THE UNDERPINNING OF DISTRESSED FOUNDATION
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ABSTRACT:
This paper describes the basic concept of the underpinning of distressed foundations. Underpinning is a repair process that strengthens foundations that have been weakened by a variety of factors. It can be found in many kinds of repair projects since it deals with the temporary and permanent supports of existing foundations in order to provide additional depth or to increase the soil's bearing capacity, without failure and settlement. In other words, in the process of underpinning, the area underneath the load of the foundation is repaired or made stronger by reinforcement. To choose the right type of underpinning, it is necessary to understand the structure of the whole foundation, including the supports of the foundation and the factors that caused the foundation to get damaged. In this paper, many types of underpinning are reviewed, and methods of analysis are presented under a variety of soil and foundation conditions. This paper also includes the topic of underpinning distressed foundations of railroads, railroad bridge piers, and abutments.

INTRODUCTION:
Every now and then, structural failures of different types of structures can be found in the news. Some of these structural failures are a result of static and dynamic loading being applied to structures beyond their life cycle. It is imperative for engineers to understand the behavior of structures under different types of static and dynamic loading. This paper outlines some of the innovative methods that can be used to analyze a structure undergoing underpinning operations. It also covers examples and structural analysis methods that can be used to avoid failures during underpinning operations *[1].*

In general, underpinning is the method of providing additional strength to the foundation of an existing building and/or its associated infrastructure. This can be achieved by providing additional depth or increasing the soil's bearing capacity by adding suitable supports to existing foundations. Underpinning is a repair/rehabilitation process that strengthens existing deteriorated foundations. Its main intent is to hold the structure without structural failure and differential/total settlement that would be detrimental to the integrity and function of the structure. The right underpinning method should be decided upon only after understanding the foundation structure, foundation support, and factors responsible for the foundation damage *[2].* In this paper, many types of underpinning and methods of analysis are reviewed.

When a foundation is not designed properly for substructure and superstructure loads, foundation failure can take place under adverse load combinations. Under such conditions, underpinning of foundations is recommended in order to regain the structural stability and serviceability. This is because underpinning is often used to repair and strengthen distressed foundations of existing buildings/infrastructure. Underpinning is usually executed when the structure is loaded with dead, live, and other types of loads, and hence, temporary shoring is required to avoid the failure of the structure. This paper focuses on different underpinning methods, procedures, and their applications in strengthening different types of foundations *[3].*

History of Foundation Failures *[4]*:

Normally, foundation failure (structural as well as settlement) is common in building structures, but it rarely becomes national/international news. One example of such a foundation failure is the failure of the South Padre Island's Ocean Tower in Texas. The Ocean Tower was originally designed to be a 31-story building that housed high-end condominiums. However, construction of the tower could not be completed because of foundation problems that were discovered in 2008. The expansive soil beneath the tower began to compact, causing the building to sink and lean. Construction of the tower was ceased, and ultimately, the building had to be demolished in 2009. The foundation failure was so significant that no underpinning method was feasible.

Another example of a foundation failure is the Transcona Grain Elevator. The Transcona Grain Elevator was a grain storage facility used by the Canadian Pacific Railway. It did not even survive for a small duration (less than a day) before foundation problems started. On October 18, 1913, the building began to settle as grain was moved indoors. In the first hour after unloading, the building sank one foot into the ground. By the next day, the building was tilted an entire 27 degrees to the west. Researchers found that the foundation was extremely unstable because it was constructed on stratified clay, which contained layers of silt salt.

The leaning tower of Pisa is also another famous example of a foundation failure. In the case of the leaning tower of Pisa, the foundation failure did not completely ruin the building. When construction started on the Tower of Pisa around 840 years ago, soil-related foundation issues were found from the beginning. Work stopped for nearly a century due to political unrest in Italy, but construction continued in 1272 despite the tower's famous stature. Today, the tower continues to its downward settlement at a much slower pace due to significant foundation underpinning repair/rehabilitation work. The concepts of geotechnical engineering were used for the analysis of the tower failure and its solution.

When the Tower of Pisa was first being built, it started leaning after just five years. The reason behind this was its weight and foundation. The tower was too heavy to support itself, and the foundation was too soft to support the heavy tower. The foundation was poorly laid, and the soil was too loose, which allowed the foundation to shift underneath the tower for so many years. The tower began to lean because it was built on weak clay rather than a sturdy material, such as stones. Engineers have been making improvements on the tower's foundation for many years. They have tried mixing cement into the clay, in order to create a more stable foundation and to prevent too much water from getting under the tower. This operation failed because it caused the tower to lean even more, and hence, another engineering operation was planned. Engineers decided to remove some of the soil under the north side of the tower, let it settle, and then pull the tower straight. This operation worked, and it helped the leaning tower of Pisa to continue standing for a few more centuries *[5,6].* In order to prevent a failure like the Leaning Tower of Pisa in the future, geotechnical engineers need to analyze the foundation and ensure that the soil is compact enough to support the whole load of the building.

