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Deep soil mixing for stabilizing deep excavations

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"In the name of ALLAH, the Most Gracious, the Most Merciful"

Acknowledgment

In the Name of Allah, the Most Gracious, Most Merciful.

Special thanks should be given to my hardworking supervisor ***Dr. Rafik Boufarh,*** *I truly appreciate* ***his*** *leadership along the whole work,* ***he*** *took all kinds of weird questions with great patience, and he did not hesitate to go through every little detail of the work, I am honestly glad that I made the best decision of working under his supervision.*

Thank you Sir, for dedicating a lot of time to this work.

Deep soil mixing for stabilizing deep excavations

Abstract

To mitigate the low Flexural strength and unexpected failures of Deep Cement Mixing piles, a new type of DCM pile called Stiffened Deep Mixing Pile (SDCM) is introduced. A jet grouting method was utilized in the installation of DCM piles. The SDCM pile consists of a DCM pile with a steel H beam inserted at its centre. A 3D model of an excavation in soft clay supported by a deep cement mixing walls were simulated, and then the results was validated to a field case study in Bangkok, Thailand. The effect of various parameters on wall deflection and stability is then evaluated using a parametric study. Individual column size, column embedment, and column strength are among these parameters. The obtained results showed that the settlements and lateral movements of the SDCM pile were less than those of the DCM pile. Also, the findings are utilized to make design recommendations and guidelines.

ملخص

للتخفيف من قوة الانحناء المنخفضة والفشل غير المتوقع لأعمدة خلط الأسمنت العميقة، تم تقديم نوع جديد من الأعمدة DCM تسمى أعمدة الخلط الإسمنتي العميق الصلبة. تم استخدام طريقة الحقن الدفقي في تركيب الأعمدة. تتكون أعمدة الخلط الإسمنتي العميق الصلبة من أعمدة الخلط الإسمنتي العميق مع عارضة فولاذية يتم إدخالها في مركزها. تمت محاكاة نموذج ثلاثي الأبعاد للتنقيب في الطين الناعم المدعوم بجدران خلط أسمنتية عميقة، ثم تم التحقق من صحة النتائج بمقارنتها مع نتائج دراسة ميدانية في بانكوك، تايلاند. ثم بعد ذلك تم تقييم تأثير العوامل المختلفة على انحراف الجدار وثباته باستخدام دراسة بارامترية. تعد أبعاد العمود الفردي، عمق العمود، وقوة العمود من بين هذه العوامل. أظهرت النتائج التي تم الحصول عليها أن هبوط التربة والتشوه الجانبي للأعمدة الصلبة كانت أقل من تلك الموجودة في حالة الأعمدة العادية. أيضا، يتم استخدام النتائج لتقديم توصيات التصميم والمبادئ التوجيهية.

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List of Symbols and acronyms

σ': Effective stress.

φ: Angle of internal friction

σ_v: Vertical stress

k_0: coefficient of earth pressure at rest

σ_h: Horizontal stress

σ_a: Active earth pressure

σ_p: Passive earth pressure

SM: Soil Mixing

DSM: Deep soil mixing

DCM: Deep cement mixing

SDCM: Stiffened Deep cement mixing

SSM: Shallow soil mixing

SDI: Strength development index

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Introduction

Urbanization contributes to land scarcity around the world in order to accommodate ever-increasing populations, a phenomenon that leads to increased use of underground space. Densely populated places emerge as a result of urbanization. Building construction noise, pollution, and vibration rules are particularly strict in densely residential areas. The deep cement mixing (DCM) wall is thus an effective solution to retaining underground excavation projects in the urban environment. The DCM walls were successfully implemented in many countries, such as, Sweden [1], Belgium [2], Portugal [3], USA (Lindquist et al., 2010), Japan [4], China [5], and Thailand [6]. In the DCM wall, cement additive in either slurry or powder form is injected into the ground and mixed with the in situ soft clay by mixing blades or jet grouting to form a hard-treated soil-cement column [7]. Improving the soft clay deposit by installing DCM walls has been used in various field projects to reduce construction costs and minimize the potential impact on the ground environment.

However, excavation in soft clays exhibits undrained creep behaviour in which deformation and movement proceed under a state of constant stress. Significant creep time causes excavation failure in cases of insufficient thickness of a DCM wall [8]. Thus, a DCM wall will typically have a thick cross section due to its low tensile strength and is typically struts (Wang et al. 2010). Consequently, DCM walls are unsuitable for deep excavations in urban areas because of insufficient working space. Therefore, The SDCM wall, a type of composite wall constructed by inserting steel H-beams into individual DCM columns to increase the bending moment capacity and the stiffness of the wall, is an improvement over the DCM wall and enables the thickness of a DCM wall to be reduced (Wang et al. 2010). DCM (SDCM) walls, which are alternative retaining walls, have been introduced to support deep excavations in soft clays.

This study focuses on the numerical analysis of a field case study of a DCM wall for a deep excavation in soft clay in Bangkok, Thailand. The 3D finite element analysis incorporated in the commercial software program PLAXIS 3D CE V20 was used for the analysis. In the first, the validation of FEM model is performed. The effect of various parameters on wall deflection and stability is then evaluated using a parametric study. Individual column size, column embedment, and column strength are among these parameters. The findings are utilized to make design recommendations and guidelines.

This work is divided in 3 parts

The first part represents 2 chapters of literature review about earthworks, excavations, retaining systems and the Deep Soil Mixing method in details, concerning its history, development, procedure, and its different types.

The second part represents the numerical analysis of the Deep Soil Mixing pile of a field case study and comparing the performances of SDCM (stiffened deep cement mixing) and DCM (deep soil mixing) walls under deep excavation in soft clay in Bangkok Thailand, using commercial software program PLAXIS 3D CE V20.

For the third part, a parametric study was realized to evaluate the behavior of the walls with different concepts and changes, and also to decide the best solutions and approaches when using this technique with the economic factor in consideration.

CHAPTER I Earthworks, Excavations & Retaining systems.

Part I Earthworks

1. Introduction:

Each construction project consists of multiple phases, one of the principle phases is the earthwork, which is a great importance, it has specific guidelines and steps established throughout the history of civil engineering, in this chapter earthworks in general details, are presented along with its functions, types and some considerations.

1.2. Definition

Earthworks are engineering works created through the moving of massive quantities of soil or unformed rock. They correspond to the first phase which is the preparation work for the infrastructure of civil engineering works on a structure. Also include all the work intended to temporarily or definitively modify the shapes of a land, which can be:

- Excavations

- Cuts, backfills

- Trenches, embankment, etc.

The term earthworks correspond to two main types of work:

1- Carrying out a deep excavation, for example on an urban site, to carry out underground levels, which often requires supports.

2- The realization of a platform, for example to build a road, opening of a track, build a distribution, adduction, sewerage network or the construction of dams. These operations generally involve significant backfill.

The earthworks for all the works are broken down into several phases:

- Preparation: demolition for example
- Excavation: the excavation is carried out directly by production machinery

- Transport of excavated material
- Installation of "backfill" materials with possible consolidations

Figure 1.1 Earthworks realization

1.3. Various operations

- Excavation by cutting, consists of removing land initially in place.
- An earthwork by backfill consists in putting in place, generally by contribution or deposit, previously removed soil.

- General earthworks are often a work involving very large cubes of earth, and generally do not require special procedures (preparation of areas for the siting of factories, industrial areas, residential areas, etc.).
- Earthworks are generally preceded by siting and staking operations intended to materialize land movements according to the final leveling to be obtained.

NB: the art of earthwork is to ensure a balance between cuttings and fill.

1.4. Special precautions

Earthmoving operations are often carried out under difficult conditions which require special precautions:

- Earthworks in bad terrain (inconsistent, unstable roundabouts, etc.)
- Deep earthworks require shoring operations (shielding)
- Earthworks in urban areas near existing constructions also requiring precautions.
- Earthworks in the presence of water (presence of a water table)

1.5. Types of earthworks

1.5.1. Classic earthworks:

This type of earthworks is used for any new construction project.

Laying a foundation for new construction requires some preparation of the land and soil in question. It must be ready to receive the first building elements which will serve as a solid foundation. In this case, the digger carries out several interventions to better prepare the construction zone, and to dig the excavations which will receive the concrete of the foundations of the infrastructure.

Some sites will require backfilling, leveling or any other means to ensure that the construction area is level.

1.5.2. Surface earthwork

Surface earthwork brings together the various interventions of the digger to ensure that the ground is flat:

- Stripping to remove the surface layers of the soil,
- On the contrary, the backfill to fill the differences in ground levels,
- The extraction of earth or large rocks.

1.5.3. The earth backfills:

By this type of intervention, the digger is responsible for leveling as much as possible a ground which would have a slope or a very concave plot. Earth must therefore be brought on site in order to integrate it into the ground, to fill the area that needs it, with prior construction of a retaining wall if necessary.

1.5.4. Evacuation of earth or rubble:

It is with the help of machines and trucks that the earth evacuation following the realization of one or more interventions mentioned above, will be carried out. Depending on the size of the works and the depth and nature of the soil, earthworks are carried out either **manually** or **mechanically**.

When it comes to small volumes, it is possible to carry out an earthwork **manually**, by shovel jet. Here are a few types:

The horizontal jet: cuttings thrown horizontally or with a slight inclination, at a maximum distance of 2 meters.

The stream on the bank: cuttings thrown at the edge of the excavation at a maximum height of 1.80 meters.

The jet on bench: cuttings deposited on an intermediate bench in an excavation greater than 1.80 meters deep, then recovered to deposit at the edge of the excavation.

On the contrary, when the volumes are too large, earthworks are carried out using machines:

Mechanical excavator: Backhoe, Bulldozer, Grader, Scarifier, Scraper.

1.6. Classification of fields

In nature different types of soils are found. More precisely, from the point of view of the "earthworks" operation, the soils are classified according to the degree of consistency or hardness.

In this specific case two main categories exist:

1.6.1. soft or easy soils:

- light fields (topsoil, loose sands, recent rubble formation)
- Ordinary fields (clay soils, stony or stony soils, tuffs...)
- heavy soils (compact clays, clay, sands strongly consolidated)
- very heavy soils (rocks and boulders)

All these fields generally only require mechanical means for extraction.

Figure 1.2. Soft soil

1.6.2. Rocky or difficult field

- Soft rocks
- Semi-hard rocks
- Hard rocks
- Very hard rocks.

These lands require in most cases the use of special means such as explosives or the use of large devices such as rock breakers or jackhammer.

Figure 1.3 Rocky field

1.7. Earthwork process

1.7.1. Preparatory work

- Tree felling

- Various stumps

- Various demolition

- Possible relocation of existing networks

- Site installation

- General staking (topographic work)

1.7.2. The stripping of the topsoil

How?

- Remove the surface layer of the natural ground to a well determined thickness (15 to 30 cm)

Why?

- Remove tree debris (roots, branches, leaves, etc.) and surface plant soil

- Storage of the topsoil to take it again at the end of the work in order to establish the various vegetalized arrangements (embankment, rest area, etc.)

1.7.3. Execution of earthworks

How?

- Execution of cutting (removal of land) and backfilling (raising of the level of the natural field)

Why?

- Model the natural terrain according to the geometric conditions defined by the execution plans (plan layout, longitudinal profile, cross sections) of the project owner

1.8. Field of major earthworks

The Earthworks activity includes the construction of earthworks for all types of transport infrastructure and associated facilities:

- Road and motorway infrastructure
- Railway infrastructure including high-speed lines
- Harbor and airport facilities
- Logistics and multimodal platforms
- Waterways including large canals
- Hydraulic and hydroelectric facilities: embankment dams, dikes, ...

1.9. Geotechnical studies for earthworks

As mentioned above, the main purpose of geotechnical studies is to identify materials in order to determine their reusability opportunities in the project.

1.9.1. Studies on the re-use of materials

They are based on the results of the following main operations:

- drilling: shovel, auger, core drilling
- laboratory tests: identification, treatment study
- in situ tests: test section (or site test), if justified by technical interest

1.9.2. Material identification

The identification of materials makes it possible to predict which materials are suitable for use under certain conditions depending on their nature, state and foreseeable behavior and final destination in the structure, with reference either to a material classification (see paragraph 4.3) or to specific tests.

The earthworks project and the identification of materials make it possible to define the methods and techniques to be applied to use the materials.

1.9.3. Stability studies: cuts, backfills, backfill foundations

Main tests:

- core drilling
- penetrometer
- pressure meter

- laboratory tests: triaxial, oedometer, shear
- geophysical tests

1.9.4. Execution studies

- Taking into account the final data of the project
- Implementation plans and possible calculation notes

1.10. Conclusion:

Earthworks are the primary phase in each civil engineering project, they represent a vast domain with multiple types, also they require a lot of experience, studies, financial resources and guidelines to follow before they could be realized, but when earthworks are done properly, and an important part of the project is completed.

Part II Excavations

1.11. Introduction

The excavations are one of the major phases of any construction project, they need to be realized with extreme precautions and good experience, they represent a great importance and one of the project basics, in this section the procedures and types of the excavations are presented.

1.12. Definition:

Excavations can be defined as the process of moving earth, soil, rock, or other materials from areas where there are unwanted, using tools, equipment or explosives. The excavation process uses different tools and techniques to move the materials to form a cavity and prepare the area for construction. Excavations are an important part of any project.

1.13. Key steps of excavation

1.13.1. Clearing

Clearing means cleaning the site, which includes removing the obstacles from the site such as roots of plants, poles, hard rocks, etc.

Figure 1.4 Land clearing and grubbing

1.13.2. Marking:

It should be in accordance with the excavation plan and should be marked along the surface with thread and lime

Figure1.5 Land marking

1.13.3. loosening:

It is the process of breaking the material for removing by drilling, blasting, shipping, ripping, pounding or cutting with the help of rams, pounder explosive fusion cutter, rotary drill, etc.

Figure1.6 Vibratory ripper

1.13.4. Digging and hauling:

Digging means to excavate and hauling means the horizontal movement of that dug material, digging efficiency depends upon factors such as capacity and size of the container, proper choice of methods, how fast equipment operates, number and size of hauling equipment and optimum travel path during dumping and delivery.

Figure 1.7 digging a pit foundation

- **Backfilling:**

It is the process of filling back the excavated trench pit with the excavated material. After the completion of work, backfilling material should ensure the following properties: adequate strength in compress ability, stability against volume change, durability.

1.13.5. Spreading and leveling:

This give the advantage of improved appearance, maintain proper drainage patterns, and soil not interfering in surveying work.

Figure 1.8 Site leveling and compacting

1.13.6. Compacting:

Compacting is the process in which the air voids are removed from the soil, making it denser, and this could be done by rolling, tamping, and vibrations

Figure 1.9 Soil compaction for road building

1.14. Permissions and precautions for excavations

1.14.1. Permissions:

Permissions are required for excavations when:

- Any gas, water, telephone line, or electricity lines are passing through the excavation site, then it is important to obtain permission to move them to another location

- Proper permissions should be obtained for cutting trees or storing materials on private property

1.14.2. Precautions

- There should be arrangements for dewatering the excavation

- Soil strength and stability is to be checked to ensure shoring equipment

- The safety of adjacent buildings must be assured before starting the works

1.15. Types of excavations

Construction companies use several different types of excavations in projects. whether to construct a residential or commercial building, roadways, bridges, or install pipes and underground utility lines, the land needs to be inspected and prepared to ensure it provides a strong foundation by excavating. The type of excavation used depends on the material used and the purpose. Below are common types:

1.15.1. Top soil excavation:

This type involves in the removal of the exposed layer or the top-most area of the earth's surface, this process refers to removing soil beneath the surface with the purpose of building foundations or embankments. this removes vegetation, top soil, and any other decaying material that could make the soil compressible and unfitting to bear structural loads

Figure 1.10 Top soil excavation

1.15.2. Rock excavation:

This type of excavation involves the removal of the rock that might obstruct construction projects. this type is the most complex as compared to other types. it can be done by blasting, ripping, or breaking rock. a bulldozer can be used to supply the force. blasting is using explosives placed in drill holes and then detonate.

Figure 1.11 rock excavation

1.15.3. Footing excavation:

To ensure that buildings, bridges, and other structures do not sink or collapse, they need support. This excavation is fairly more precise than other types of excavation as footing concrete is poured and left to set

Figure 1.12 Footing excavation

1.15.4. Earth excavation:

This involves the removal of various layers of earth allows a construction company to lay a foundation for buildings and bridges or to construct drainage ditches.

Figure 1.13 Earth excavation

1.15.5. Cut and fill excavation (stripping):

Also known as stripping excavation, this type of excavation is used to clear large areas before construction or engineering projects. The process involves the removal of broad and shallow layers of topsoil, rocks, sand, and other unwanted materials. The procedure may also include grading the land

1.15.6. Trench excavation:

This type is called like that when the length greatly exceeds the depth. The trench excavation is typically used to form strip foundations, to install pipelines and sewer systems etc.

