesion between steel and grout or in turn, between the grout and the soil. It is necessary to inject in the lowest part of the pipe, where it is possible to obtain higher pressures. The bearing capacity is obtained in practice by a kind of point bearing supplied by the deeper layers, instead of by skin friction as in the case with pali radice. Figure 5.2 shows two typical curves of load transfer from the pile to soil, for a palo radice and a metal micropile respectively. For this reason, the settlement of a metal micropile is in the order of some centimeters, and not millimeters as in the case with a palo radice. Both were constructed on the same site for a building that needed underpinning and a partial reconstruction with additional new structures. The same figure shows the characteristics of the subsoil. The diagrams demonstrate that metal micropiles, even if (owing to the resistance of the steel) they are potentially fit for supporting greater loads, cannot be used for underpinning, because of their high settlement. In fact, for the underpinning of the building, pali radice were used, while the steel micropiles could be used as foundations for the new structures.

(b) The risk of corrosion in steel pipe micropiles cannot be ignored.

(c) Buckling, which is not normally taken into consideration in the case of very slender piles, cannot be ignored in the case of steel micropiles which are heavily loaded and not adequately supported by the soil in the upper layers. For this reason, such piles are only installed vertically.

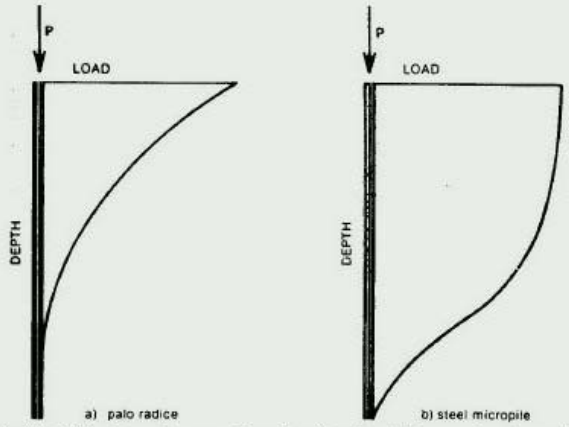


Figure 5.2 Typical load transfer curves from the pile to the soil, for a palo radice and for a steel micropile.

The preloading on micropiles:

As shown above, the palo radice, if used carefully within well-defined, and not excessive, load limits, is able, with its prompt response, to give a definitive and rational support to foundations incurring problems. But, as has also been shown, the bearing capacity of a palo radice in the absolute sense can be very high, much higher than required: it cannot be utilized, because the corresponding settlement would not be acceptable for a building in distress. This has sometimes suggested the idea of preloading the micropiles, in order to make better use of their bearing capacity without exposing he building foundation to the corresponding greater settlement. This tendency must be decisively rejected (except, of course, for temporary use in particular cases) for the following reasons.

(a) The pre-loading introduces into both soil and building stresses which constitute a striking disturbance to the existing stability, the consequences of which can be very severe.

(b) The factor of safety is now

$\eta = \eta p$

That is, it has to rely only on the bearing capacity of the piles, without the essential contribution of the existing subsoil.

(c) The building is transferred on to the piling, losing its contact with the soil. Freed from the building load, the soil sooner or later loses its high degree of consolidation, reached, sometimes, after centuries. Should the building settle again, pressing anew on the soil, this would create conditions leading to consequences more serious than were possible before the building was so imprudently detached.

(d) The connection between the piles and the structure has to be postponed until the time when the piling is complete, at least in part, and in a state of preloading. Instead of a progressive improvement of the piling, as in the case with normal pali radice underpinning, a long period of distress would occur, terminating only with the completion of the structure above ground level.

In the meantime, shoring or other supporting structures would be necessary.

Recent types of pali radice:

The palo radice described previously has, with time, developed from its original form. This has allowed better adaptation to the demands of specific problems, always remembering the fundamentals principles which inspired its creation.

Among these developed forms, the 'pali radice a base espansa' (root pile with expanded base) must be mentioned. The innovation consists basically of a vacuum 'cell' at the toe of the reinforcement, made of a resistant deformable cell, which remains empty during the grouting of the pile (by the usual system of a tremie pipe). After hardening of the grout, a neat cement grout mix is injected into the cell through a grout pipe. As indicated in the figure, a single steel pipe can generally be used for reinforcement as well as grouting. The cavity allows the formation of a fluid 'bubble' which, breaking the walls of the cell produces a uniform pressure on the soil and creates a base bulb. This applies in any type of soil, whatever its permeability.