Basic Concept of Underpinning *[7]*:

The process of excavating for a new building foundation, especially in urban settings, can often result in damage to adjacent buildings even though everything looks alright in the design document. In some instances, the damage can be severe, resulting in the need to temporarily vacate a building or sometimes even in a partial/total collapse. The consequences can include injuries and loss of life, excessive property damage, construction delays, and expansive litigations. Therefore, it is recommended that the engineer should do all within his/her control to prevent these types of accidents from occurring when underpinning foundations.

Many of the failures that have occurred in the past are preventable with less/no added cost. This paper identifies problematic structural situations and provides preventive recommendations. It further discusses the strategies for dealing with buildings that are exhibiting distress. These underpinning guidelines will be helpful to engineers who are trying to avert unwanted accidents by prioritizing health, safety and the welfare of the public. It is found that damage to existing buildings, resulting from new construction, can be minimized/avoided, if the concerned parties of the existing and new construction have a better understanding of foundation underpinning. By performing appropriate predesign investigations of the existing and new construction, foundation underpinning can be done successfully without any unwanted incidents.

Foundation Underpinning Operations *[7]*:

Foundation underpinning operations should be planned in a proper sequence based on design documents and specifications. The design document normally includes the procedure of underpinning operations **as shown in Figures 1 and 2.** The sequence of a typical underpinning operation is described below.

1. An approach pit is created, and the sides of pit are properly shored with timber. Normally, a minimum pit width of 4 feet is kept to accommodate a worker.
2. An underpinning pit is dug underneath the existing foundation and properly stabilized with shoring.
3. Foundation underpinning is designed for specific reinforcement details. That particular reinforcement is placed in the foundation underpinning pit.
4. After properly verifying the foundation underpinning reinforcement, concrete is poured according to the set guidelines.
5. Once the underpinning concrete has gained strength, the gap between the original foundation and underpinning concrete is dry packed.
6. Initially, this process is done for A series of pits. After completion of the A series, the same process is repeated for the B, C, D…. series and so on until all the walls are underpinned. It is to be noted that the sequence of operation is very important to prevent failure.
7. Depending upon the scope, depth, and complexity of the underpinning, it can be done in several “lifts”.