The choice of this techniques depend on factors such as: the purpose of the trench, the ground conditions, the trench location, the number of obstructions and so on.

Figure 1.14 Trench excavation

1.15.7. Dredging excavation:

Sediment deposits can build up over time underwater making construction, as well as the passage difficult. The process of dredging involves excavating and removing sediments and debris from underwater to allow boats and ships to pass easily and for other construction purposes.

Figure 1.15 Dredging excavations

1.16. Conclusion

In the previous section the basics of excavations were reviewed, along with its types and some special precautions and considerations

In the following part the different retaining systems for of the excavation and the problems related to it are presented in general.

Part III Excavation retaining systems

1.17. Introduction:

Many deep excavations pits are localized in urbanized cities, surrounded by streets, buildings, and other structures, which generates a lot of problems and risks to the actual project and to the structures themselves, in this section we are going to present the different types of retaining systems for excavations, water problems, and earth pressure applied to them.

1.18. Types of earth retaining walls

More than several types of in-situ walls are used to support excavations. The criteria for the selection of type of wall are size of excavation, ground conditions, groundwater level, vertical and horizontal displacements of adjacent ground and limitations of various structures, availability of construction, cost, speed of work and others. One of the main decisions is the water-tightness of wall. The following types of in-situ walls will be summarized below:

1. Braced walls, soldier pile and lagging walls
2. Sheet-piling or sheet pile walls
3. Pile walls (contiguous, secant)
4. Diaphragm walls or slurry trench walls
5. Reinforced concrete (cast-in-situ or prefabricated) retaining walls
6. Soil nail walls
7. Cofferdams
8. Jet-grout and deep mixed walls

1.18.1. Braced wall, soldier pile walls and laggings

Excavation proceeds step by step after placement of soldier piles or so called king posts around the excavation at about 2 to 3 m intervals. These may be steel H, I or WF sections. Rail sections and timber are also used. At each level horizontal waling beams and supporting elements (struts, anchors, nails) are constructed. Soldier piles are driven or commonly placed in bored holes in urban areas, and timber lagging is placed between soldier piles during the excavation. Various details of placement of lagging are available, however, precast units, in-situ concrete or shotcrete may also be used as alternative to timber. Depending on ground conditions no lagging may be provided in relatively shallow pits. Historically braced walls are strut supported. They had been used extensively before the ground anchor technology was developed in 1970‟s. Soils with some cohesion and without water table are usually suitable for this type of construction or dewatering is accompanied if required and allowed. Strut support is commonly preferred in narrow excavations for pipe laying or similar works but also used in deep and large excavations (See Figure 1.17). Ground anchor support is increasingly used and preferred due to access for construction works and machinery. Waling beams may be used or anchors may be placed directly on soldier piles without any beams.

Figure 1.16 soldier pile wall and laggings

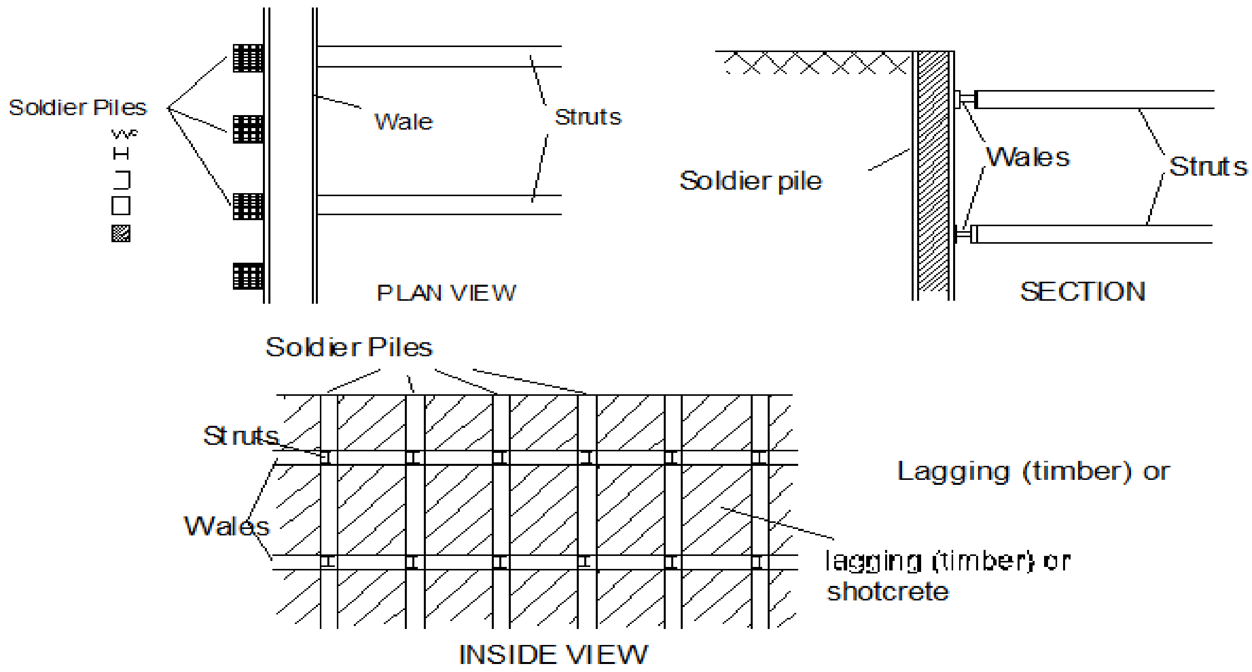


Figure 1.17 Braced walls; plan, section and inside views

1.18.2. Sheet-piling or Sheet Pile Walls

Sheet pile is a thin steel section (7-30 mm thick) 400-500 mm wide. It is manufactured in different lengths and shapes like U, Z and straight line sections (Fig. 1.18). There are interlocking watertight grooves at the sides, and they are driven into soil by hammering or vibrating. Their use is often restricted in urbanized areas due to environmental problems like noise and vibrations.

New generation hammers generate minimum vibration and disturbance, and static pushing of sections have been recently possible. In soft ground several sections may be driven using a template. The end product is a watertight steel wall in soil. One side (inner) of wall is excavated step by step and support is given by struts or anchor. Waling beams (walers) are frequently used. They are usually constructed in water bearing soils.

Steel sheet piles are the most common but sometimes reinforced concrete precast sheet pile sections are preferred in soft soils if driving difficulties are not expected. Steel piles may also encounter driving difficulties in very dense, stiff soils or in soils with boulders. Jetting may be accompanied during the process to ease penetration. Steel sheet pile sections used in such difficult driving conditions are selected according to the driving resistance rather than the design moments in the project. Another frequently faced problem is the flaws in interlocking during driving which result in leakages under water table. Sheet pile walls are commonly used for temporary purposes but permanent cases are also abundant. In temporary works sections are extracted after their service is over, and they are reused after maintenance. This process may not be suitable in dense urban environment.

Figure 1.18 sheet pile wall

1.18.3. Pile Walls

In-situ pile retaining walls are very popular due to their availability and practicability. There are different types of pile walls (Fig. 1.19). In contiguous (intermittent) bored pile construction, spacing between the piles is greater than the diameter of piles. Spacing is decided based on type of soil and level of design moments but it should not be too large, otherwise pieces of lumps etc. drop and extra precautions are needed. Cohesive soils or soils having some cohesion are suitable. No water table should be present. Acceptable amount of water is collected at the base and pumped out. Common diameters are 0.60, 0.80, 1.00 m. Waling beams (usually called 'breasting beams') are mostly reinforced concrete but sheet pile sections or steel beams are also used.

Tangent piles with grouting in between are used when secant piling or diaphragm walling equipment is not available (i.e. in cases where ground water exists). Poor workmanship creates significant problems. Secant bored pile walls are formed by keeping spacing of piles less than diameter (S<D). It is a watertight wall and may be more economical compared to diaphragm wall in small to medium scale excavations due

to cost of site operations and bentonite plant. There is also a need of place for the plant. It may be constructed “hard-hard” as well as “soft-hard”. “Soft” concrete.

Pile contains low cement content and some bentonite. Primary unreinforced piles are constructed first and then reinforced secondary piles are formed by cutting the primary piles. Pile construction methods may vary in different countries for all type of pile walls like full casing support, bentonite support, continuous flight auger (CFA) etc.

Figure 1.19 Pile wall

1.18.4. Diaphragm Walls

Diaphragm wall (Fig 1.20) provides structural support and water tightness. It is a classical technique for many deep excavation projects, large civil engineering works, underground car parks, metro pits etc. especially under water table. These reinforced concrete diaphragm (continuous) walls are also called slurry trench walls due to the reference given to the construction technique where excavation of wall is made possible by filling and keeping the wall cavity full with bentonite water mixture during excavation to prevent collapse of the excavated vertical surfaces. Wall thickness varies between 0.50 m and 1.50 m. The wall is constructed panel by panel in full depth. Panel lengths are 2 m to 10 m. Short lengths (2-2.5 m) are selected in unstable soils or under very high surcharges. Nowadays depth of panels exceeded 100 m, excavation depths exceeded 50 m. Different panel shapes other than the conventional straight section like T, L, H, Y,

+ are possible to form and used for special purposes. Panel excavation is made by cable or kelly supported buckets and by a recent design called „cutter" or „hydro fraise" which is a pair of hydraulically operated rotating disks provided with hard cutting tools. Excavation in rock is possible. Slurry wall technique is a specialized technique and apart from the bucket or the frame carrying the cutter equipment like crawler crane, pumps, tanks, desanding equipment, air lifts, screens, cyclones, silos, mixers, extractor are needed. Tremie concrete is placed in the slurry starting from the bottom after lowering reinforcement cages. Joint between the panels is a significant detail in water bearing soils and steel pipe, H-beam or water stops are used.

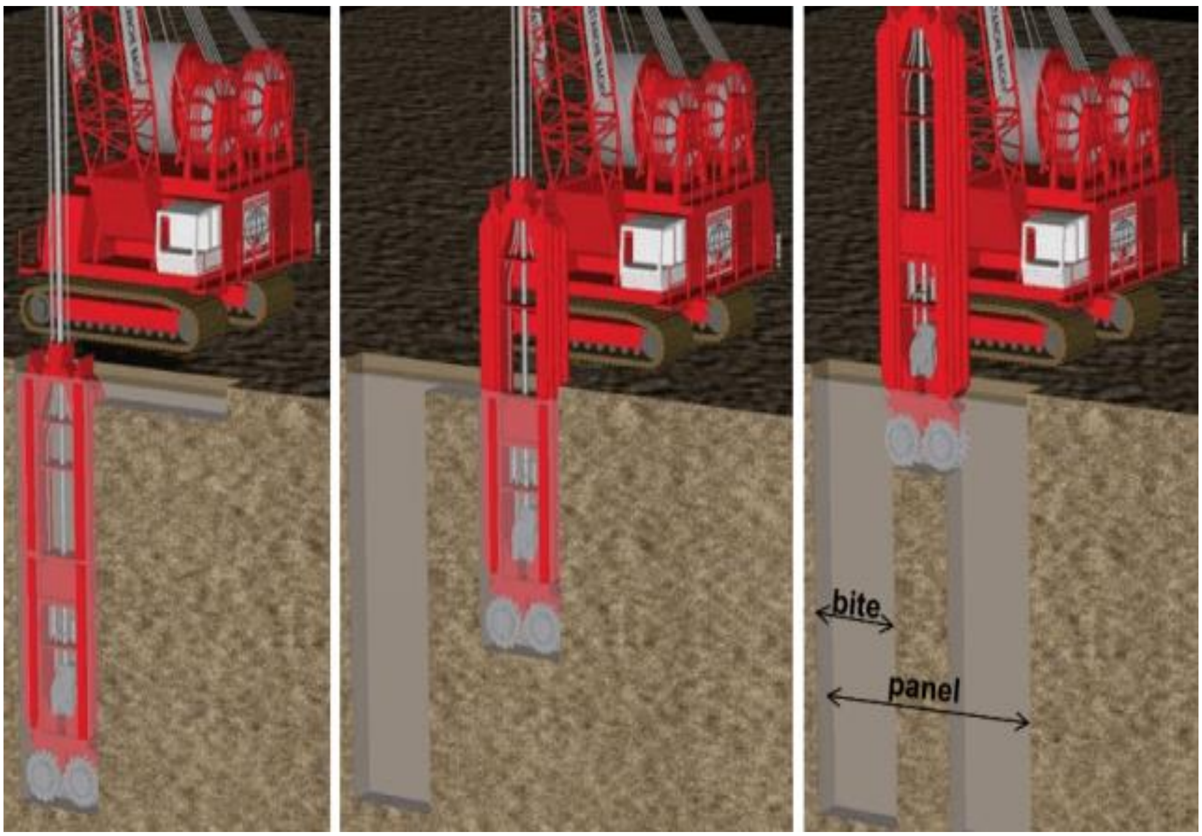


Figure 1.20 diaphragm wall

1.18.5. Reinforced Concrete (Cast In-Situ or Prefabricated)

It is a common type of staged excavation wall (Fig. 1.21). Usually supported by ground anchors Soils with some cohesion are suitable because each stage is first excavated before formwork and concrete placement. No water table or appreciable amount of water should be present. Sometimes micropile support is given if required due to expected cave-ins.

Figure 1.21 Reinforced concrete retaining wall

1.18.6. Soil Nail Walls

The excavation is made step by step (1.5 to 2 m high). Shotcrete is common for facing and wire mesh is used. Soft facing is also possible making use of geotextiles.

Hole is drilled, ordinary steel bars are lowered, and grout is placed without any pressure. The soil should be somewhat cohesive and no water table or significant water flow should be present.

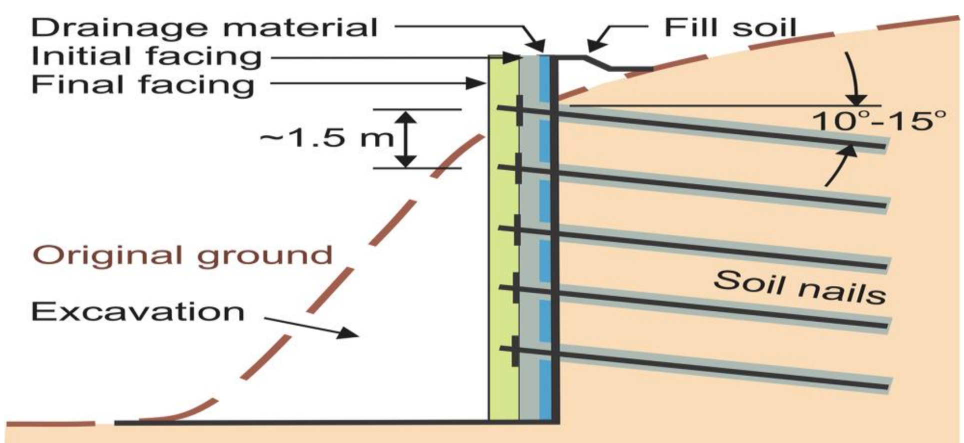


Figure 1.22 Soil nail wall

1.18.7. Cofferdams

Cofferdam is a temporary earth retaining structure to be able to make excavation for construction activities. It is usually preferred in the coastal and sea environment like bridge piers and abutments in rivers, lakes etc., wharves, quay walls, docks, breakwaters and other structures for shore protection, large waterfront structures such as pump houses, subjected to heavy vertical and horizontal loads. Sheet piling is commonly used in various forms other than conventional walls like circular cellular bodies or double walls connected inside and filled with sand. Stability is maintained by sheeting driven deeper than base, sand body between sheeting and inside tie rods. Earth embankments and concrete bodies are also used. Contiguous, tangent, secant piles or diaphragm walls are constructed in circular shapes, and no internal bracing or anchoring is used to form a cofferdam. Reinforced concrete waling beams support by arching (Fig. 1.23). Shafts are also made with this method. Large excavations or project details may require additional lateral support.

Figure 1.23 Cofferdam

1.18.8. Jet Grout and Deep Mixed Walls

Retaining walls are made by single to triple row of jet grout columns or deep mixed columns. There is a soil mixed wall (SMW) technique specially developed for wall construction where H sections are used for reinforcement. Single reinforcing bar is placed in the central hole opened for jet grout columns. Anchors, nails or struts may be used for support.