In outline, this system recalls the procedure of injection in steel micropiles using valved pipes. However it is substantially different, because the grout injected, instead of going through rubber valves which allow a limited, irregular passage with a noticeable loss of pressure, is first collected in the cell, where it forms a fluid 'bubble' which acts on a wide surface (the side surface of the cell) with full pressure (which can be controlled at the surface). Also, as stated above, the system can be applied in any soil, not only the granular ones, which are the only types suitable for normal injection. The formation of this 'bulb' provides an increase in end bearing resistance to the essential characteristic of the palo radice, i.e., its high skin friction.

The palo radice with expanded base is also used in those situations where the pile must react to tension as well as compression – as is the case, for instance, with towers for electricity transmission lines.

In the most recent form of pali radice, the bars are covered with a special, very thin layer of sand-resin mortar, after a patented procedure. This treatment is intended to increase the skin friction and supply an additional protection against corrosion.

Micropiles for new foundations in difficult soils:

Conventional foundation piles, especially large-diameter piles cannot be drilled easily in any soil. Sometimes the presence of boulders, old foundations or other obstruction in the subsoil makes the drilling of such piles difficult or impossible. But the penetration of for example, large boulders present in the subsoil to make way for large-diameter concrete piles seems illogical, due to the waste of time and energy involved. It would usually be much more convenient to substitute for the large-diameter piles an adequate number of micropiles, which on account of their more flexible technology, can be more easily drilled through any obstruction.

Figure 5.6 illustrates the foundation of a very high modern highway viaduct. The ground comprised old quarry fill, including large boulders, so the large diameter piles adopted along the other sections of the same highway could not be constructed in this particular section. Instead, a micropile foundation proved to be very efficient and easily executed. The boulders were penetrated without any difficulty, so

becoming part of the foundation. As in the case of landslides, once reinforced with root piles, the boulders became a positive element instead of a negative one.

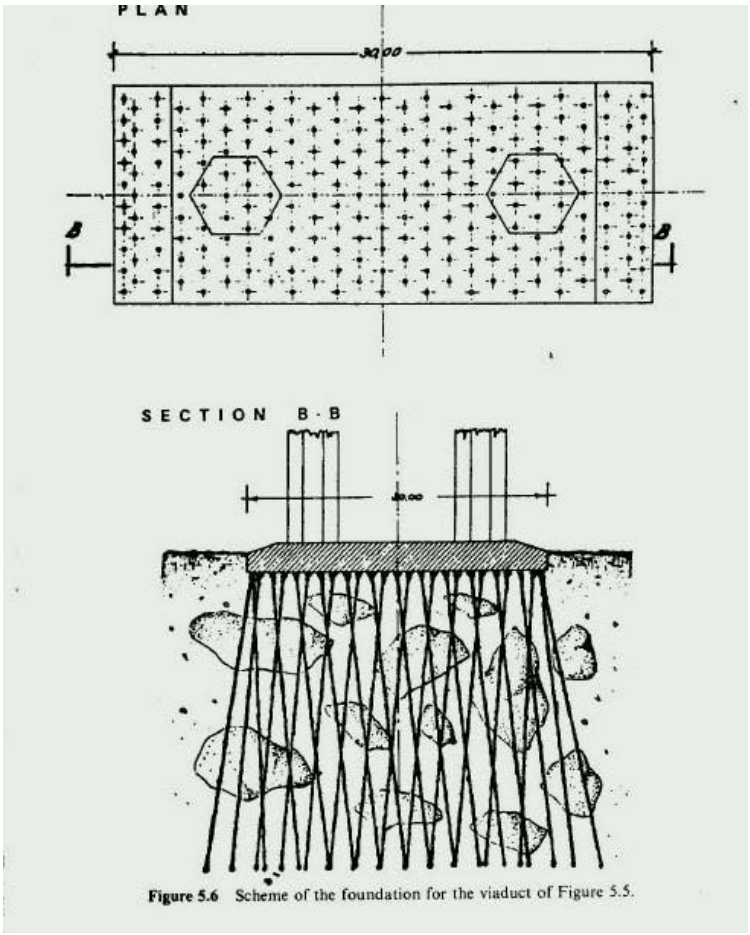


Figure 5.6 Scheme of the foundation for the viaduct of Figure 5.5.