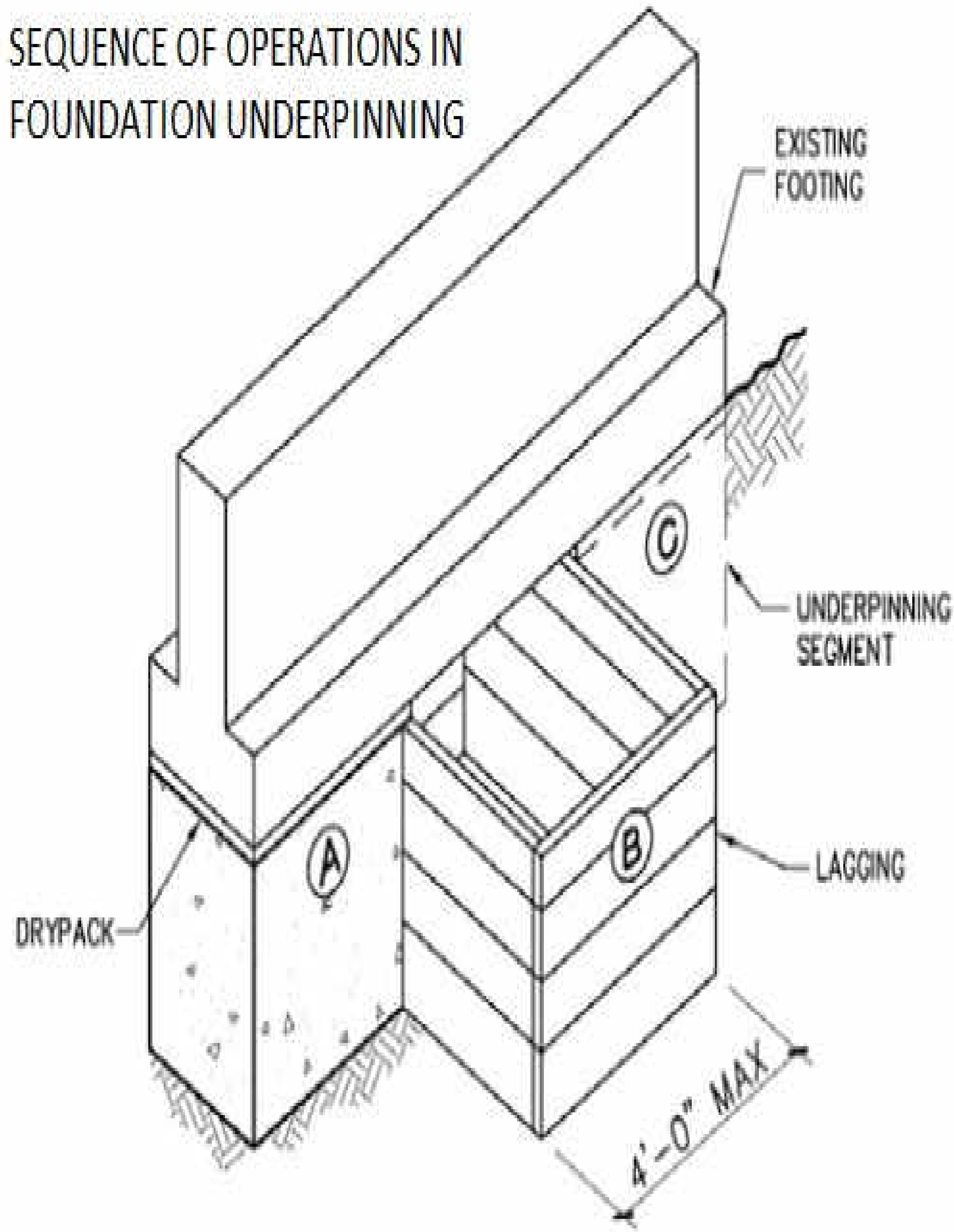

Figure 1: Close-Up View of Foundation Underpinning Operations ***[7]***

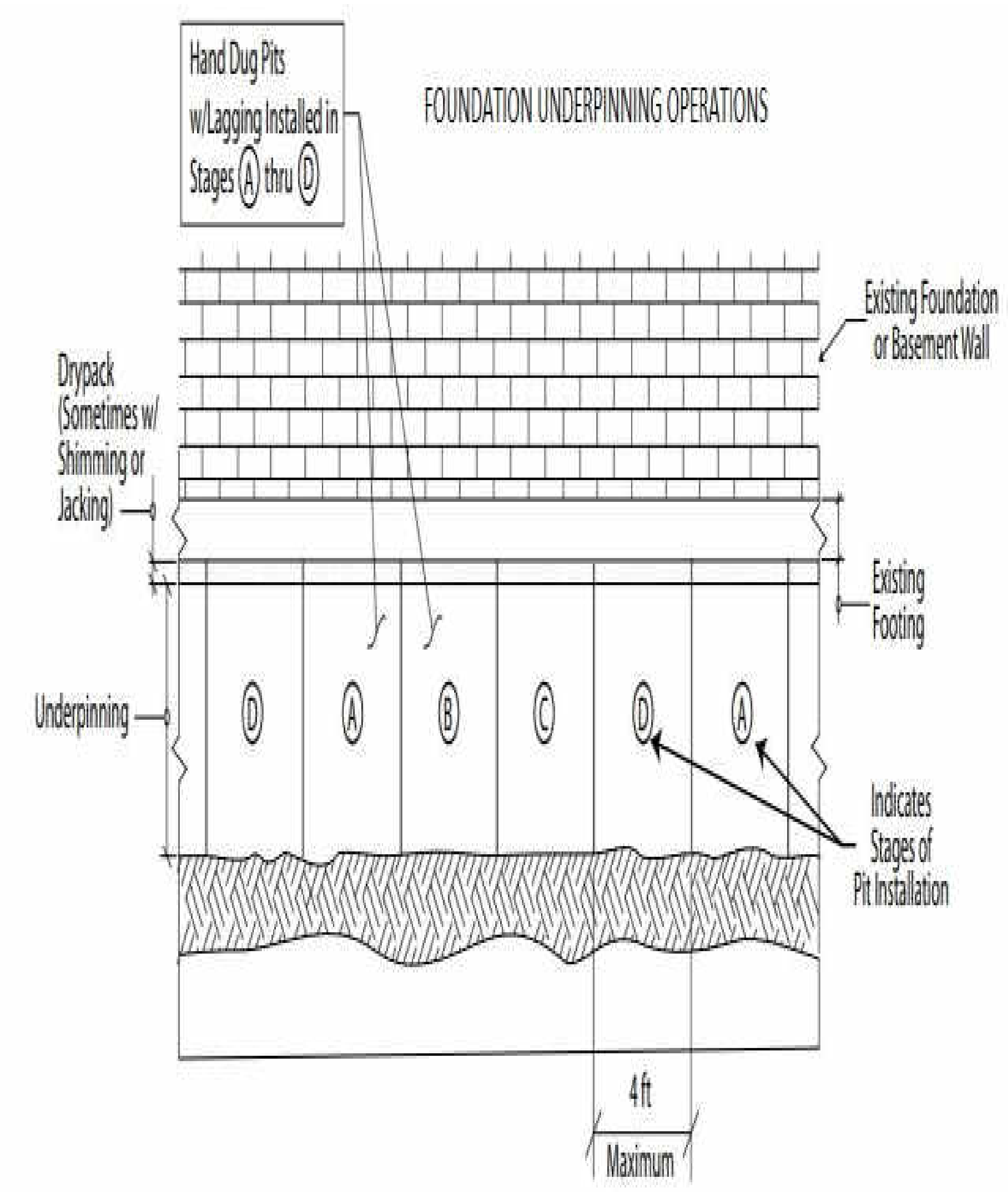

Figure 2: General Arrangement of Foundation Underpinning Operations ***[7]***

Why Underpinning of Foundations is Recommended:

Underpinning is often used because the original foundation is simply not strong or stable enough, e.g. due to decay of wooden piles under the foundation. Other reasons why underpinning is required include but are not limited to the following: (1) the usage of the structure has changed, (2) the properties of the soil supporting the foundation have changed/was mischaracterized during planning, and (3) the construction of nearby structures necessitates the excavation of the soil supporting the existing foundations. Underpinning is accomplished by digging underneath shallow footings and extending the foundation by pouring concrete. This extends the reach of the foundations in depth or in breadth so that the foundation either rests on a stronger soil stratum or distributes its load across a greater area. Some common methods of underpinning are jet grouting and using micro-piles. One common alterative to underpinning is strengthening the soil by grout *[1].*

Foundation subsidence and settlement can be controlled by underpinning foundations. Usually, subsidence and settlement are taken as interchangeable terms. Subsidence typically occurs in low-rise and medium-rise buildings that have shallow foundations or cellars that are about three meters deep. On the other hand, settlement refers to the sinking of the ground on which a structure is founded. In addition to sinking, grounds can also rise, and this phenomenon is referred to as a heave. Depending on the cause of the subsidence or heave, horizontal stretching or squeezing of the ground can accompany the vertical movement. Underpinning is generally the best solution when the movement of the structure has become so excessive, to the extent that the usage/safety of the building has been/will be compromised *[8].*

Underpinning of Foundations:

Underpinning is the act of strengthening an existing foundation system in an existing building. It is usually done when the building is showing signs of cracking or sinking into the ground, indicating that the foundation system is unable to bear the weight of the building. Underpinning can also be done when a structure is either being enlarged or converted for a new type of activity, resulting in heavier loading than its original design. Additionally, underpinning can be performed when a large new building with deep foundations or basements is being constructed close to an existing building, causing problems for the existing building. In this case, the danger to the building can come from deep excavations in the adjacent plot - if the excavation cuts into the cone of soil that supports the foundation, the foundation can lose some or all of its bearing capacity *[8].*

Multiple structural conditions require underpinning. The rising and lowering of the water table can cause the bearing capacity of the soil to decrease, making it more likely for the structure to settle. Generally, settlement results when structures are built over unsuitable soil, i.e. soil does not have enough bearing capacity. An engineer might suggest underpinning when an existing structure starts to show certain changes as a result of settlement or some type of distress. In such a case, it is necessary to establish vertical level readings as well as offset levels on a timely basis. The time period depends upon the severity of the settlement. Note that before the excavation for a new project begins, professionals (engineers) have to determine if the site's soil will be able to resist the structure that is coming over it. Based on this report, it is determined whether underpinning is required *[3].*

Foundation Underpinning Requires Extensive Foundation Analysis:

This paper covers some salient features of foundations, which is the basis of underpinning a distressed foundation. In construction, foundations are needed to provide the overall stability of the structure and to provide a level surface for the construction of the superstructure. They are also needed to safely resist the effects of permanent and transient loads transmitted to the founding strata, without any settlement and deformation. Since all loads from the structure are finally transmitted to the foundation, foundations must be judiciously designed.