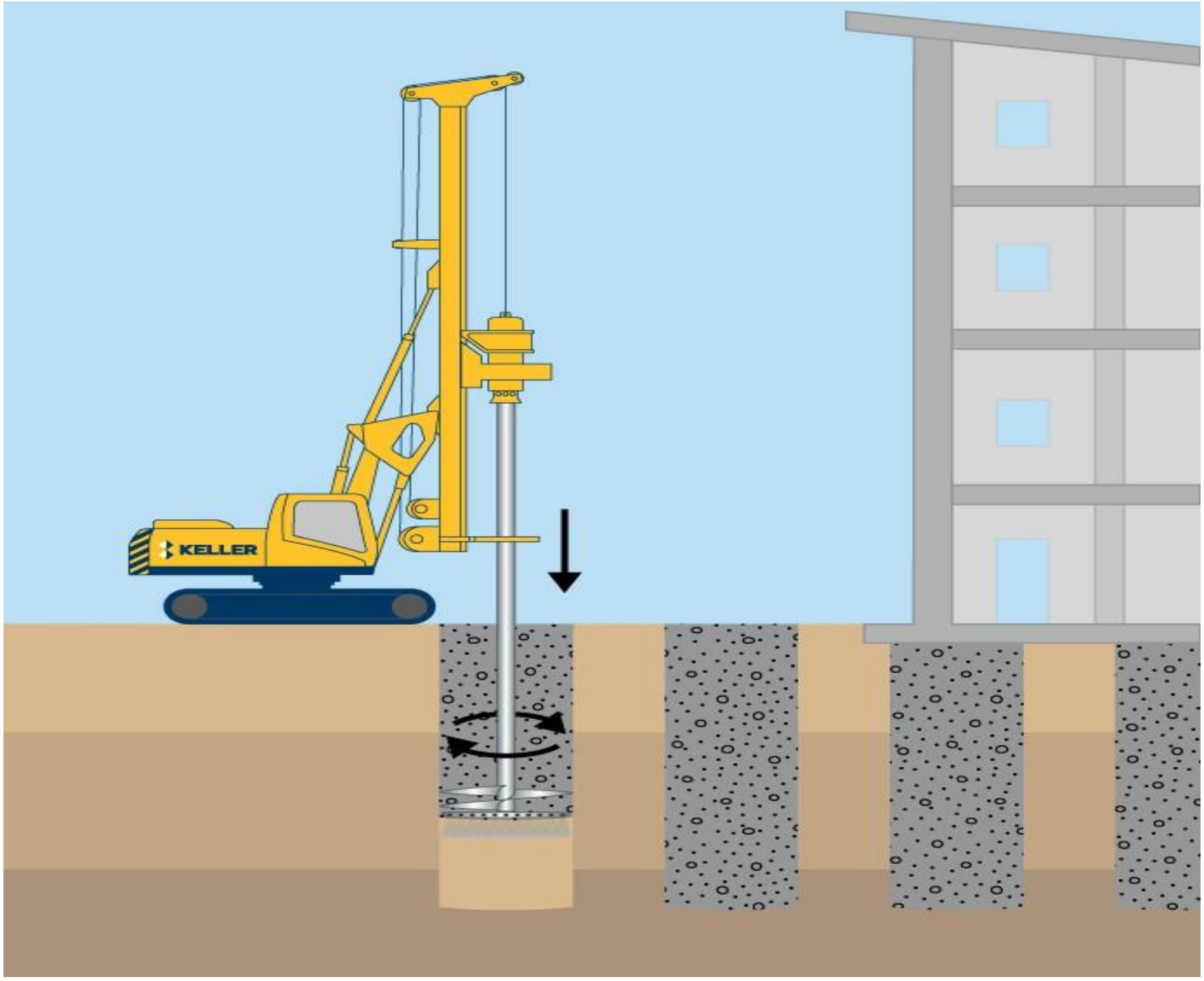


Figure 1.24 Deep mixed walls

1.19. Water pressures acting on retaining systems and related problems

1.19.1. Definition:

The presence of water or water table is one of the most important criteria for the choice of the type of wall and construction method. Site investigation studies frequently report water in borehole logs but sometimes it may not be clear whether it is a water table, a perched level, a significant source of water, leakage from a water main, surface water infiltration or due to granular pockets and lenses. If there is plenty of water a watertight type of wall has to be selected otherwise water seeping through the wall is drained off. Most municipalities do not allow pumping and groundwater lowering. If the excavation is located at an area without such a restriction it may be economical to lower groundwater table and to select a wall which is not watertight. This procedure was common in the past decade. In open areas there may not be need for walls, and sloped excavation and dewatering will suffice. Groundwater lowering causes both total and differential settlements of structures if relatively compressible soils are present

1.19.2. Soil Investigations

Technical data related to existing groundwater conditions should be investigated, and the need for groundwater control in making the excavation, planning a dewatering system to meet the job requirements and its effect on adjacent structures, specifications, monitoring and the necessity for recharge of the exterior water table should be assessed. Soil investigations generally include determination of piezo metric levels, presence of perched, depressed or artesian water levels, detailed description of soil layers, grain size analyses of aquifer soils. Depending on the project more detailed investigations may be made like borehole permeability tests, water pressure tests, well pumping tests and observation wells. Local studies on groundwater regime are also helpful if available.

1.19.3. Water Pressure on Walls

No water pressure is considered on walls through which water can pass. Drainage measures are taken inside the excavation pit at every and final stages. Acceptable amount of water should be drained this way. Water pressure acting on watertight walls shows variations depending on type of soils throughout depth and below base of wall. If there is no seepage beneath the base due to impermeable soil or impervious grout slab (blanket) hydraulic pressure distributions prevail. If there is seepage into the excavation through the base in case of permeable soil (case 1) flow should be acceptable and there should not be any risk of piping. Flow of water exerts a hydrodynamic pressure in addition to hydrostatic pressure. As it flows downwards on the active side of the wall it increases effective overburden pressure. Reverse effect occurs on the passive side and effective overburden and earth pressures are reduced. The effect on the passive overburden is more significant as far as the passive resistance is concerned. In other words, water pressures on the active side are reduced compared to hydrostatic values and increased on the passive side. Approximate estimation of water pressure during steady seepage without sketching flow nets. This method is not suitable for narrow trench like excavations, and use of flow nets are recommended.

Very permeable soils cause high flows, and should not be allowed. The flow, drainage and pumping out result in drops in water levels outside the excavation. Recharge wells may be required outside the walls if drops in water level are not allowed. If there are compressible soils in the profile, buildings and lifeline structures are expected to settle due to groundwater lowering.

1.19.4. Dewatering

Dewatering methods are applied in cases where there is need for control of water pressures and/or flow. Fig. 1.25 shows some dewatering schemes using wells and well points in permeable soils. Mainly, base pressure gradients and/or flow are reduced or eliminated.

Several methods are available. Detailed description of dewatering works can be seen in CIRIA (1993), CIRIA (1986) and Powers (1992) [9]. Common techniques are:

a. Shallow ditches, training walls, sumps and pumps

b. Single-staged or multi-staged well points

c. Shallow or deep wells

Water flow problems may sometimes be encountered in excavation projects unexpectedly. These are flow through flaws on the watertight walls, from unidentified perched levels, sources or pockets through non-watertight walls, through soil-wall interface under artesian conditions or leakage from anchor holes.

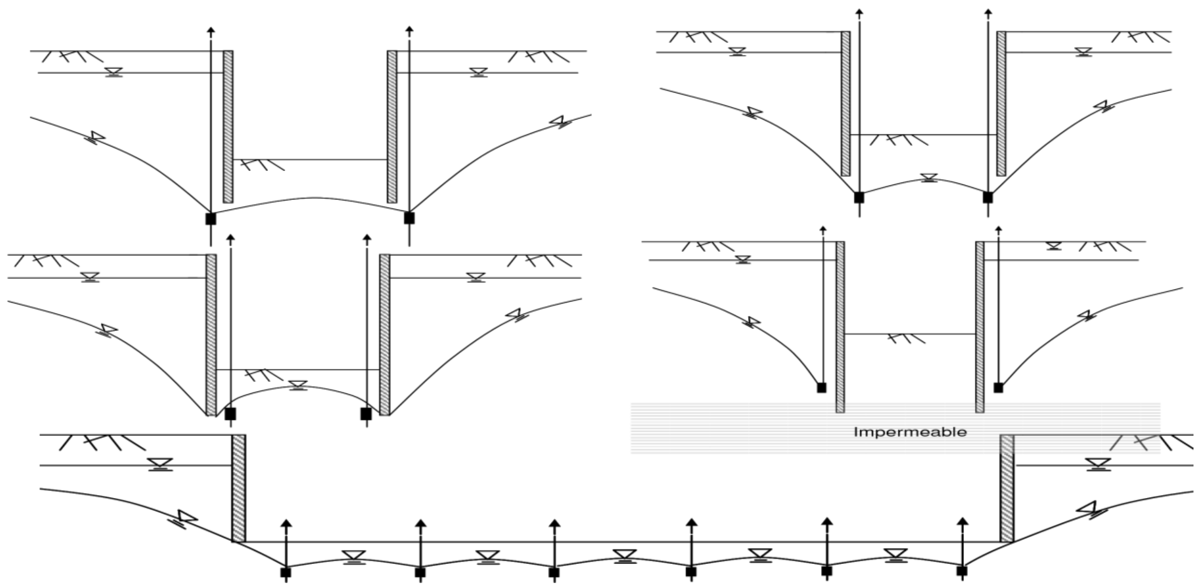


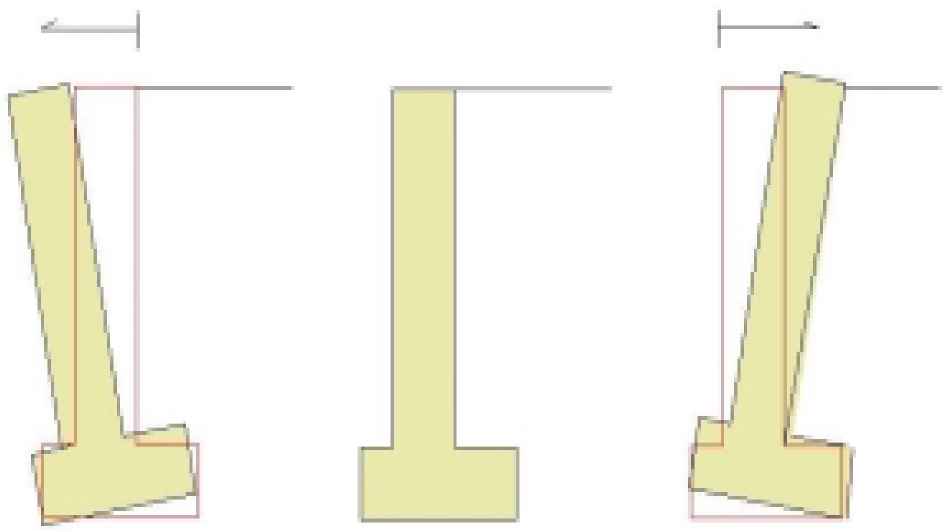
Figure 1.25 Examples of dewatering schemes using wells and well points in permeable soils

1.20. Earth pressure

There are three categories of lateral earth pressure and each depends upon the movement experienced by the vertical wall on which the pressure is acting. In this course, we will use the word wall to mean the vertical plane on which the earth pressure is acting. The wall could be a basement wall, retaining wall, earth support system such as sheet piling or soldier pile and lagging etc.

The three categories are:

- At rest earth pressure
- Active earth pressure
- Passive earth pressure



Active Case (Wall moves away from soil) **At Rest Case** (No movement) **Passive Case** (Wall moves into soil)

1.20.1. At rest earth pressure

This pressure develops when the wall experiences no lateral movement. This typically occurs when the wall is restrained from movement such as along a basement wall that is restrained at the bottom by a slab and at the top by a floor framing system prior to placing soil backfill against the wall

The shear strength of the soil is given by the MOHR-COULOMB equation: $\tau_r = c + \sigma'. \tan\varphi$

where: **φ:** Angle of internal friction.

σ ′: Effective stress.

- At any depth (z) in the soil the vertical stress is: $\sigma_v = q + \gamma.z$

If the wall is fixed and does not undergo any displacement the lateral pressure at a depth (z) is defined by:

$\sigma_h = k_0. \sigma'v + u$

where: **u**: hydrostatic pressure.

K_0: coefficient of earth pressure at rest.

1.20.2. Active earth pressure

1.20.2.1. Cohesive soils

1.20.2.1.1. Rankine's active earth pressure (1857):

The calculation of active earth pressure in the previous section is for walls that do not undergo any displacement. However, when the head of the wall tends to move away from the ground by an amount **Δx** then the thrust on that wall at any depth z gradually decreases. When the friction between the floor and the wall is assumed to be zero (**δ** = 0) which is the Rankine hypothesis, the horizontal stress σh will be:

For Δx = 0 ………… σ h = k0. γ.z

For Δx> 0 …………. σ h <k0. γ.z

If the lateral displacement of the wall Δx continues to increase, then According to MOHR-COULOMB the equation at failure as a function of the main stresses is written:

$\sigma3=\sigma1.\lambda-2c.\sqrt{\lambda}$ with **λ**= (1−sin∅) / (1+sin∅)

1.20.2.1.2. Coulomb's active earth pressure (1776):

The active earth pressure evaluated by the Rankine method was made on the basis of the assumption that the friction angle between the wall and the ground is zero (**δ** = 0).

This can be calculated by the simple equation: **σa =(½).ka.γ.H²**

With **H** the height of the wall and **ka** the coefficient of active earth pressure of coulomb given by:

$$\mathbf{ka} = \frac{\sin 2(\beta + \emptyset)}{\sin 2\beta . \sin(\beta - \delta) * [1 + \sqrt{(\frac{\sin(\emptyset + \delta) . \sin(\emptyset - \alpha)}{\sin(\beta - \delta) . \sin(\alpha + \beta)})}]^2}$$

1.20.2.1.3. Rankine's passive earth pressure:

we have **σh=σp**

where : $\sigma p = \sigma v . \tan 2\left(45 + \frac{\emptyset}{2}\right) + 2c . \tan(45 + \frac{\emptyset}{2})$

If: **kp** = tan2 (45 + ∅2) is the coefficient of the passive earth pressures of Rankine the equation at failure in a simpler form will be: **σp=σv.kp+2c.√kp**

1.20.2.1.4. Coulomb's passive earth pressure:

Coulomb in 1776 also presented a method to evaluate the passive earth pressure of a retaining wall having a non-zero friction with a granular soil, i.e. δ ≠ 0.

The passive Coulomb force will be the minimum. This can be expressed by the mathematical equation:

Pp= (1/2) γ.H²kp

Where: **kp** is the coefficient of the passive earth pressures of Coulomb, given by the formula:

$$kp = \frac{\sin 2(\beta - \emptyset)}{\sin 2\beta . \sin(\beta + \delta) * [1 + \sqrt{(\frac{\sin(\emptyset + \delta) . \sin(\emptyset + \alpha)}{\sin(\beta + \delta) . \sin(\alpha + \beta)})}]^2}$$

1.20.2.2. Cohesionless soils:

1.20.2.2.1. Active pressure:

When the soil backfill behind the retaining wall is powdery (cohesion c = 0) with a superficial surface inclined at an angle **α** with respect to the horizontal and that the friction soil wall is supposed to be zero (**δ** = **0**):

The active Rankine stress at any depth (z) will then be: **σa = γ.z.ka**

with : $Ka = cos\alpha . \frac{cos\alpha - \sqrt{(cos^2\alpha - cos^2\emptyset)}}{cos\alpha + \sqrt{(cos^2\alpha - cos^2\emptyset)}}$

and the total force per unit length of the wall: **pa =(½).γ.H². Ka**

1.20.2.2.2. Passive pressure:

The resultant of the passive Rankine forces for a wall of height H with a sloping backfill is:

Pp = (½).γ.H². Kp

with : $Ka = cos\alpha . \frac{cos\alpha + \sqrt{(cos^2\alpha - cos^2\emptyset)}}{cos\alpha - \sqrt{(cos^2\alpha - cos^2\emptyset)}}$

1.21. Conclusion:

The excavations are not easy to realize due to the related problems of water presence in the soil and the pressure of earth applied on it.

The laws of Rankine and Coulomb are the tools to calculate different pressures values of the ground so the proper solutions can take place and project safety is assured

Every civil engineer should be familiar with these laws in order to be ready to deal with excavations retaining systems

CHAPTER II Deep Soil Mixing Method

2. Introduction

There exist a lot of soil improvements techniques, each one has its conditions, advantages and limitations, the soil mixing technique is one of the most reliable and economic approaches in soil improvements, it can almost be used with every type of soil, however it has a specific guidelines and criteria that need to be followed, and in this chapter the method with its specifications are presented.