It is worth noting the pattern adopted for the piling: it is a reticulated pali radice scheme, in which the loadbearing capacity of the single piles is increased by a 'group effect' – owing to the density of the piles (one per square metre approximately) – and by a 'network effect', owing to their mutual inclinations.

The foundations can therefore be considered from two aspects:

(a) As a normal pile foundation relying on the loadbearing capacity of the single pile. This was the basis of the design, derived from load tests.

(b) As a 'reinforced soil foundation', where all the structure (piles, soil, boulders etc.) is contributing to the loadbearing capacity of the foundation. This is a result of the reinforcement introduced by the piles, which connect and, as it were, 'integrate' the different ground condition.

The loadbearing capacity of the 'reinforced soil' according to this second viewpoint is greater than the loadbearing capacity of the total piles acting individually as in (a). This was clearly demonstrated in practice, when the settlement of the foundation (once of the viaduct had been completed) gave results of practically zero, instead of the few millimeters that could be expected after the load tests carried out on single piles.

This result looks much more important than the problem that brought it about. It demonstrates once more that the modern tendency to increase more and more the diameter of foundation piles, in order for them to support greater loads in the range of thousands of tonnes, is perhaps a mistake. Such piles, spaced widely, are generally very long – sometimes 50 metres or more – because they have to rely essentially on the deep strata, neglecting (at least in terms of safety) the possible contribution of the upper layers of soil. A denser pattern of smaller-diameter piles (not necessarily micropiles), however, of not exaggerated length, is probably more suitable for involving the collaboration of the soil, so returning to it its essential role as principal support of any manmade construction.

C) Conventional piles in underpinning

The objective of underpinning as discussed earlier is to create new foundations on which the existing load may be wholly or partially transferred without harmful movements. The need to use piles comes about when

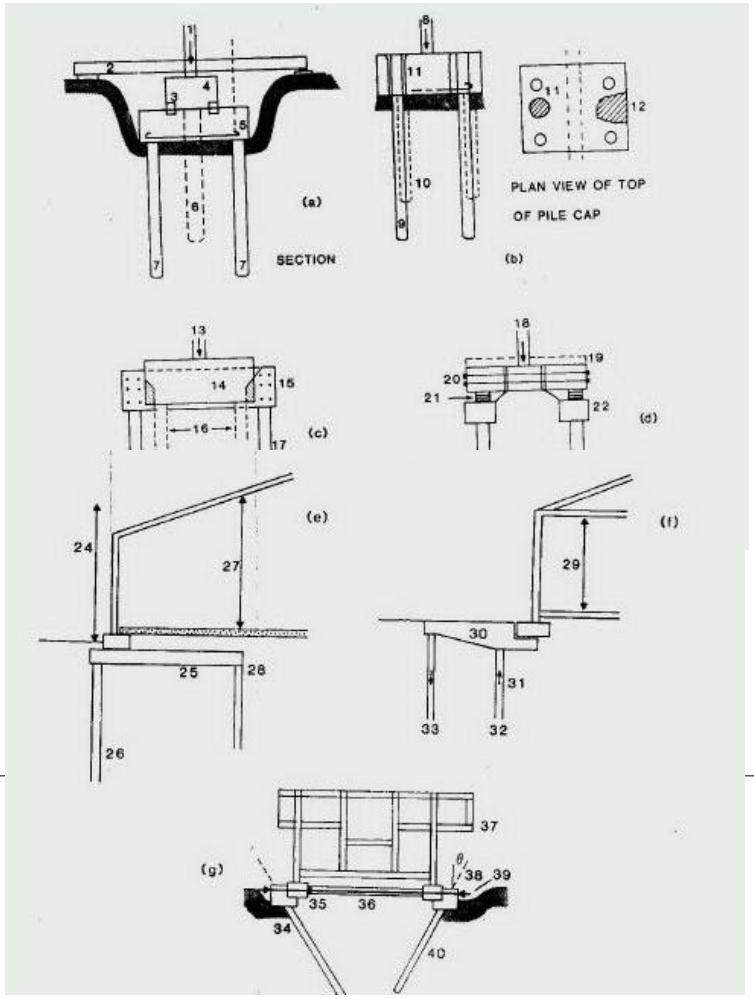
(a) the normal procedure of underpinning by excavating and forming mass concrete foundations is not possible, or is uneconomical either because of the depths to which the excavations would be taken, or because of problems caused by groundwater; or

(b) the loads on the ground from the existing structure are so great that the large dimensions of the excavations necessary for normal underpinning would cause the structure (or nearby structures) to settle or move sideways by unacceptable amounts.