Shallow foundations are responsible for transferring the load of the superstructure to the soil at the base of the substructure. (Isolated footings, combined footings, raft/mat foundations, cantilever footings, grillage foundations, and spread footings are examples shallow foundations.) Their main function is to provide adequate support to the building structure that they carry. However, shallow foundations should only be selected when the bearing capacity of the soil is good and when the structural load will not cause any settlement of the underlying soil layer. Hence, they are commonly used for residential buildings.

Basic Guidelines for Foundation Underpinning:

Normally, the underpinning process needs to be designed or led by a structural engineer for better results, but here, a few guidelines are mentioned in order to gain a better understanding of the process. The underpinning process must be started from the corners, working inwards, and they can only be made on load-bearing walls. Moreover, the underpinning should start under the strip of a footing. (It is recommended that the footing is at least 3 feet long, two feet wide, and two feet in depth.) Once the excavation has been completed, concrete must be added to the cavity. (Note that the concrete should be one-part cement, three-parts sand, and six-parts aggregate. The concrete also should be properly cured before loading it.) A rod bar can be used to ensure that the cavity under the existing foundation is filled up. Afterwards, formwork must be provided on the edges, and the placed concrete should be allowed to set for at least two days. When the concrete has gained sufficient strength, the projected footing should be broken off, and the concrete should be cut with the mass of the concrete surface. Then, backfilling and compacting are continued. If there are any problems in achieving the required consolidation, a hose should be used to add water to the soil *[8].*

Common Methods of Underpinning Foundations:

One common method of underpinning is improving the foundation system by enlarging the existing foundation, adding a new foundation, or finding alternative ways to transfer the weight of the building to the soil. Another common method of underpinning is improving the soil below and around the existing foundation, without damaging the structure. This second method is often preferable since the building is not disturbed, and in some cases, this method can be applied even when the building is occupied *[8].*

There are several types of underpinning methods, but each of these methods are only applicable in certain cases. The first common method, **shown in Figure 3**, is referred to as the traditional mass concrete underpinning method/pit method and is best suited for shallow underpinning. This process involves excavating the weak soil underneath the foundation and replacing it with mass concrete to provide more strength. The second common method of underpinning involves the use of a beam and base. This method makes use of the traditional way of constructing mass concrete bases and incorporates beams to serve as a support for the existing foundation. The third common method of underpinning is referred to as mini-piled underpinning, and it involves transferring the load of both the structure and the foundation to stable soils deep under the ground *[1, 8].* Other underpinning methods include underpinning by the cantilever needle beam method, underpinning by the pier and beam method, underpinning by the pile method, and underpinning by the pre-test method *[3].*