2.1. History of soil mixing

Soil mixing is a relatively recent specialization in geotechnical building techniques that is rapidly expanding. It's becoming a popular technique all around the world. The strategy can be used to solve a wide range of ground improvement problems in a wide range of soil types and circumstances (Bruce et al. 1998) [10]. For more than 50 years, in situ soil mixing has been used in the geotechnical area. The approach is thought to have been originally introduced in the 1950s in the United States (US), and then further developed in the 1960s, 1970s, and 1980s throughout Europe (most notably Scandinavia) and Japan (Bruce et al. 1998). The Jackson Lake Dam project (Ryan and Jasperse 1989; Ryan and Jasperse 1991) [11], which was finished in 1987, is widely regarded as the reintroduction of soil mixing into the American market. The strategy used in this project was to improve the ground in two distinct ways. First, auger mixing was employed to create six-sided cells near and beneath the dam's toe upstream and downstream. The soil mixed composite has a minimum strength of 1380 kPa. The design, like modern designs, was based on the fact that liquefied soils would be contained within the soilcrete cells in the event of an earthquake and subsequent liquefaction, and the relatively strong cells would prevent a shear failure in the dam foundation, which could result in the dam's collapse. In addition, as the original dam was built without any seepage cutoff in the foundation soils, auger mixing was employed to construct a 610 mm thick cutoff wall along the whole upstream toe of the dam to control under seepage. Since its reintroduction in the United States (Bruce et al. 1998), the approach has been developed, particularly as a tool for environmental remediation. The technology is being more widely used around the world as it becomes better understood, and an increasing number of companies offer soil mixing construction choices. In the United States, soil mixing was first used to construct foundation support elements and earth retention structures (Ryan and Walker 1992). Soil mixing for geotechnical ground improvement today involves a variety of procedures and materials, all of which are meant to blend soil and additives into a mostly homogeneous blend known as in situ soil-cement (if cement is used), soil-reagent, or sometimes soilcrete. In the late 1980s and early 1990s, soil mixing was initially employed in environmental applications, and it is now widely regarded as a technically sound and cost-effective method for remediating a variety of soil pollutants. Since its inception, soil mixing for the cleanup of contaminated lands has progressed significantly. In the United States, the technology has shown to be an effective method of in situ cleanup that has been approved by the US EPA and a number of other agencies for a variety of applications.

2.2. Concept and classification

Since the 1960s, when it was developed in Japan, the United States, and Scandinavian countries (Porbaha, 1998) [12], the SM approach has been widely used as a soil improvement method. The approach was originally developed to improve the engineering and environmental qualities of soft or contaminated ground. The method's popularity has risen in recent years, particularly in its home nations, but also in Southeast Asia, China, Poland, France, Germany, and the United Kingdom, as well as to some extent in other countries. This reflects an increasing international interest in and acceptance of this still-developing technology (Topolnicki, 2004) [13]. The approach can meet cost-effectiveness requirements while still being environmentally benign. The SM method entails combining elements of mixed-in-place soil with a cementitious ingredient (such as cement, lime, gypsum, or fly ash) to form composite stiff materials. In situ treated soil columns are created using specially specialized equipment with shafts with mixing blades and stabilizer injection nozzles. The binder can be added as a powder or as a slurry (wet technique). Dry binders are better suited to soft soils with high moisture content, thus the dry method is suitable. The wet approach, on the other hand, is better suited to low-water-content soft clays, silts, and fine-grained sands, as well as stratified ground conditions with interbedded soft and stiff or dense soil layers, as well as stratified ground conditions with interbedded soft and stiff or dense soil layers (KELLER, 2013). In-situ remolding and mixing of the soil is done with rotary tools. A number of tools have been developed. The expected form of the SM element determines their kind. As a result, single columns are produced using simple rotary tools. Figures 2.1 and 2.2 illustrate many examples of this type of auger for dry and wet approaches, respectively. Begin with a blank canvas to create panels or blocks.

The SM element must be installed in five phases, regardless of the technique used (Figure 2.4). To begin, the fitted shaft is placed over the planned spot. Second, the rotary tool is placed into the dirt and mixed until the desired depth is reached. The cementitious agent is then introduced, either by an auger or along the revolving shaft. However, in some cases, slurry might be injected during the penetration as well. The majority of the time, it is determined by the soil conditions. The following step is the withdraw phase, which involves continuing injection and rotating until the ground surface or the desired depth is reached. Finally, the reactions between the soil and the stabilizing substance increase the ground's strength.

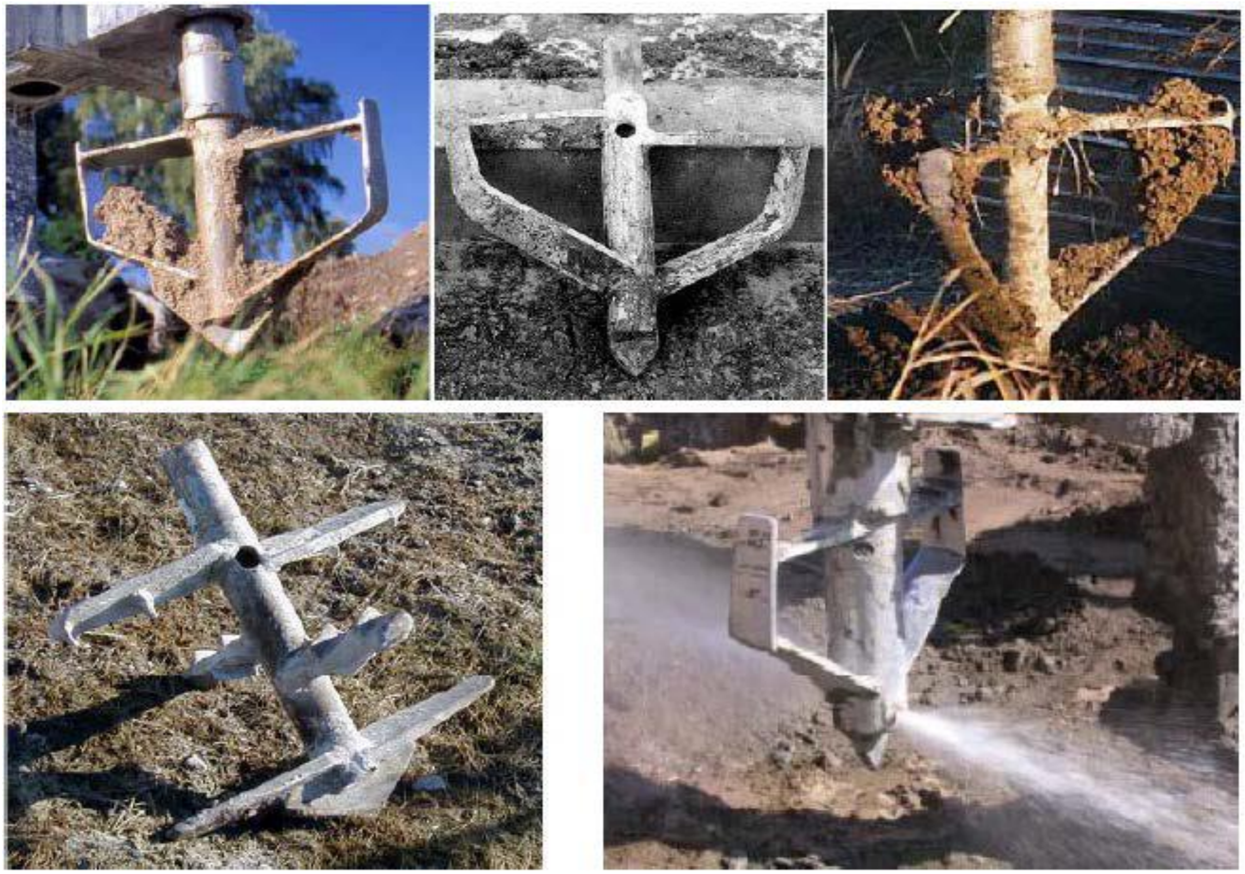


Figure 2.1 Example of simple rotary tools. Nordic dry mixing tools: a) standard, b) modified (Larsson, 2005)

Figure 2.2 Examples of simple rotary tools. Augers used to wet mixing: a) Springsol® by Soletanche Bachy (Guimond-Barrett, et al., 2012), b) DSM rotary tool by Keller (KELLER, 2013)

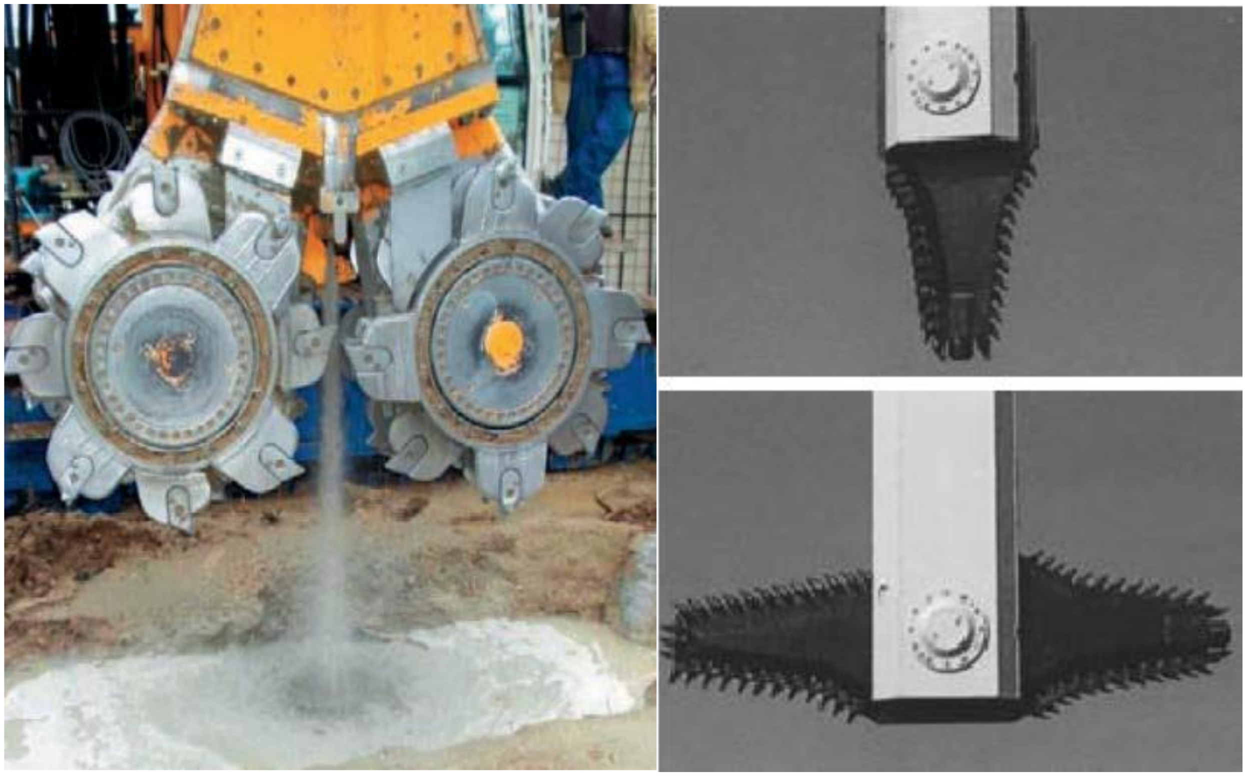


Figure 2.3 Examples of multi augers tools: a) cutter Soil Mixing by Bauer (Caltrans, 2010), b) blade used in Spreadable Wing method by SWING (Topolnicki, 2004)

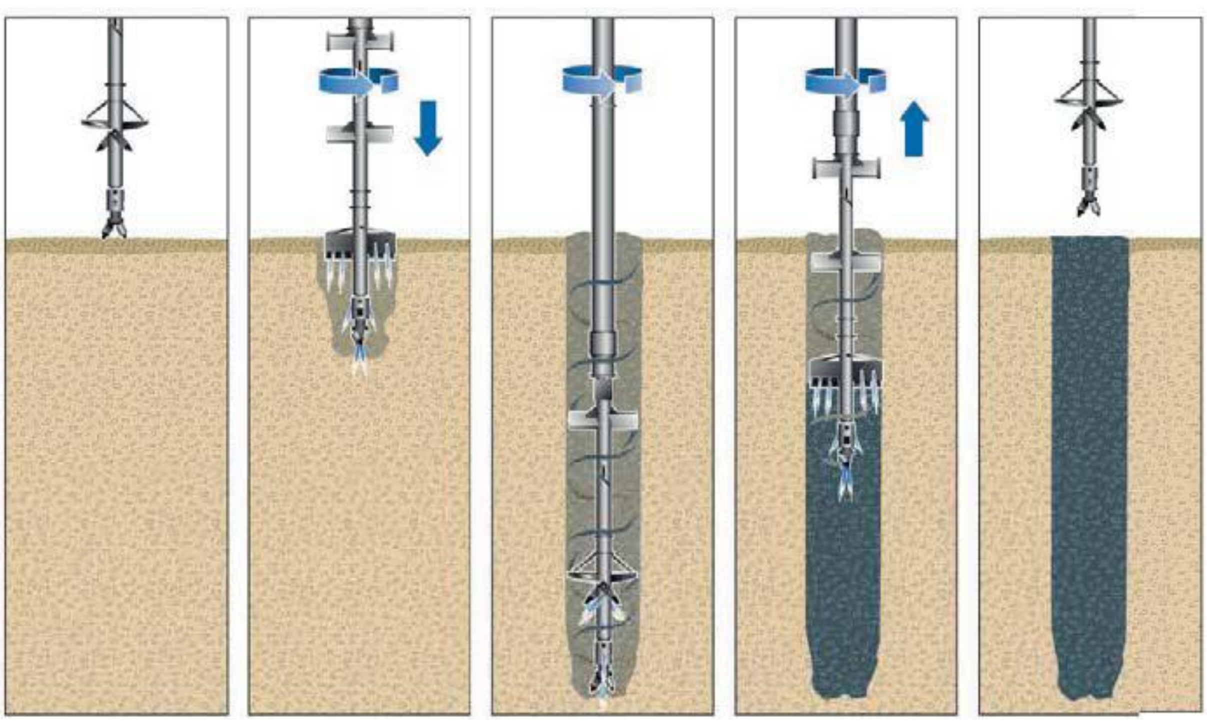


Figure 2.4 The Soil Mixing column production process (LIEBHERR, 2012)

The DSM technique can be categorized in a variety of ways. All approaches can be categorised based on three essential operational features [15] according to an FHWA report (Bruce, 2001) [14]. (See Figure 2.5.) The contrast between wet and dry methods is the most obvious, and thus the most extensively employed, in terms of the type of binder put into the soil. Compressed air is commonly used for binder transportation in dry techniques. Whereas, in the case of wet methods, transportation is usually done by water.

The second feature has to do with the mixing process. Mechanical mixing, in which the binder is injected at a low velocity, jet mixing, in which the fluid grout is injected at a high velocity (jet grouting), and hybrid mixing, which is a blend of both prior procedures, are the three methods of delivering agent.

The third characteristic is the location, or vertical distance, across which the drilling shaft mixes the dirt (Topolnicki, 2004).

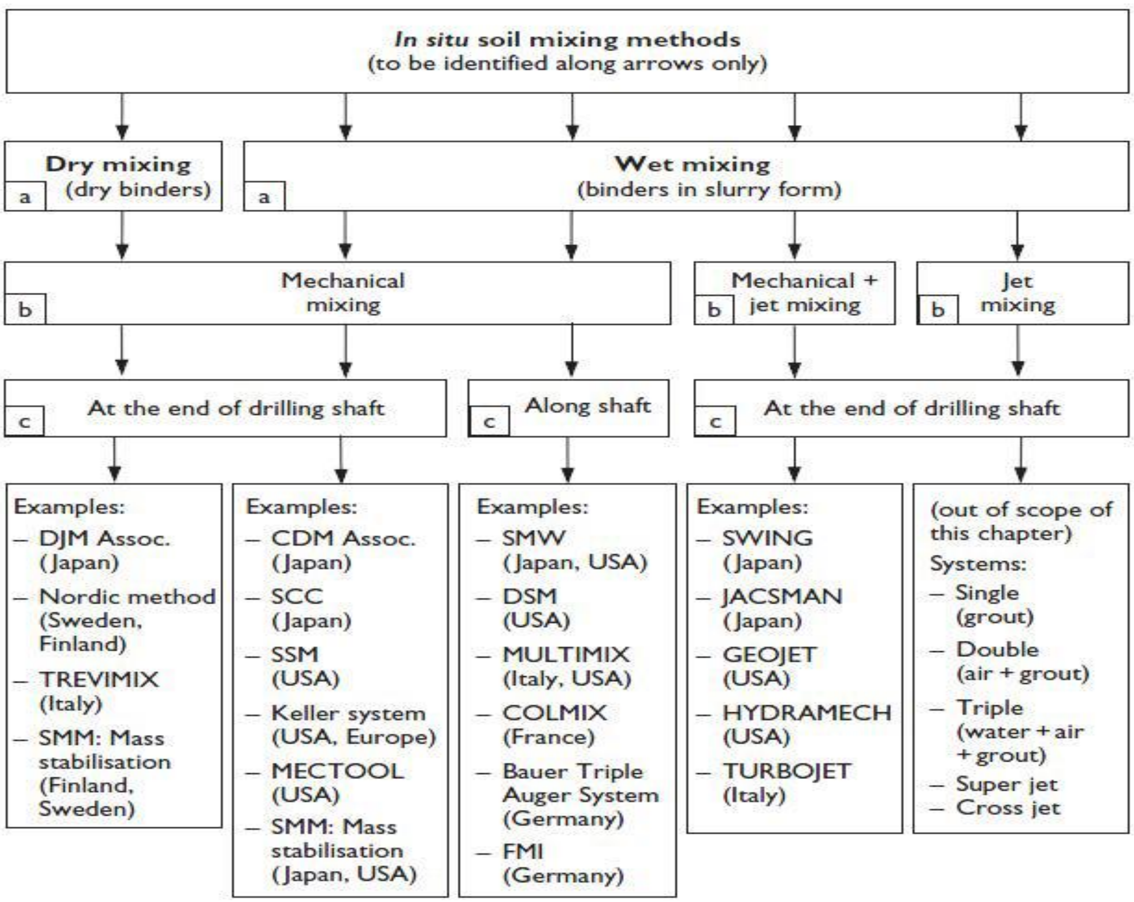


Figure 2.5 General classification of in situ soil mixing based on: a) binder form, b) mixing principle and c) location of mixing action, with allocation of selected fully operational methods developed in various countries (Topolnicki, 2004)

2.3. Depth of soil mixing

Near-surface soil mixing refers to applications of soil mixing that are very shallow, often less than 0.6 m from the ground surface. At this depth, the majority of the applications are for road construction/repair and agricultural purposes. At this depth, several shallow geotechnical (such as relieving platforms) and environmental (such as soil mixed liner projects) projects are accomplished.