Connecting piles to the structure:

The cardinal rule in underpinning is that whatever method is used, the structure being underpinned should not be irreparably damaged by the underpinning process, as otherwise the whole point of underpinning is lost. In practical terms this means that if installing the underpinning will be damaging, a prior stage of underpinning will be necessary.

This is illustrated in figure 3.1(a) which shows a temporary 'needle' beam inserted to support the load while the existing footing is undermined to insert the new spreader beam which distributes the load to the new pile foundations. As illustrated in figures 3.1(a) and (d), pockets can be made to allow the insertion of jacks, or the entire structural arrangement can be made suitable for lifting the existing structure to a higher elevation. Figures 3.1(b) and (c) illustrate how the new underpinning piles can be connected to the existing foundations either by being constructed in holes drilled through them or pockets cut out of them, or by transferring the load through a 'corset' structure.



In all cases a large measure of symmetry of the new pile positions about the existing loads is desirable to prevent large bending moments and consequent high stresses being imposed on the existing structure.

Where possible the piles should be placed close to the lines of action of the loads so as to minimize the amount of connection structure. In many cases, the headroom required by conventional drilling and driving equipment will be greater than is available immediately adjacent to the loads to be supported, and structural arrangements of varying degrees of complexity, such as those illustrated in figures 3.1(e), (f) and (g), may be necessary.

The alternatives if headroom is less than that required by conventional equipment, are as follows.

(i) Adopt a method which installs the piles in short sections. For driven piles this can be done using short pile lengths of either precast concrete or steel H-sections or tubular piles, and a low head driving frame requiring about 5m of headroom. Joints are expensive, vulnerable to damage if not properly aligned, and time-consuming to complete, so the cost of using short sections will be greater than for unrestricted conventional piling. One pile type, the Franki Mega pile, is designed specifically to be installed in short lengths using a hydraulic jack to thrust the pile into the ground against the reaction of the existing structure.

(ii) Construct bored piles using very low headroom tripod rigs and percussion boring equipment. The rate of construction is likely to be slow, and the process may produce large amounts of mud slurry of which it is difficult to dispose. Minipiling processes may offer less disruptive and more economical methods, particularly in circumstances where the piles have to be installed from basements or such places where access is confined.

Conventional piles:

Conventional piles are those which in usual circumstances are constructed to support new structures but can be adapted to the role of underpinning; non-conventional piles are unsuitable for underpinning, particularly in circumstances where the space available to construct piles is restricted.

The conventional piles considered in this chapter have the following characteristics.

(a) Types of piles. Conventional piles are available from a wide range of types, all falling within the categories of displacement types or non-displacement types. Displacement piles are forced or driven into the ground by vibratory or thrust techniques, whereas for non-displacement piles the ground is (to a large extent) excavated and the pile placed or formed within the excavation.

(b) Material. Piles used for underpinning consist generally of steel and concrete or grout (sand-cement mix) reinforced with steel. The steel reinforcement may be of rods, structural sections, wires or tendons.

(c) Shapes. Piles installed by vibratory devices or by hydraulic jacking techniques have sections that combine the greatest possible stiffness with lightness, so that they do not deform unduly while being handled and installed, and yet are light in weight for economy in handling and use of materials. Bored piles are cylindrical in shape, being formed either by percussion boring or by rotating machinery, and often have concentric enlargements of the excavations called the 'bells' or 'bulbs'. A cylindrical excavation, with or without cylindrical steel 'lining' tube to support the ground, is inherently the most stable shape likely to remain open, and in good condition to receive the plastic concrete.

(d) Sizes. The two dimensions which characterize the size of a pile are its diameter (or side dimension, if square) and length. The diameter often quoted is nominal, meaning that a cylindrical pile should nowhere be less than the diameter stated, or for an octagonal pile it is the diameter of the equivalent circular pile. Piling contractors often offer a range of sizes, and care should be taken to establish the actual size as constructed, rather than to rely on the nominal size described.