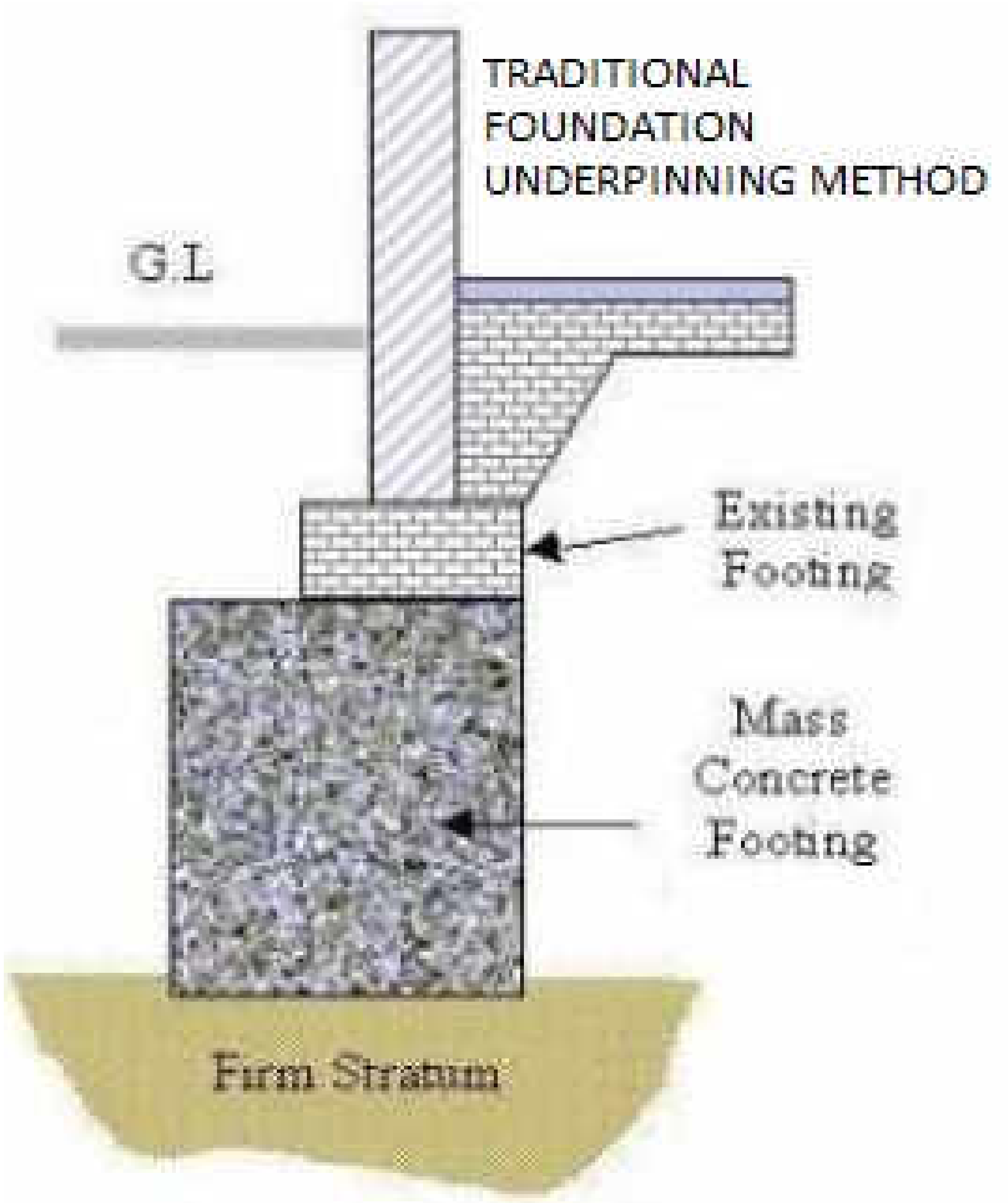

Figure 3: Common (Conventional) Method Used in Underpinning Foundations *[9]*

Common Problems Encountered When Underpinning Foundations:

Underpinning is usually required whenever a new excavation compromises the stability of the soil that supports the foundation. It involves extending a building's foundation downward, usually by adding concrete underneath the existing foundation wall. Hence, it is a specialty operation that has considerable risk associated with it *[1].* Conditions that make foundation underpinning difficult to perform are:

A. **Rubble Foundations:** Older buildings may use foundations composed of large stones, which may or may not be mortared together. These rubble foundations, while perfectly adequate for distributing gravity loads to the soil, are not well suited to bridge over underpinning pits. They lack the continuity that is inherent in reinforced and unreinforced concrete footings *[1].*
B. **High Water Table with Silts and Clays:** Consider the example where a high-rise building was constructed next to an abutting church. The basement of the high-rise building extended several levels below the church, which required underpinning the perimeter foundations of the church. In addition, the presence of a high-water table meant that the site would have to be dewatered. Performing these tasks, without causing any damage to existing structures, is something that is very difficult to accomplish *[1].*
C. **Sandy Soils:** The issue with sandy soils is that they settle when vibrated. Pile driving is one potential source of these vibrations. Even if the permanent building does not use piles, the contractor may decide to use piles as a part of the temporary soil retention system *[1].*

When Underpinning is Not Necessary:

It is important to understand the situations when underpinning is not necessary. Foundation underpinning is usually not recommended when the ground movement cause has ceased (and is unlikely to recur) since repairing the damage would be sufficient. Foundation underpinning is also not recommended when the rate and total magnitude of the anticipated ground movement is unlikely to significantly threaten the structure's strength, stability, and integrity. It is to be noted that underpinning may not be necessary in certain cases, but periodic repairs and redecoration should be performed. Doors and windows may have to be eased or changed for other types that are more tolerant to frame distortion *[1].*

Benefits of the Underpinning System:

Underpinning is beneficial when properties of the soil supporting the foundation may have changed or were mischaracterized during design. It is also beneficial when the construction of nearby structures necessitates the excavation of the soil supporting the existing foundation. Underpinning is more economical when the depth/load capacity of existing foundations need to be increased in order to support the addition of another story to the building (above or below grade). This is because usually, there is less cost involved in working on the present structure's foundation instead of constructing a new one *[1].*

The process of underpinning a foundation makes buildings accessible for inspection, correction, and improvement. As underpinning is usually undertaken in older homes, plumbing, electrical, and insulation systems can be replaced with new ones. Overall, as a result of underpinning, long term savings in the energy, safety, and comfort of the house can be made. Moreover, foundation underpinning dramatically increases the usability of the below ground space, up to fifty percent of the available rooms in a house. For example, the basement may simply become an entertainment field, spa, training room, etc. *[1].*