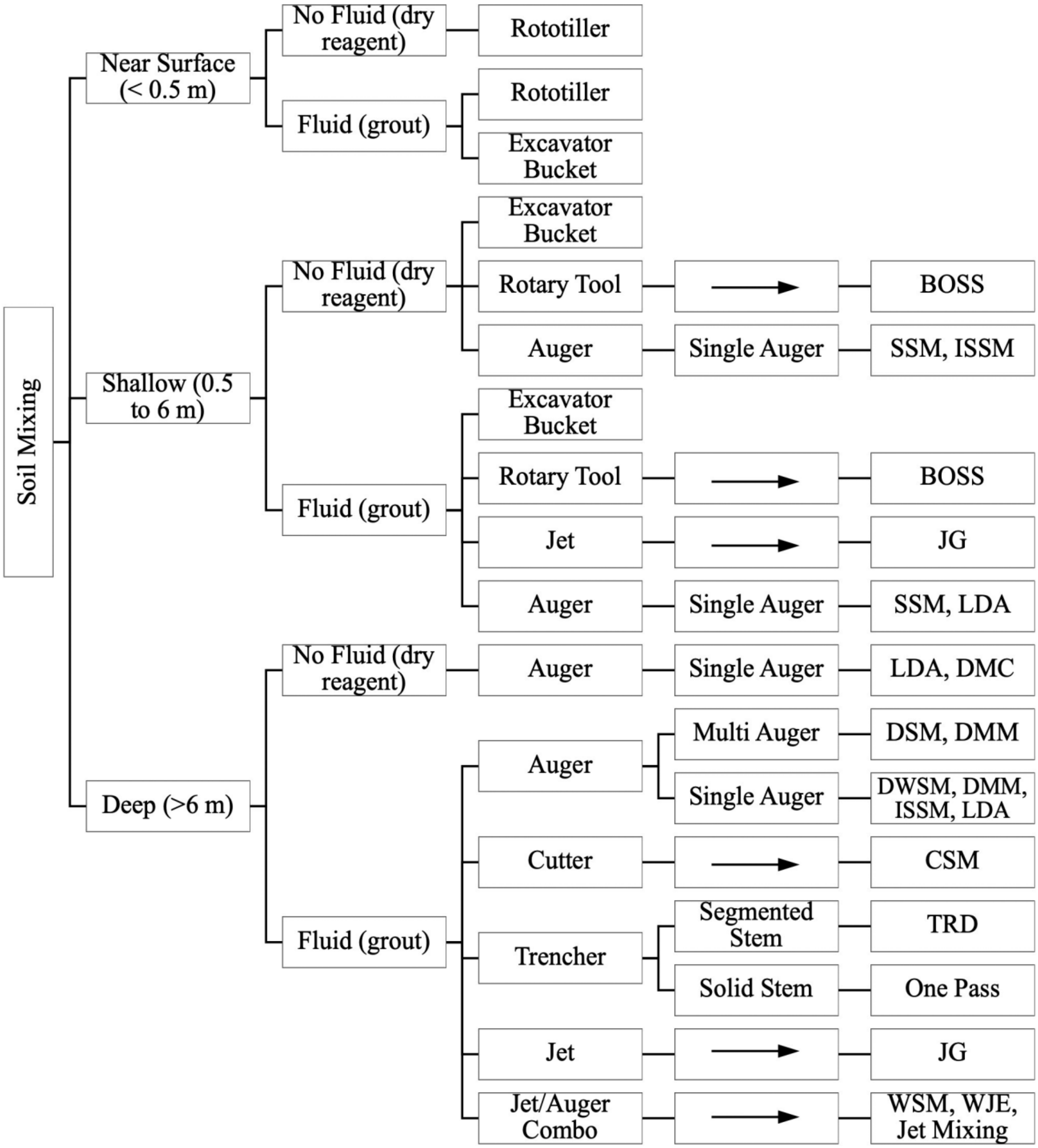


Figure 2.6 Classifications and common acronyms for soil mixing.

This chapter does not explore these extremely limited applications. Shallow soil mixing (SSM) refers to applications of soil mixing that are relatively shallow (in comparison to deep soil mixing) and cannot be completed with near-surface soil mixing equipment. SSM is performed 0.6 m to 6 m below ground surface. Agricultural, geotechnical, and environmental applications are also possible in this depth range. In industry, the abbreviation SSM is frequently used to refer to this group.

DSM refers to soil mixing treatments that are quite deep (in comparison to SSM), and is defined as soil mixing applied to depths greater than 6 meters below ground surface. At this layer, applications are solely geotechnical, environmental, or a combination of the two, i.e. geoenvironmental. As previously stated, the abbreviations DSM and DMM are frequently used to refer to soil mixing in this category.

2.4. Characteristics

Porbaha (Porbaha, 1998) [16] lists the following benefits of the SM method and compares them to traditional soil development techniques:

• Speed of construction. The SM method is distinguished by rapid solidification, which speeds up the construction process. In some situations, such as metropolitan areas, existing railway tracks, or existing foundations, the building time is the most important element in determining the approach to use. The time constraint could be due to the necessity to maintain traffic service during construction or a contract deadline.

• Strength calibration. The required strength of SM is accomplished by adjusting the binder ratio, which is usually cement, to suit the project needs, taking into account the loads, soil type, and intended serviceability.

• Reliability. Advancements in mixing equipment, control device coordination, and integrated real-time monitoring systems allow effective quality control of SM elements, increasing the technique's reliability. The performance of the SM method is compared to that of other soil development strategies in terms of reliability, cost-effectiveness, and environmental friendliness (Ando, et al., 1995) in Figure 2.7.

• Variety of application. The vast range of application areas of the SM approach is demonstrated by the high number of published cases in the literature. The following paragraph goes over it.

• Effective use of resources. The SM process does not require a large amount of additional material to be carried and then stored on site because the soil is solidified in situ. It's especially useful when there's a limited amount of space. Granular fill, for example, is required in huge quantities for stone columns or the sand compaction method.

• Small environmental impact. SM columns generate far less noise and vibration during construction than traditional methods of granular soil improvement, such as stone columns or sand compaction piles. Figure

2.8 compares the connections between noise level and distance from the source of noise for numerous soil improvement approaches (Ando, et al., 1995).

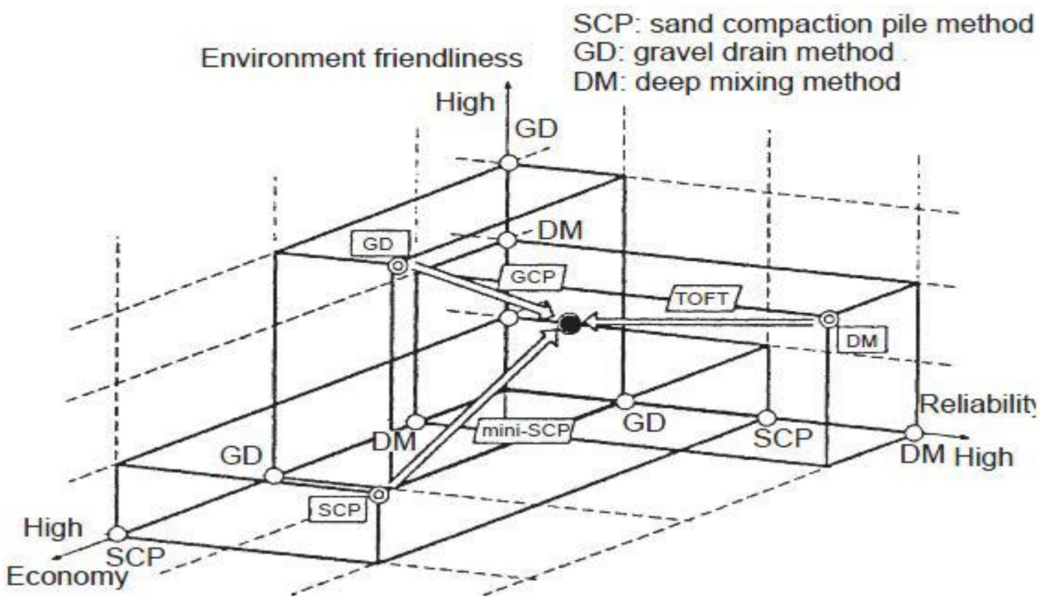


Figure 2.7 Performance of different soil improvement techniques (Ando, et al., 1995)

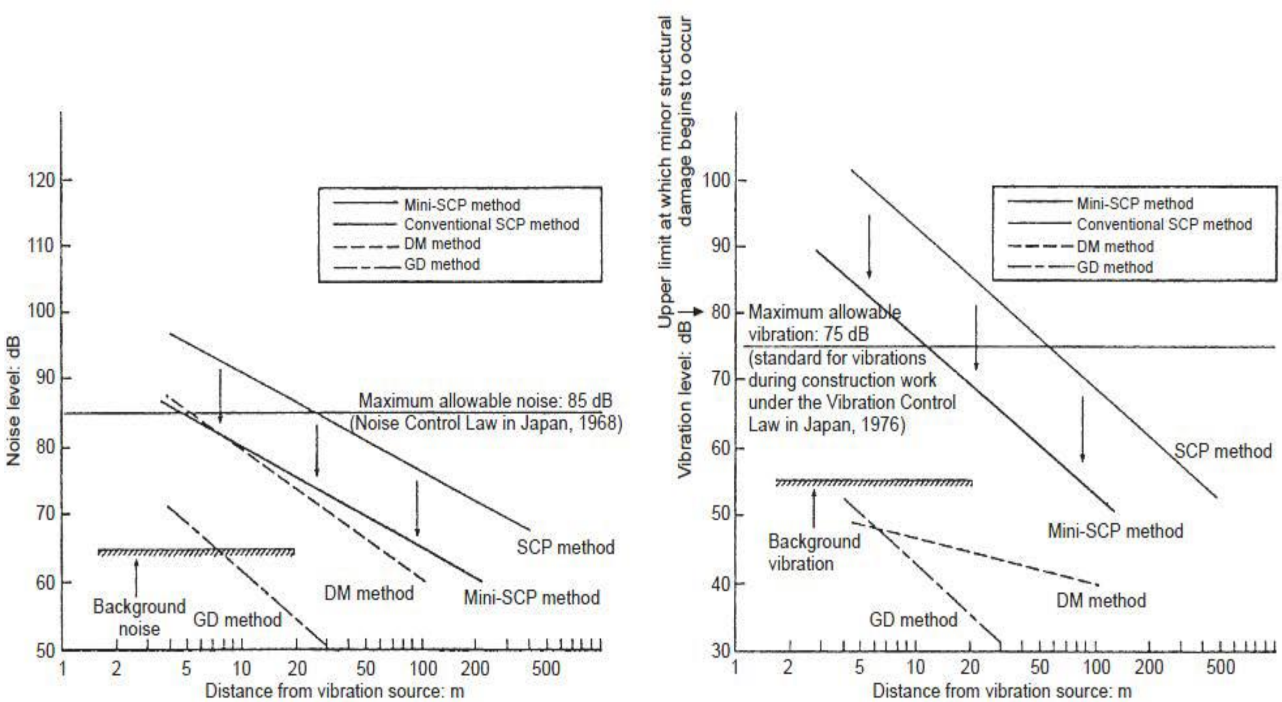


Figure 2.8 Environmental impact of various ground improvement techniques: a) noise effect, b) effect of vibration during construction (Ando, et al., 1995)

2.5. Applications

Soil mixing technology modifies the engineering properties of existing soil in defined zones such as columns, panels, and blocks. By designing engineering features and treatment patterns, SM creates subsurface soil-cement structures for a wide range of applications in civil engineering construction and environmental remediation.

2.5.1. Purposes

The major goals of SM method improvement are to increase strength, regulate deformation, minimize permeability of loose or compressible soils, or clean contaminated areas in general (Porbaha, et al., 1998). SM technology has, however, been used for certain purposes:

- increasing bearing capacity,
- Controlling seepage and acting as a cut-off barrier,
- minimizing shear deformation,
- reducing settlement,
- preventing slide failure,
- protecting structures surrounding the excavation site (liquefaction mitigation),
- Ground anchorage,
- Vibration impediment,
- Remediation of contaminated ground,
- Increasing drivability for tunneling in soft ground,

The fact that SM techniques may be utilized on practically any type of soil, even soft rocks, is an undeniable advantage. Organic soil and sludge stabilization is also conceivable, although it is more complex due to the need for custom-tailored binders and execution processes.

2.5.2. Patterns

The mixing can be done at a 100 percent replacement ratio, which implies that the entire soil is treated by the cementitious agent and is contained within a specific block. Other types of SM elements, such as columns, walls, and grids, are employed when the replacement ratio is lower, also known as the ratio of area improvement. The chosen ratio reflects the applied method's mechanical capabilities and properties. Using spacing or overlapping, single or mixed columns, varied patterns of column installations are employed to produce the desired result depending on the purpose of SM elements, unique site circumstances, and treatment costs. To compare different column patterns in terms of treatment area, the ratio of area improvement, ap, is determined as in Equation 1, with all constants stated in Figure 2.9. (Topolnicki, 2004). Figure 2.10 shows several typical patterns.

$$ap = \frac{At}{A} = \frac{\text{net area of SM}}{respective\ total\ area} \qquad 1$$

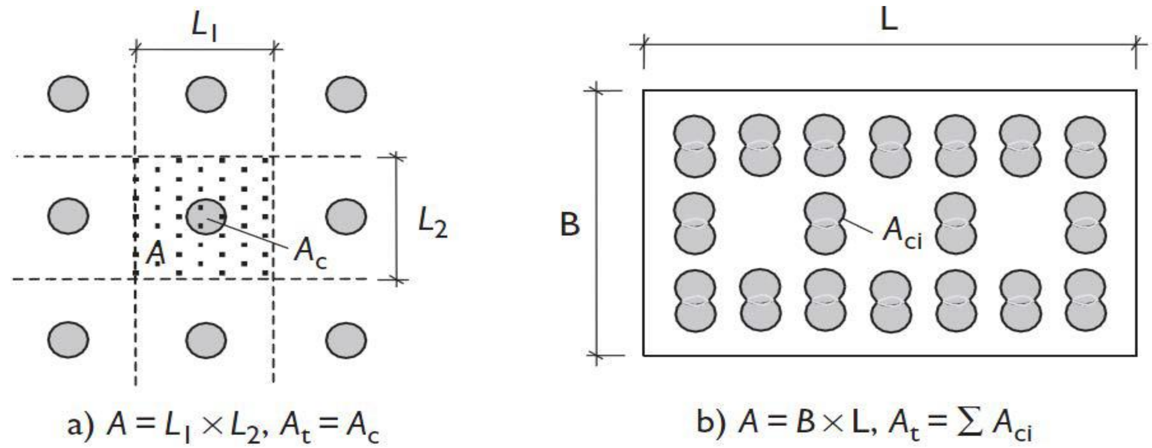


Figure 2.9 Evaluation of the ratio of area improvement for: a) regular grid of columns, b) foundation slab (Topolnicki, 2004)