A pile is considered to be of 'large' size if it has a nominal diameter (a) greater than 750 mm for a bored pile; and (b) greater than 600mm nominal diameter (or width) for a driven pile. A pile is considered to be 'small' if it has a nominal diamter or width of (a) less than 300mm for a bored pile; or (b) less than 150mm for a driven pile. There is no special term for piles with intermediate dimensions. Piles with lengths greater than 20 times of their nominal diameter or longer than 20m are considered to be 'long'; piles of such length exposed above the ground surface usually require support against buckling. For piles largely beneath the ground buckling is unlikely to be a problem unless the ground is very weak.

Designing piles

The process of designing piles for underpinning consists of

(i) gathering together and understanding information about the site, the existing structures and the ground condition;

(ii) conducting ground investigations to determine the soil, rock and groundwater properties;

(iii) conducting investigations into the shape, strength and stability of the structure to be underpinned, and also of any nearby structures that may be affected by the underpinning;

(iv) selecting a type of pile (or types of piles) suitable for the ground conditions, and able to withstand the groundwater conditions; driven piles must not be used if their installation would adversely affect the environment or the condition of surrounding buildings;

(v) performing calculations (or, if calculations are not relevant, making judgements) to establish the likely levels at which the bases of the piles should be founded.

The outcome of the design should be drawings showing in plan the positions of the piles, and if they are to be inclined from the vertical ('raked'), the deviation and amount of rake. Sections should be drawn to show how the piles are related to the assumed ground and groundwater conditions, and how they are to be finished at the heads of the piles and then connected to the existing structure.

The design normally also includes a specification, which stipulates the qualities of, and tests on, the materials to be used in making the piles, and lays down constraints on construction methods, and procedures for testing the load-settlement behaviour of trial piles (special piles made to be tested well above the expected load, to confirm the margin of safety) and procedures for testing piles installed as underpinning.

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Case Study: Torieview Mansions

Location: 10 and 10A Lorong 29 Geylang, Torieview Mansion, Spore 388066/7

Background Information

The development is a pre-historical building that was completed sometime back in the 1930s or 1940s. In view of its architecture, the building had won the Architectural Heritage Award in 1996 presented by the Urban Redevelopment Authorities.



TorieView Mansion

Points to note

- We found that the building had undergone a major refurbishment and restoration works sometime in 1996.
- There were construction works on both sides of Torieview Mansions
- We observed piling works in progress on the left hand side of property for the extension works at the rear of a religious association.

- The construction works on the right hand side of Torieview Mansions had commenced at a much earlier date and was almost completed

Defects Analysis

From site observation, there was evidence of some form of settlement on the left column of the porch. We were informed that there would be ponding of water beneath the left column in the event of a downpour. From our observations and the age of the building and the severity of the cracks, it would appear that both columns of the affected building were most likely sitting on pad foundation. In our opinion, the cracks on the columns are caused by differential settlement of soil. It also resulted in numerous defects within Unit 10 and its vicinity. From our observations, it would seem that the columns tilted towards the front as a result of the differential settlement.

The cause of the soil subsidence could be due to the excessive downward force acting on the columns due to loads placed in the master bedroom especially near the columns. There was no historical information on the previous usage or occupation. It was not known when the cracks or movement first occurred.

There were several possibilities of the occurrence of the cracks:

1. The master bedroom might have housed furniture or equipments that might impose excessive loads on the columns and foundations.

2. There might not be any form of underpinning or strengthening of the foundation during the construction of the two blocks of resident apartments within the site.

3. The piling works to the left of the unit might have caused the differential settlement or aggravated the cracks.

The 4m long crack along the base of the left boundary wall would most probably be caused by settlement of soil due to the construction works of the extension block to the religious association. We observed that there was no form of support provided for the shared boundary in the adjacent construction works.