Underpinning to Repair Faulty Foundations:

Underpinning is a method used to either increase the foundation depth or repair faulty foundations. This might be the case if one plans to add stories to an existing structure or when the foundation of an existing structure has been damaged (cracks are visible). A building needs to underpin its foundation when cracks are wider than ¼ inch, and there are some signs of a faulty foundation (easily identifiable by diagonal cracks). Foundation failures, i.e. cracked or buckled walls and cracked concrete floors, can also be considered as heaved foundations. In order to repair such faulty foundations, the mass pour method of underpinning is used. In this process, sections are excavated in sequence to a pre-established depth below the footing, and then, concrete is placed on each pit. This method is repeated until the entire affected area has been underpinned *[8].*

Miscellaneous Methods and Techniques to Underpin Foundations:

Underpinning with screw piles and brackets is normally used in instances where the traditional underpinning process is not possible. For example, some buildings might require excavating to great depths or maybe it is unfeasible to use a piling rig. In such cases, screw piles and brackets are ideal because they can be easily installed by hand or through small equipment from a two-man crew. Screw piles have many advantages over traditional pilings. These advantages include the speed of installation, little noise, and minimal vibration that may cause damage to the surrounding area. They can withstand vertical and lateral wind forces, overcome vibration and shear forces, and be installed in foundations that can work in both tension and compression. They are ideal when underpinning support brackets. The structure can then be lifted back to a level position, and the weight of the foundation can be transferred to the pier and bracket system *[10].*

Underpinning with piles and beams is another great and preferred method to alleviate footings. In this system, a mini pile is installed on either side of the affected wall. After the piles have been installed, the brickwork is removed below the wall. Then, the reinforced concrete needle beam is used to connect the piles and support the wall. By reducing the distance between the needle beams, high loads can be accommodated. The bearing capacity of the underlying strata will determine the number, diameter, depth, and spacing of piles used. Augered piles or case driven piles can be used with this method of underpinning. The advantages of underpinning with piles and beams are that they are suitable for areas with restricted access, they are faster than traditional underpinning, they have a high load capability, and they have minimal disruption to surrounding areas *[8].*

Necessary Precautions/Safety Issues of Underpinning Foundations:

During underpinning operations, the dead load, live load, and other associated loads keep acting on the foundation system. Temporary supports are very significant as it supports the distressed foundation system during the transformation from the existing foundation to the rehabilitated foundation. That said, underpinning is a messy, noisy, and traumatic operation for buildings and their occupants alike. Unless sophisticated and expensive jacking systems are incorporated, underpinning will almost inevitably promote some additional subsidence as the work settles in. If a structure is partially underpinned, for example a house on a terrace, then future damage may recur as the rest of the non-underpinned structure continues settling. For these reasons, underpinning should be avoided whenever possible *[1].*

Most types of underpinning involve digging holes in confined spaces under buildings. The existing structure is expected to defy gravity and temporarily arch over the excavation. However, collapses can occur. Hence, risks must be identified and managed well before and during the underpinning process *[1].*

Before digging, it is recommended to check the stability of the underpinning pits, the flooding condition, the strengthening superstructure, and the support sides of the excavation (ensuring that workers can escape from the pits easily in the case of an emergency). It is also recommended to ensure that instead of dowel bars, threaded couplers are used to connect reinforcement rods between sections of shallow mass concrete underpinning. Moreover, it should be ensured that there is safe access, ventilation to pits, and a competent person to oversee safety *[1].*

Underpinning Distressed Foundations of Rail-Road Track Structure:

A road-road track structure consists of rail, ties, ballast, sub-ballast, and subgrade/formation. Mud pumping, **as shown in Figure 4**, represents a complex process of degradation under the foundation. In the recent decades, mud pumping under railway tracks has received an increasing amount of attention from academic and practical perspectives, even though the actual mechanisms and possible solutions are still under investigation. Frequent investigations in countries such as Japan, Canada, the United States, China, Australia, the United Kingdom, and other European nations, where railway systems are the largest and most advanced, indicate that mud pumping leads to high maintenance costs. There are three primary aspects of mud pumping: (i) its phenomena and mechanisms, (ii) its assessments, and (iii) its solutions.

Subgrade fluidization and infiltration to the upper coarse layers, upwards migration of accumulated non-subgrade fines, and the flush-up of peat (peat boils) in soft saturated roadbeds can all generate mud pumping. The three major factors that are needed to trigger mud pumping are excess fines, excess water, and cyclic loads. Excess fines can be induced as a result of cyclic softening and fluidization of the subgrade, the breakage and abrasion of the ballast, and insufficient drainage, which causes the amount of water in the original foundation to significantly increase. Solutions to mud pumping include: (1) cleaning, modifying, and completely replacing fouled materials at muddy sites, (2) enhancing the drainage at the foundation, (3) reducing ballast degradation and subgrade softening by using geosynthetics and geocomposites, and (4) chemical stabilization. Of these solutions, options (1) and (2) are the most conventional approaches, and physical mechanisms and track management play important roles.