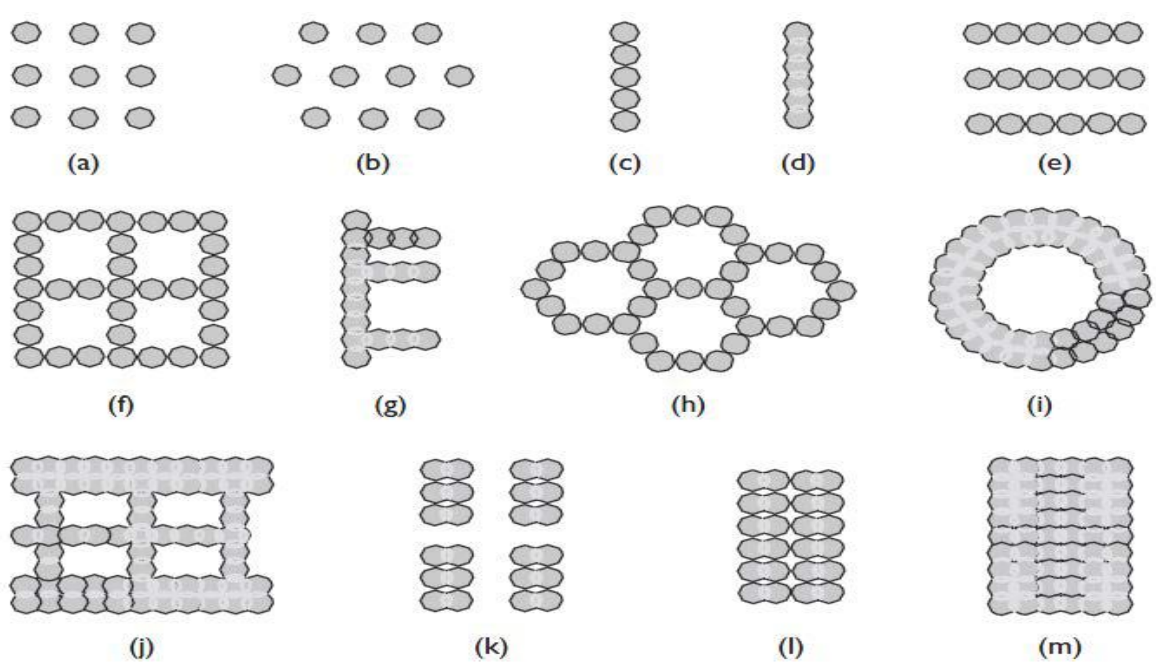


Figure 2.10 Examples of deep soil mixing patterns: a), (b) column-type (square and triangular arrangement), c) tangent wall, d) overlapped wall, e) tangent walls, f) tangent grid, g) overlapped wall with buttresses, h) tangent cells, i) ring; j) lattice, k) group columns, l) group columns in contact, m) block (Topolnicki, 2004)

2.5.3. Fields of application

Because the approach can meet cost-effectiveness standards while also being environmentally friendly, it has a wide range of applications. It should be mentioned that the SM approach is commonly used on both land and sea. The most common geotechnical and environmental applications can be divided into two types: non-structural and structural.

Porbaha et al (Porbaha, et al., 2005) categorized SM application into six main applications:

• Hydraulic barrier systems,

• Retaining wall systems,

• Foundation support systems,

• Excavation support systems,

• Liquefaction/seismic mitigation systems,

• Environmental remediation systems.

Various applications of SM methods are presented also in Figure 2.11 Figure 2.12 and Figure 2.13 illustrate some typical executions of the SM method in projects.

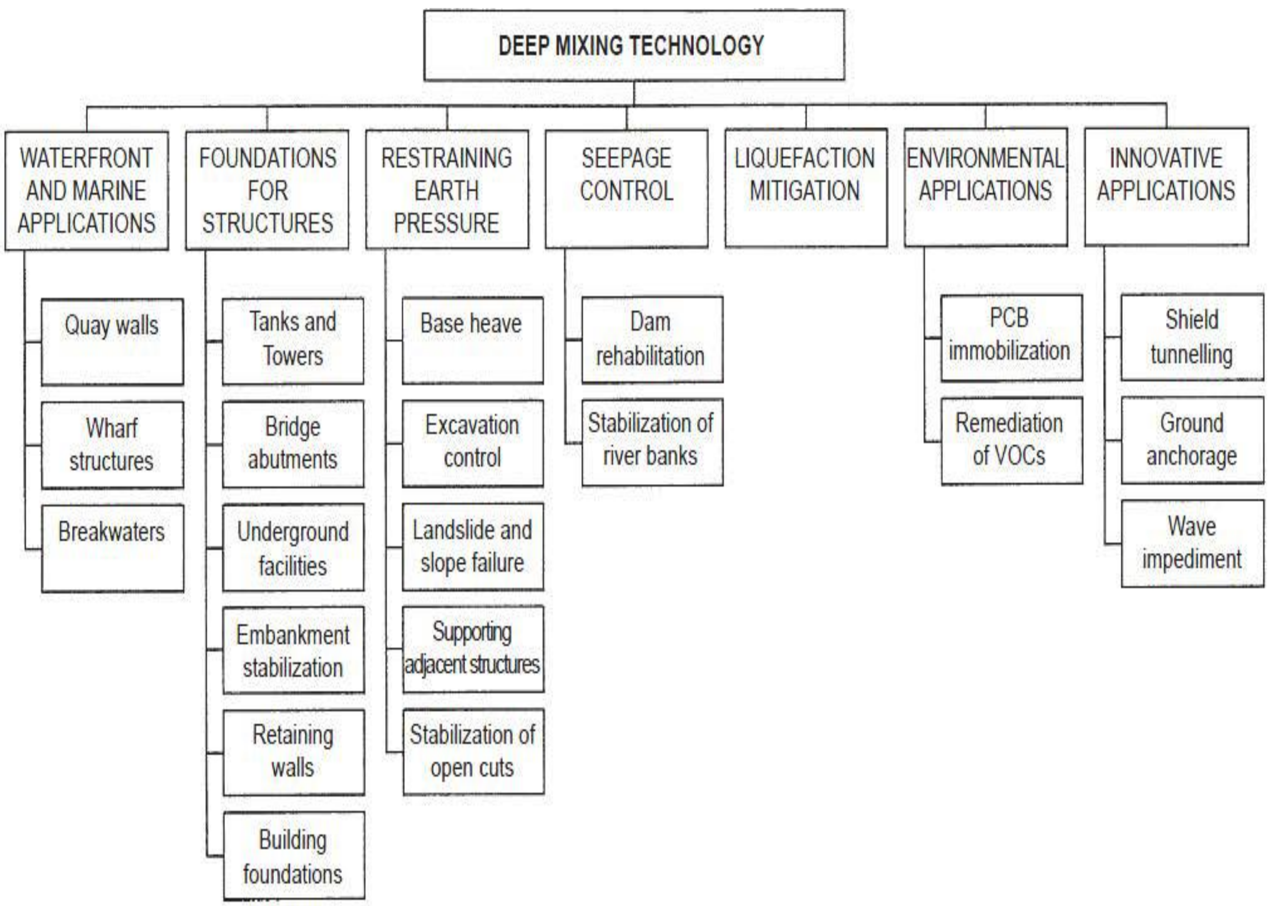


Figure 2.11 Chart of various applications of SM (Deep Mixing) technology (Porbaha, et al., 1998)

Figure 2.12 Foundation support executed by SM method. a) Railroad Bridge supported by deep mixing column at San Francisco International Airport (Porbaha, et al., 2005), b) columns under the foundation for A2 Motorway near Katowice, Poland (Massarsch & Topolnicki, 2005) [17]

Figure 2.13 Application of SM: a) under the railway track (INNOTRACK, 2009), b) under building foundation (Nozu, 2005)

2.6. Properties of the material

The sort of SM method to use is determined by the application site's features as well as the intended performance of the treated soil. Physical and chemical features of soil, such as grain size distribution, water content, mineral type, organic matter content, and cation exchange capacity, have a significant impact on the treated soil's qualities. However, in order to comprehend the impact of all of the aforementioned components, one must first comprehend the process that occurs in the SM material. In the case of treated soil, three major groups of reactions have been discovered: dehydration, ion exchange, and pozzolanic reaction (Porbaha, et al., 2000).

The dehydration process is based on the introduced agent consuming the water in the mixture. Calcium hydroxide, Ca(OH)2, is formed as a result. Calcium cations, Ca2+, are attracted to negatively charged (anions) clay particles as calcium hydroxide dissociates in water, increasing the electrolytic concentration and pH of the pore water – ions exchange (Assarson, et al., 1974).

Pozzolanic reactions are the most important for increasing the shear strength of the treated soil over time. The pozzolans (silicates and aluminates) in the clay react with calcium hydroxide in the soil water to generate binders or cementing ingredients. The strength of the SM material is determined by the binder used (cement, lime, fly ash and so on).

The unconfined compressive strength (UCS) and the modulus of elasticity are the two key metrics that are often used to assess properties of treated soils using the SM approach. As previously stated, a variety of factors influence these qualities. The most important are listed below in sections.

2.6.1. Unconfined compressive strength

The stress-strain curve of treated soil (Figure 2.14) is shown to quickly increase until the peak compressive strength qu is reached. Then, all of a sudden, it drops to a very low residual value. Because of their brittle or quasi-brittle failure modes, SM material and pure concrete can be compared.

Although this type of response to unconfined load has been observed in all documented cases, there is also a significant impact of parameters such as soil type, age, binder, cement, and water content, as well as strain at failure, on the results of the unconfined compressive strength test.

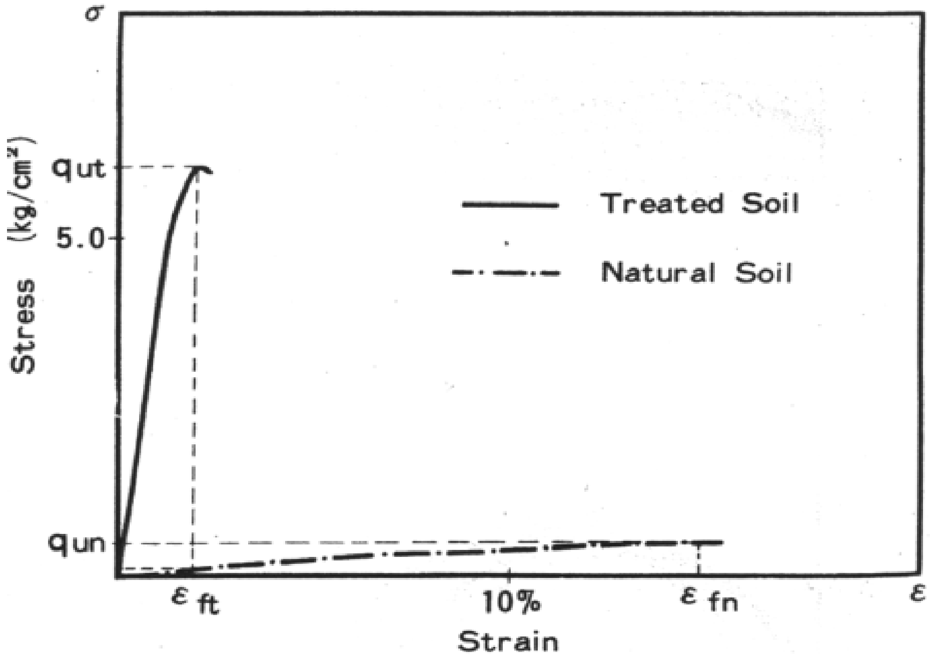


Figure 2.14 Typical stress-strain curve of cemented soil (Endo, 1976)

2.6.2. Soil type

The final strength of the SM material is influenced by the physical and chemical qualities of the soil. Due to poorly defined crystallinity, Hilt and Davidson (Hilt & Davidson, 1960) [18] and Wissa, et al. (Wissa, et al., 1965) found that clays containing montmorillonite and kaolinite minerals react more easily than illite. Furthermore, when compared to illite-containing clays, they were found to be potent pozzolanic agents. It has been demonstrated that as the amount of clay in the soil increases, so does the amount of the needed stabilizing reagent. The increase in surface area and particle interaction, according to Bell (Bell, 1993), explains this. Kawasaki, cement-soil mixture compressive strength as a function of cement content (Figure 2.15). Figure 2.16 depicts the effect of soil particle size on the unconfined compressive strength of SM material, as measured by Taki and Yang with high cement content (Taki & Yang, 1991). Some issues have been recorded in the case of soils with a high level of organic matter and soils with an excessive salt content, both of which can slow the cement's hydration. Increased cement content was proposed as a remedy (Porbaha, et al., 2000).

It has been discovered that SM material prepared in the laboratory with the same soil, water, and cement content as that acquired in the field behaves differently. Material mixed in situ has a lower unconfined compressive strength than material mixed in a laboratory. The laboratory strength looks to be 50 percent to 20% of field strength, according to research. It can be explained by Tang, et alsize .'s influence on maximum aggregates (Tang, et al., 2011). After Topolnicki, Table 2.1 shows typical field strength for a variety of cement content and soil types (Topolnicki, 2004).

Table 2.1 Typical field strength for ranges of cement contents and soil types (Topolnicki, 2004)

Soil type	Cement ratio [kg/m3]	q_u after 28 days [MPa]
Sludge	200 – 400	0.1 – 0.4
Peat, organic silts/clays	150 – 350	0.2 – 1.2
Soft clays	150 – 300	0.5 – 1.7
Medium/hard clays	120 – 300	0.7 – 2.5
Silts and silty sands	120 – 300	1.0 – 3.0
Fine-medium sands	120 – 300	1.5 – 5.0
Coarse sands and gravels	120 – 250	3.0 – 7.0

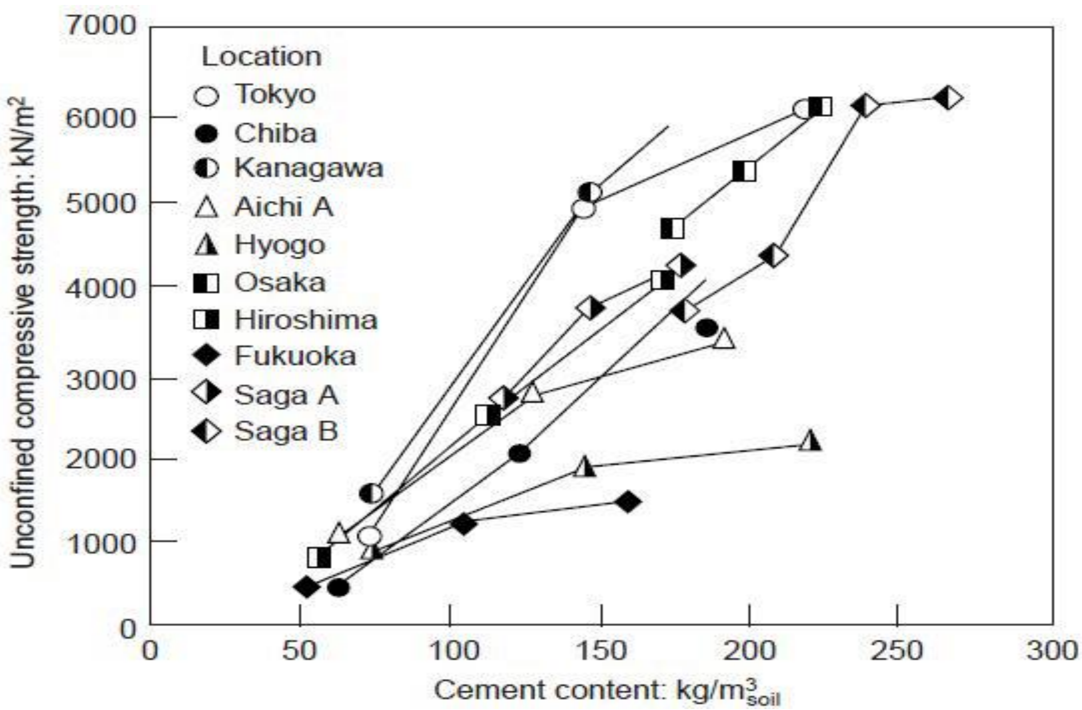


Figure 2.15 Stabilization of different soils in Japan (Kawasaki, et al., 1981)

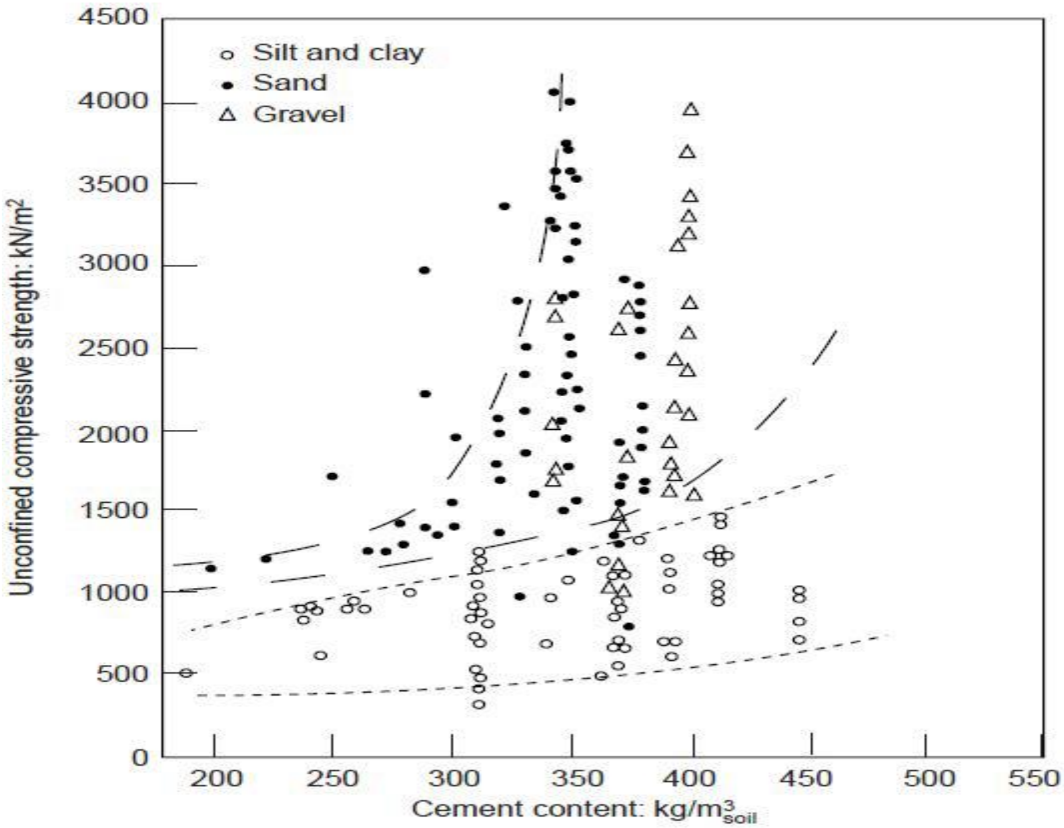


Figure 2.16 Effect of soil type on compressive strength of cement-soil mixture (Taki & Yang, 1991)

2.6.3. Binder

In recent years, the significance of the binder and its contents has been extensively researched. Other compounds, in addition to various types of cement, can be used to stabilize soils. Can be utilized as cement substitutes (alone or in combination with cement) with a substantial impact on all properties of the SM material (Topolnicki, 2004):

• Bentonite. It improves stability of slurries with high water – cement ratios, furthermore, reduces material permeability,

• Slag. It improves chemical stability and durability, however retards strength gain,

• Kiln dust. This kind of binder is used mainly in environmental applications,

• Fly ash. It increases chemical durability and reduces heat being result of hydration,

• Lime and gypsum. They are used when relatively low strength of the material is needed,

• Silicates, polymers, etc. They are used in special environmental applications.