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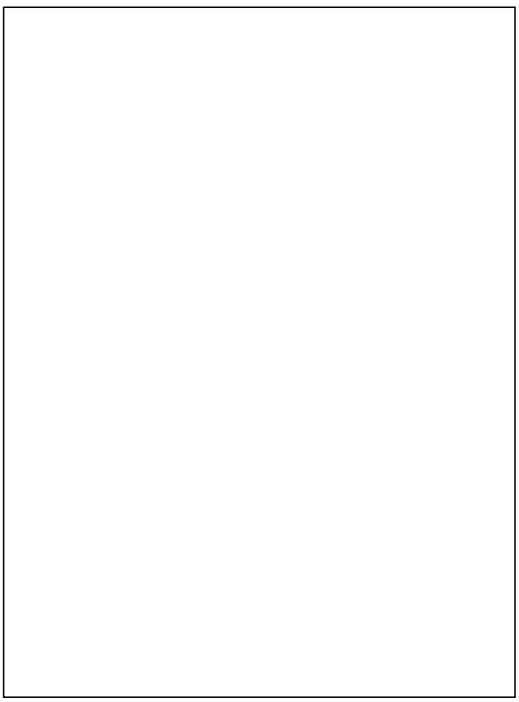


Figure 1
Horizontal crack

left column



Figure 2
Separation gaps at left column



Figure 3: Split at right column top

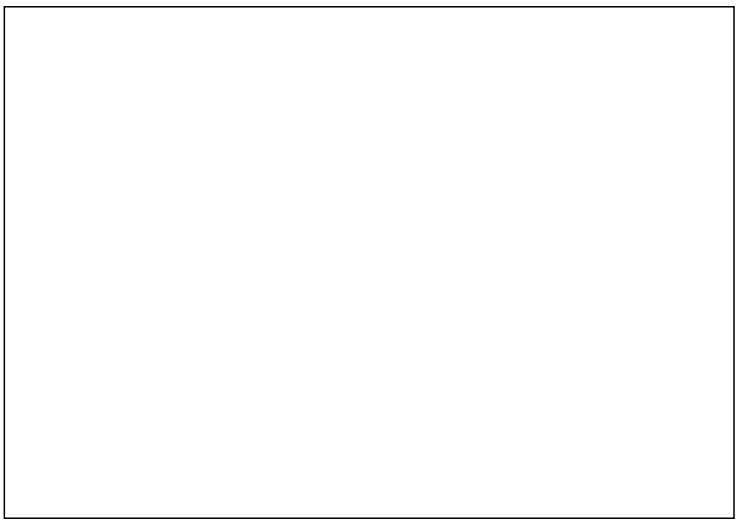


Figure 4: Water ponding at front

Recommendations

Soil investigation

A detailed investigation has to be carried out to understand the nature and the profile of the soil beneath the column. Detailed calculations have to be made to determine the bearing capacity and consolidation behavior of the soil. We recommend the trial pit test (By hand) to be carried out around the vicinity of the premises. Due to limited working space and presence of nearby residents, the test is to be carried out only to areas around the front pouch, close to the columns (See plan). Detail information on the ground water conditions would also be required.

Site preparation prior to underpinning

Although the affected unit is current vacant making it more convenient for underpinning works to be carried out, the unit is surrounded by habited residential units, including two high rise blocks, thus confining works to a limited amount of working space.

Temporary supports have to be erected prior to the commencement of the underpinning works. Raking shores can be erected to provide support to the front of the porch area. Dead shores or large vertical struts can be used to provide vertical support the master bedroom, especially below the beams to relieve the columns of their loads before underpinning. The dead shores or vertical struts can also be used to provide support for the unaffected windows and door openings.

Other than providing supports the affected building, it would also be required to provide raking shore support to the nearby high rise block and boundary wall. Before the works are carried out, the space has to be seal off from the resident and notices should be provided to inform the residents of the ongoing underpinning works. Notices should also be given to the two adjacent properties. Water pump shall be provided for pumping of water out of excavation. Space shall be allocated for storage of site equipment and materials.

(Refer to plan)

Underpinning

We recommend underpinning the existing foundation beneath the columns to a suitable stratum where the safe bearing capacity of the soil is adequate. As for the

boundary wall, it may be necessary to provide with additional support and/or strengthening of its foundation to prevent the deepening of the existing crack due to adjacent construction works.

Columns

In our opinion, if the right assumption of the columns resting on pad foundation, then one of the possible method of underpinning, the use of underpinning brackets (Chance HELICAL PIER® Foundation Systems). The size of underpinning brackets to be use will be STANDARD sized underpinning brackets (Figure 1 & figure 2). We would recommend the use of about three to 4 sets of bracket to each footing under the columns.