Underpinning distressed foundations of such track structures can be performed in multiple ways. The most basic way is to properly compact/consolidate the subgrade or formation before laying the track components. If the subgrade or formation is not compacted/consolidated to the optimum limit, subgrade mud pumping occurs. This is a serious track defect which can lead to train accidents. Another way to underpin such track structures is to rehabilitate the formation or subgrade, after which the track structure is lifted and packed to improve the track rideability *[11].*

Underpinning Railroad Bridge Piers and Abutments:

An abutment is a bridge substructure component that supports one of the ends of the bridge superstructure. In addition to abutments, bridges with more than one span also have piers. A pier is an intermediate bridge substructure component that provides support to components that are located between the two abutments. Due to wear and tear or accidental damage of bridge piers and abutments, they often need repair/underpinning. However, cofferdams are not always needed for critical pier and abutment repairs above and below the waterline. This delivers significant cost savings by eliminating heavy equipment and the need to impede the right-of-way. **Figure 5** depicts typical underpinning of railroad bridge piers and abutments.

Concrete Repairs - Various concrete repair methods offer effective choices that can both reduce cost and ensure a quality repair. Whether it is above or below the waterline, existing concrete can either be repaired or replaced with new concrete. Usually, access to the damaged structure is difficult. Hence, innovative thinking is required to effectively transport and place concrete within a limited time schedule.
It is often thought that a successful concrete repair must be done in a dry environment; however, this is not always the case. There are several methods of underwater concrete placement that best fit each project. Examples of various underwater concrete repair options include preplaced aggregate concrete (PAC), formed cast in place concrete, pre-cast concrete, and pressure grouting.

Grouting Repairs - Pressure grouting is used to consolidate masonry bridge abutments and piers in order to increase strength that was lost as a result of degradation. This can be done both above and below the waterline on several types of structures to restore integrity. Pressure grouting increases the bearing capacity, consolidates structure interiors, and arrests water infiltration *[12].*

Figure 4: Subgrade Mud Pumping ***[13]***

Figure 5: Underpinning Railroad Bridge Piers and Abutments ***[12]***

CONCLUSION:

Underpinning foundations is a repair/rehabilitation process used to increase the strength of a foundation system. This process is controlled by a variety of soil and foundation conditions. It is often associated with increasing the foundation depth or dispersing the incoming load from a smaller area to a larger area. It can be required for many reasons, i.e. the original foundation is not strong enough or the usage of the structure has been modified. In both of these cases, underpinning is used to increase the soil's loading capacity so that structural failure and excessive settlement can be prevented. In the process, temporary and permanent supports are used on the existing footing/foundation. Proper shoring is an example of a temporary support, and it is almost always required during underpinning processes when the foundation is fully loaded.

Depending on the type of distress on the foundation system, different types of underpinning processes should be used. In order to make the justified choice, it is recommended to gain a thorough understanding of the structural behavior of the whole foundation system. Traditional underpinning is the process of constructing a new foundation beneath an existing one to a deeper level where the soil has a greater load bearing capacity. Another common underpinning method is to enlarge existing foundations. Alternatively, the properties of the soil below the foundation can be improved upon in such a way that the building is not impacted at all. However, underpinning is not recommended in cases where the foundation underpinning operation will cause extensive damage to the structure. Thus, before recommending underpinning, it is recommended for a structural engineer to analyze the distressed foundation and decide how beneficial the underpinning process would be. Additionally, building regulations should be looked into and appropriate permission to carry out the operation should be received. In terms of cost with respect to the structure's overall life cycle, underpinning is often worth it since it makes an existing piece of property structurally secure.

Future Work for Underpinning Distressed Foundations & Other Structures:

Occasionally, news of structural failures during underpinning operations arise. Often times, these failures are a result of not following proper procedures during the analysis, design, and construction phases of the underpinning of the foundation. Therefore, to avoid failures during the underpinning/construction operation, organizations around the world are focusing more on cost-effective technologies and research that can advance the field of underpinning distressed foundations. Additionally, in order to analyze complex structures, we are working on developing and selecting innovative and appropriate structural analysis methods. We have already published multiple papers on similar topics in the past [14]. The additional research on this topic will be published in the future, when available.

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