In Japan, Kawasaki et al. (Kawasaki et al., 1981) looked at the differences between slag and Portland cements for two different clays (Figure 2.17). Figures obtained by them reveal that the improving effect of slag cement varies depending on the soil type. The reason for this is that, as previously stated, various chemical reactions occur during the hardening of stabilized soil. As a result, the response to slag cement stabilization is not uniform, indicating that the improving impact does not follow a general pattern. Essentially, the effect is determined by the chemical components of the slag cement as well as the soil qualities in the area (Porbaha, et al., 2000). It can be inferred that in each situation, the improvement effect must be verified using laboratory tests. Ahnberg, et al. (Ahnberg, et al., 1995) [19] investigated the effects of various stabilizing agents such as cement, lime, and fly ash. Figure 1.18 shows a comparison of the effects of cement, lime, and a cement-lime mixture on SM material in different Swedish soils.

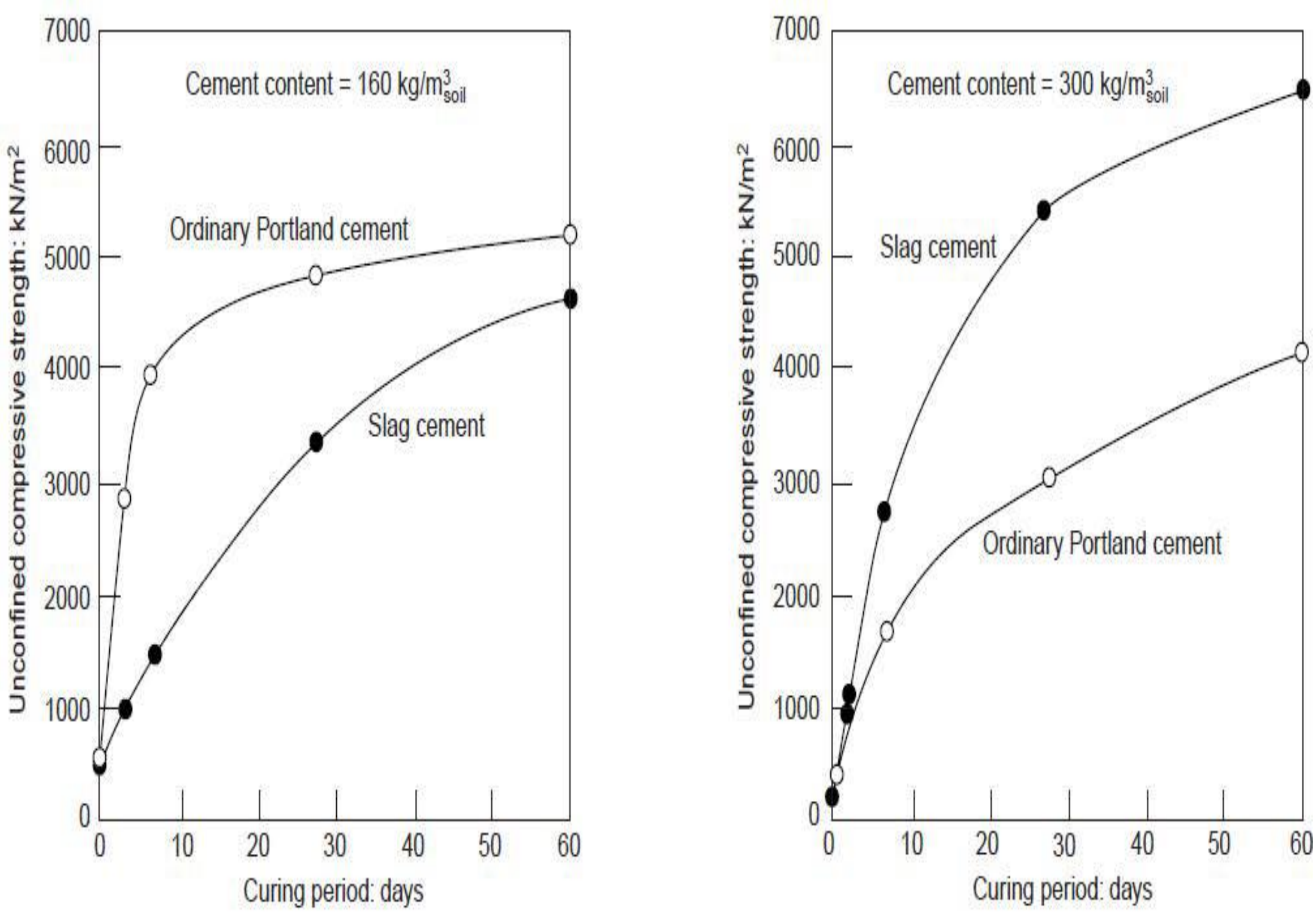


Figure 2.17 Effect of cement type on UCS of SM: a) Kanagawa in the Tokyo Bay area soil mixed with two kinds of cement - cement content 160 kg/m3, b) Saga in Kyushu Island soil mixed with two kinds of cement - cement content 300 kg/m3 (Kawasaki, et al., 1981)

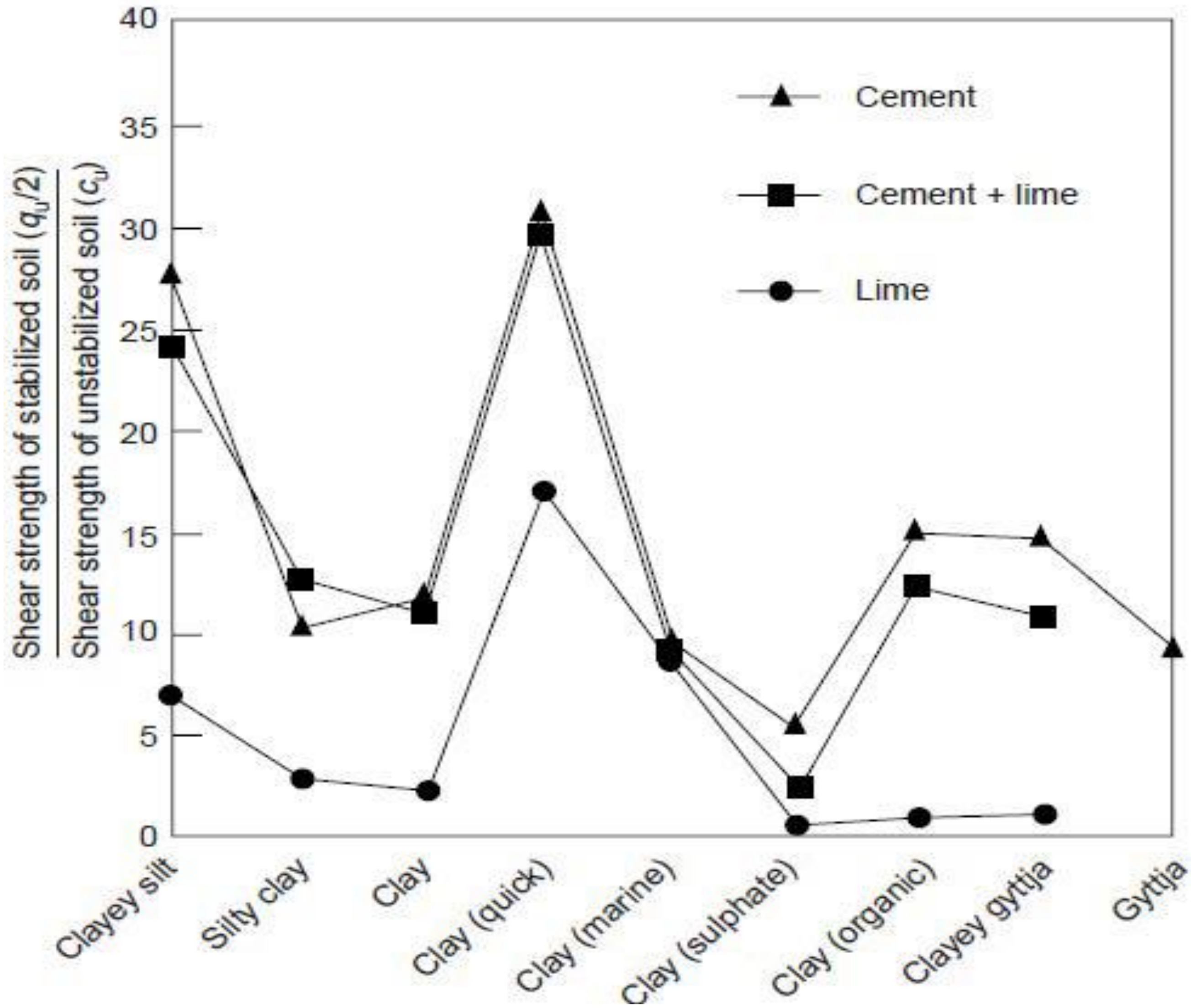


Figure 2.18 Effect of different stabilizers on compressive strength of soil in Sweden (Ahnberg, et al., 1995) [20]

As it was mentioned in case of influence of soil type, the increase of the quantity of the stabilizing agent, rise of the compressive strength can be expected. Figure 2.19 depicts results obtained by Uddin, et al. (Uddin, et al., 1997) from investigations concerning Bangkok clay. They analyzed influence of the Cement content on the strength development index (SDI), which is defined as the strength ratio of treated to untreated samples obtained by the unconfined compression test.

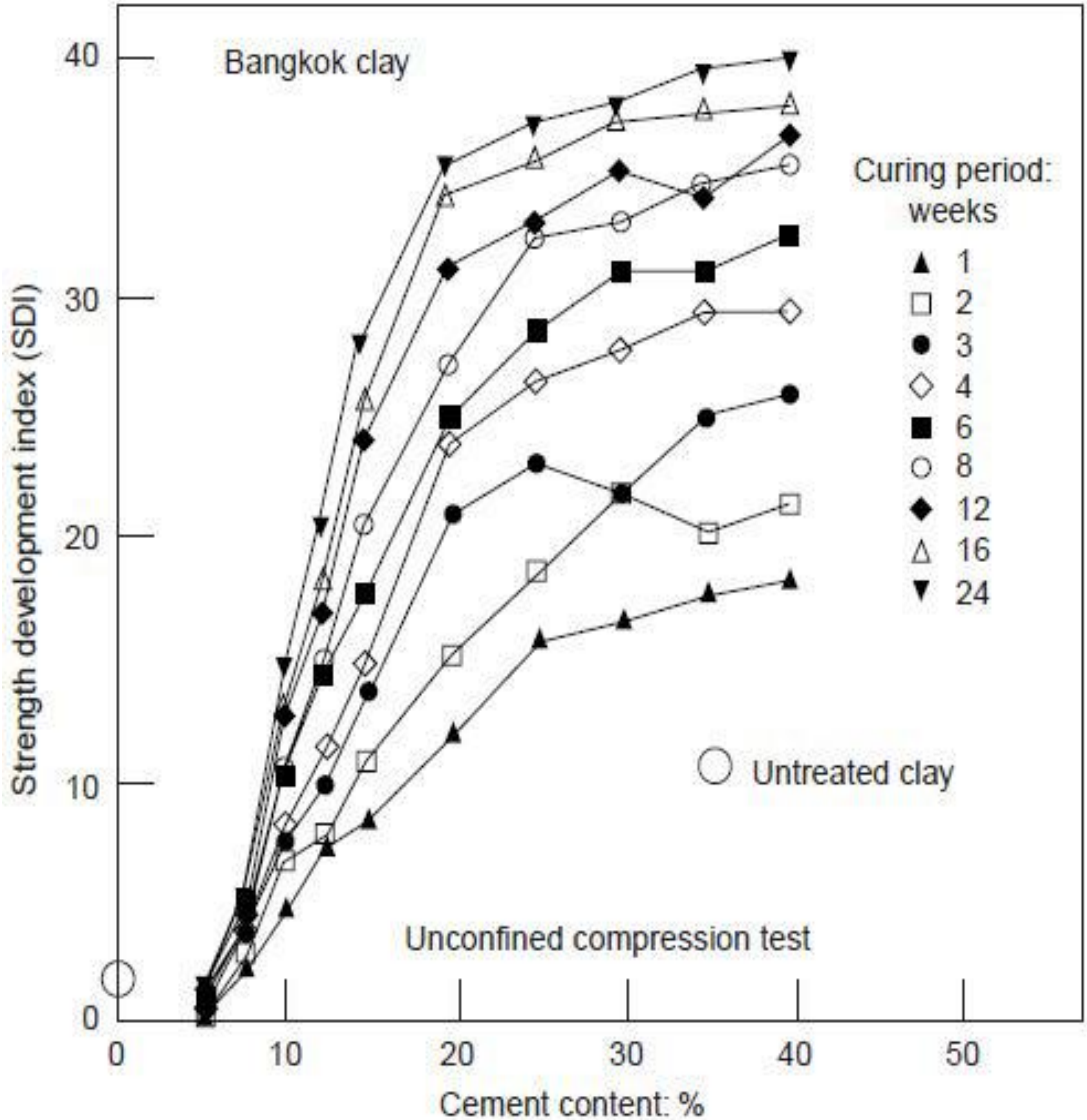


Figure 2.19 Effect of cement content on compressive strength of SM material (Uddin, et al., 1997)

2.7. Failure modes and design of the Soil Mixing

- **Modes of failure**

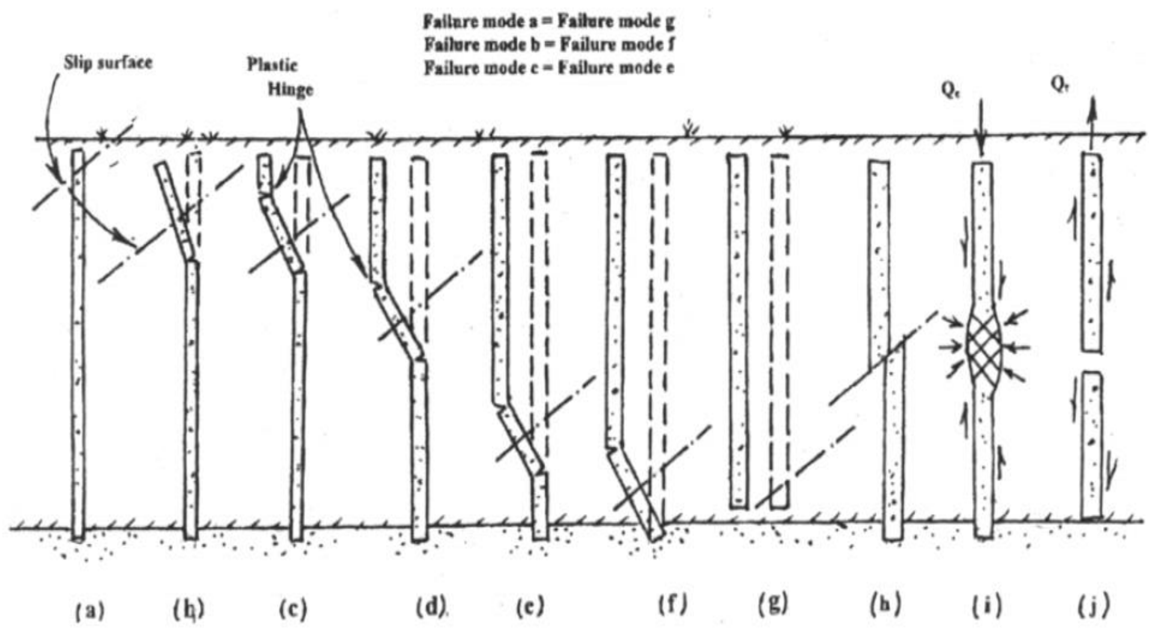


Figure 2.20 Possible failure modes for single columns (Broms, 2000)

2.7.1. Single column

Broms (Broms, 2000) [21] reported ten possible modes of failure for a single SM column (Figure 2.20). Each mode can be described (Fang, 2006) [22]:

• Type a - a shallow slip, sufficient moment capability to resist the lateral earth pressure depending on the relative displacement,

• Type b - a deeper slip, plastic hinge at the location of the maximum bending moment, moment resistance exceeded,

• Types c, d, e - two plastic hinges, moment resistance exceeded,

• Type f - extension to the firm layer, deep slip closed to the bottom,

• Type g - extension to the firm layer, deep slip closed to the bottom, moving through the soil as a rigid member,

• Type h - governed by the shear resistance of the column section,

• Type i - compression failure, governed by the load carried,

• Type j - passive zone, dominated by tensile strength.