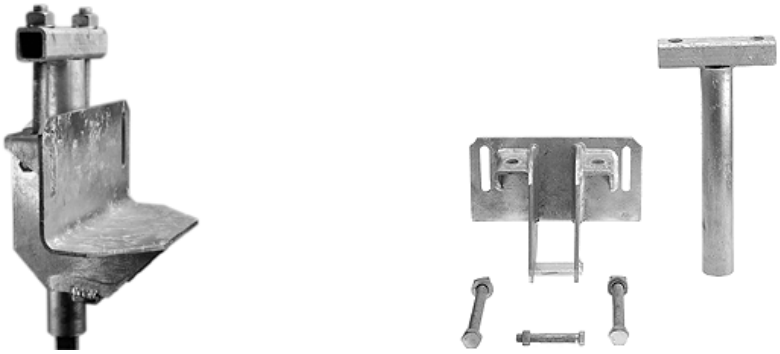


Figure 1



Figure 2

The first thing we have to consider would be the loads taken by the columns. In addition to the support provided by the dead shores or vertical struts, it is possible to transfer the load to temporary supports during underpinning works with the use of a needle and a bored pile which forms a counter weight cantilever support at a safe distance away from the underpinning excavations.

However, we are faced with the problem of limited space. The cantilever support would take up quite a fair amount of space, as the bored pile support has to be of a certain distance away from the excavation. Location of the bored pile would also be of a problem especially the affected unit is closed to other occupied blocks/units as the affected unit is located close to the entrance of the mansions, hence we are of the opinion that the use of the cantilever support to be eliminated. Stronger struts have to be used to support load transfer.

Next, the actual underpinning works can commence after the temporary supports are erected. A hydraulic jack is used to drive the underpinning brackets that are fixed with three helices discs into the ground. (Diagram) This quiet and vibration free method suits this place well as it will create noise and disturbance to the residents. The only problem that may encounter with the residents will be inconvenience as this unit is location along the entrance.

The soil beneath the column can consider to be grouted with cement not only to increase its bearing capacity but also to eliminate the necessary strutting and supports

in the excavation during underpinning. This will increase the working space in the excavation.

Boundary wall

The strengthening of the foundation beneath the boundary wall ought to be carried out after the adjacent construction works have completed. Underpinning brackets (Chance HELICAL PIER® Foundation Systems) can also be used to strengthened the footing of the boundary wall.. The size of underpinning brackets to be use will be LIGHT DUTY sized underpinning brackets (Figure 3 & figure 4)

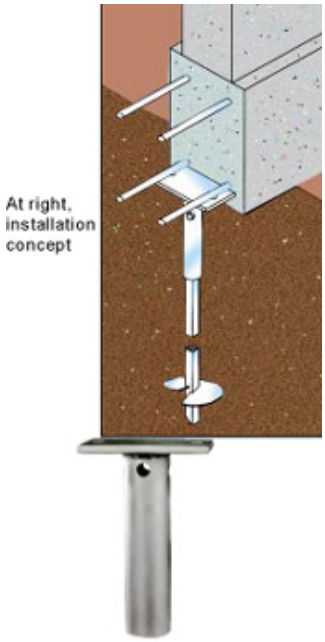


Figure 3



Figure 4

Alternative method used for strengthening the footing of the wall will be by excavation in stages and supported by concrete underpinning. The excavation will be done below the 4m long crack where concrete will be cast in to give addition support to a firmer stratum.

The use of grout is another alternative in strengthening the foundation beneath the wall, however as mention earlier, there is an uncertainty as to the life span of the grouted soil.

Temporary supports, like raking shore has to be provided to both sides along the wall and also the high rise block that is located close to the affected boundary wall.

Type of cost that will incur in the rectification works

- Preliminaries and Insurance (protection)
- Soil Investigation: to understand the nature and profile of the soil beneath the column so as to recommend the suitable underpinning method.
- Underpinning works
- Professional fees
- Repair works to internal areas and strengthening of column.
- Stitching and grouting the boundary wall
- Decoration

Consequential damages

In our opinion, consequential damages will arise from the differential settlement of the foundation and repair. The consequential damages arising from the defect will include the following:-

- Relocating the occupants to a similar of equivalent accommodation, whilst the underpinning works and the remedial works are undertaken
- Protection of personal belongings or storage whilst the works
- Loss of rental/revenue
- Inconvenience

Noise and dust generated