2.7.2. Design considerations

In general, soil mixing project design progresses through the following steps:

1. Determine project needs.

2. Translate project needs into target design parameters.

3. Select addition rates for reagent(s) needed to achieve target design parameters.
4. Develop construction objectives to achieve objectives in (2) and (3).
5. Evaluate construction objectives for overall compliance with the needs identified in Step (1).

Soil mixing design frequently necessitates the involvement of a specialty designer and/or construction team in the design process or a design-build project approach due to the specialty nature of soil mixing and the relative inexperience of the majority of general design practitioners and contractors. A construction team may be hired to assist with target parameter selection in step 2 or will almost likely be involved by stages 3 or 4 if the project is approached in a design-bid-build way. The sections that follow deconstruct the design process for soil mixing projects in greater depth, highlighting key factors.

2.7.2.1. Determine project needs

The principles and procedures for determining project needs for soil mixing projects are the same as for any other subsurface construction project, but they differ depending on whether the site objectives are strictly geotechnical, environmental, or geoenvironmental concerns, or if there are cross-disciplinary objectives. The methodologies and fundamentals for ground improvement design presented in Chapter 2 should also be applied in the early stages of soil mixing projects. The following are some specific items to consider at this stage of a soil mixing project:

1. What kind of soil mixing can/should be employed to achieve the site's overall goal(s)?
Given the specialized nature of soil mixing and the nuances connected with various construction methods, it's critical to think about the projected construction approach early in the project to develop a design that works with it. On the other hand, maintaining design flexibility for construction team optimization during the bid stage is critical to avoid extra construction expenses associated with an overly tight design.

2. Are there other methods that are or could be more cost-effective?

3. What elements of the site will influence building costs, and are there any methods to cut costs or shorten the timeline by modifying the design? The existence of difficult strata (e.g. organics), site logistical limits (space), and underground/overhead impediments or utilities must all be considered.

2.7.7.2. Select target design parameters

The objectives must be turned into quantifiable characteristics once the project objectives have been clearly specified and one or more soil mixing construction approaches capable of achieving the objectives have been found. Strength and permeability are the most often examined criteria for geotechnical soil mixing projects, while the elastic modulus and/or Poisson's ratio may be required for higher-level designs (not covered here). The most typical characteristics for environmental projects are strength, permeability, and leachability. Other characteristics in both applications could include freeze/thaw or wet/dry durability, as well as seismic performance (shear wave velocity, dynamic strength performance).

2.7.2.3. Reagent addition rates

The reagent selection process can begin after the intended objectives have been transformed into measurable metrics. The results of a bench-scale investigation employing site soil samples are used to determine which reagents to use for soil mixing. Despite the fact that experienced industry practitioners will have a good idea of the type and quantity of reagents required to produce the desired results, a bench-scale investigation will usually always be required to confirm and refine initial assumptions. When compared to the expense of re-treating soils that do not match the goal parameters or over-treating due to conservative assumptions, the cost of determining and optimizing the reagent addition rate is low. Bench-scale soil mixing experiments should be carried out by a qualified laboratory or construction team.

2.7.2.4. Reagent (binder) types and selection

For soil mixing, a variety of chemicals are utilized. The location of the project site, the soil types, the target objectives, the presence and kind of contaminants, engineer/contractor choice, and the soil mixing construction method all influence reagent selection. The location of the project site has a variety of effects on reagent selection, mostly because some reagents may not be cost-effective due to the cost of materials in that place. Because different reagents have differing efficacy in different soils, soil type influences reagent selection. When sulfate attack is a possibility, there is a high level of contamination, or organic components are present, slag is typically added to mixtures. Because different reagents are required to achieve varied soil mixing target objectives, target objectives play an important role in reagent selection. For example, an environmental remediation project with a gross contaminant mass destruction goal would include the use of an oxidizing or reducing agent, whereas a project with a leachability reduction goal might merely necessitate the use of a binding agent like PC. Contaminants can influence reagent selection in two ways: (1) certain reagents function better in the presence of particular contaminants than others, and (2) contaminants can delay or retard the set time of binding agents, resulting in the selection of other reagents or greater addition rates. Table 2.2 (following Andromalos et al. 2012, with data from ITRC 2011; Gardner et al. 1998; Irene 1996; USEPA 2009; US Department of Defense 2000; UK Environmental Agency 2004; Raj et al. 2005; Conner 1990) lists the various reagents used in ISS and IST.

Contractors and engineers in the soil mixing sector rely substantially on their knowledge of reagent selection. Even if superior reagent combinations are available, this may inherently bias these practitioners toward reagents with which they are familiar. In a variety of ways, the expected construction process can influence reagent selection. Binding agents for wet mixing include PC, bentonite, slag cement, fly-ash, lime, gypsum, sand, and kiln dust. The grout or slurry in these applications can be created by mixing the ingredients with water. The reagent selection will also be influenced by the kind and quality of water. To improve the qualities of the soil in need of improvement, many combinations and amounts of each of these binders are used. A combination of cement, lime, or lime plus cement is commonly used for dry mixing. Although PC is the most frequent binder, mixes can contain up to 50% quicklime. Other binders, including as slag, gypsum, and proprietary materials, have been employed where importing lime is too expensive. Dry mixing is commonly used to treat materials that are fairly soft, compressible, or liquefiable and have high moisture content (60 percent to 200 percent) and high organic content. "Other binders," such as slag in combination with cement, have grown more common in usage in Sweden in the twenty-first century, primarily to stabilize organic soils (Ahnberg 2006).

Table 2.3 shows the relative effectiveness (poor, fair, or good) of various binder reagents in cohesive and organic soils based primarily on European soil mixing experience, predominantly in Sweden (modified after Guide 2010).

Experience, stoichiometric calculations (if applicable), a thorough bench-scale investigation, and, if practicable, a field-scale pilot test should all be used to determine reagent selection and addition rate. If a pilot test is too expensive, a test section may be the best option. A bench-scale study in a laboratory should be completed long before the field application, a field-level pilot test utilizing full-scale equipment at the project site should be completed long before the actual work begins, and a test section should be completed just before the actual work begins. Bench-scale studies are always recommended for soil mixing projects because the expense of conducting one is negligible compared to the potential reagent cost reductions, particularly for expensive reducing or oxidizing chemicals. Pilot tests allow for a more in-depth review of bench-scale study results in real-world settings, but they are usually only warranted or possible for very big projects. Full-scale examination of the reagent type and addition rate is possible with test sections.

Table 2.2 Example ISS and IST reagents

ISS or IST	Reagent	COCs* Effectively Stabilized or Treated	Underlying Process
ISS	Portland cement	Numerous, MGP**	Binding
		waste, gasoline, and	
	Blast furnace slag	diesel range organics,	Binding
		metals	
		Numerous, MGP	
		waste, gasoline, and	
	Flyash	diesel range organics	Binding
		Metals, organics, and	
	Cement kiln dust	inorganics	Binding
		Metals	
	Activated carbon	Organics, phenolic	Adsorption
		waste	
	Bentonite clay	Organics	Adsorption
	Organophillic clay	Phenolic waste,	Adsorption
		organics	
	Attapulgite clay	Acids waste, metals	Adsorption
	Lime	Inorganics, metals	Binding
IST	Zero valent iron	TCE, arsenic	Reduction
	Potassium	TCE, acetone,	Oxidation
	permanganate	pesticides, VOCs***	
		TCE, acetone,	
	Sodium persulfate	pesticides, VOCs	Oxidation
		TCE, acetone,	
	Ferrous sulfate	pesticides, VOCs	Oxidation
		Chromium	
	Calcium polysulfide	Acetone, pesticides	Reduction

*COC – contaminant of concern

**MGP – manufactured gas plant

***VOCs – volatile organic compounds

2.7.2.5. Develop and evaluate construction objectives

All of this information must be converted into contract agreements for construction after the target parameters have been selected and the reagent dosages required to attain the goal parameters have been calculated. A scope of work (SOW), a general memorandum detailing the key objectives, or a comprehensive specification are all examples of contract documents. Regardless of the document's format, it must offer enough flexibility for the construction team to optimize and adapt the design to their specific equipment. The SOW or general technical memoranda are good examples of looser work plans that allow for construction team optimization. Specifications are more stringent in general, but they can be developed with flexibility in mind. Plans or drawings depicting site features in relation to the intended soil mixing area are other important documents generated at this stage. The user should be able to determine the extent of the work in all dimensions using plan and section view drawings. The display of generalized or specialized cross-sections in section view drawings allows for the establishment of broad baseline soil conditions. All prior target characteristics must be translated into quantifiable and measurable objectives that all stakeholders can understand and use to evaluate the building activity at this stage of the project. Experience and expertise of the construction process are required to ensure that construction objectives match this requirement. The construction team may be able to assist with the final specifics of the job, which would then be documented in a thorough set of plan documents or a work plan generated by the construction team. This plan would explain every component of the construction so that all stakeholders may assess the proposed work method and processes prior to the start of the project. The designer, owner, and, if applicable, the construction manager normally evaluates and accept this plan.

To assess the construction project. Experience and expertise of the construction process are required to ensure that construction objectives match this requirement. The construction team may be able to assist with the final specifics of the job, which would then be documented in a thorough set of plan documents or a work plan generated by the construction team. This plan would explain every component of the construction so that all stakeholders may assess the proposed work method and processes prior to the start of the project. The designer, owner, and, if applicable, the construction manager normally evaluates and accept this plan. Once the construction objectives have been defined, they should be compared to the initial project requirements stated in Step 1 of the design process to confirm that these requirements are being satisfied, and that none of the original requirements have been lost as the design advanced. This final stage may also include a review of construction team submittals that are, or will be, included in the contract documents, depending on the style and structure of the blueprints describing the construction objectives.

Table 2.3 Binder effectiveness in cohesive and organic soils

	Soil Type / Organic Content	Silt 0–2%	Clay 0–2%	Organic Soils 2–30%	Peat 50–100%
Binder Type	Cement	Good	Fair	Fair	Good
	Cement/ gypsum	Fair	Fair	Good	Good
	Cement and slag	Good	Good	Good	Good
	Lime				
	Lime and cement	Poor	Good	Poor	Poor
	Lime and gypsum	Good	Good	Fair	Poor
	Lime and slag	Good	Good	Good	Poor
	Lime and gypsum and slag	Fair	Fair	Fair	Poor
	Lime and gypsum	Good	Good	Good	Poor
	and cement	Good	Good	Good	Poor

to assess the construction project Experience and expertise of the construction process are required to ensure that construction objectives match this requirement. The construction team may be able to assist with the final specifics of the job, which would then be documented in a thorough set of plan documents or a work plan generated by the construction team. This plan would explain every component of the construction so that all stakeholders may assess the proposed work method and processes prior to the start of the project. The designer, owner, and, if applicable, the construction manager normally evaluates and accept this plan. Once the construction objectives have been defined, they should be compared to the initial project requirements stated in Step 1 of the design process to confirm that these requirements are being satisfied, and that none of the original requirements have been lost as the design advanced. Depending on the style and structure of the blueprints that define the project's goals, a review of construction team submittals that are or will be included in the contract documents may also be included in this final step.

2.7.3. Construction

Earlier in this chapter, under definitions, categories, and classifications, an overview of the numerous tools and construction methods was presented. Construction of soil mixing can be done with a range of various equipment types, each with its own set of features. Designers and construction teams who work on soil mixing projects on a regular basis are familiar with the intrinsic characteristics of each approach and should be consulted before choosing a construction method for a project. The most important message is that soil mixing construction should only be done by expert construction teams using designs provided by experienced designers. If less experienced construction teams are chosen, the job they do should be scrutinized more closely.

Dry addition or a water-based slurry/grout are the most common methods for introducing reagents to the soil. Dry reagent addition can be achieved either direct application of the dry binder on the ground surface or pneumatic transport through the mixing shaft, depending on the soil mixing strategy. Dry reagent addition at the ground surface results in limited quality control for most soil mixing building procedures and should be reserved for very shallow applications. Pneumatically transferring dry reagent particles from a storage vessel, through the mixing shaft, and out ports on the mixing tool head is how dry reagent is added through the mixing shaft. Soil mixing in high moisture content soils is especially well adapted to dry reagent addition. Reagent addition can also be done with a slurry or grout, which is referred to as "wet binder addition." Reagents are commonly combined with water in a water to solids (W:S) weight to weight ratio ranging from 0.8 to 2 in this method. Lower W: S ratios will often result in stronger strength and lower permeability soil-grout mixes at the same overall reagent addition rate as a function of soil weight. Higher W: S ratios, on the other hand, may be required to obtain the desired level of mixing homogeneity.

The quality control (QC) program for a soil mixing project should be tailored to the construction method chosen, and should include a mix of process controls with immediate feedback, quality control testing of input materials, laboratory tests on "grab" samples of the mixed material collected in the field, and in situ tests when possible. The process controls will provide rapid input that can be utilized to anticipate long-term performance and to ensure that the field operations are creating a mixture that matches the bench-scale study and/or design.

The construction team uses process controls, such as QC tests and documentation procedures, to monitor the soil mixing process in real time. These operations usually start with the preparation of the reagent slurry and end with the transport of the reagent slurry into the soil mass. The procedures used to control and document the volume or weight of each reagent in each unit volume of slurry, the volume of slurry added to each unit volume of soil, and the distribution of slurry in the mixed soil are all examples of process controls.

2.8. Numerical modelling of the Soil Mixing

There hasn't been a dedicated algorithm for engineers who want to calculate SM elements before now. Despite the fact that Porbaha (Porbaha, 2000) and Topolnicki (Topolnicki, 2004) provide some basic guidelines and examples of technique applications, they insist on field loading tests. Unfortunately, these types of measurements drive up project expenses dramatically. In this case, a numerical technique can be a useful addition, since it can reduce the number of loading tests to a bare minimum.

Many experiments have been carried out to see how soil treated with the SM technique behaves. The finite element method (FEM) and the finite difference technique are the two most prominent methods of analysis employed by researchers (FDM). Both are extremely powerful numerical approaches that are commonly used to solve a wide range of engineering issues.

2.8.1. Softwares

Numerical approaches, particularly FEM and FDM, are being used to examine a variety of soil mechanics problems. In investigations of SM elements, both commercial and in-house software systems are used:

- PLAXIS and PLAXIS 3D (FEM)
- FLAC and FLAC 3D (FDM)
- CESAR-LCPC (FEM)
- ABAQUS (FEM)
- GEFDyn (FEM), (Cuira, et al., 2013).

2.9. Conclusion

In this section the basic notions of the Soil Mixing technique along with its characteristics, properties, applications and failures were presented.

This method has a lot of advantages especially when applied to soft clays, and it is one of the best solutions to improve the soil properties to the maximum potentials possible.

CHAPTER III NUMERIC AL ANALYSIS

3. Introduction

In this chapter the simulation of the model of voottipruex et al., 2019 which was done in Bangkok, Thailand, to study the performances of DCM walls under deep excavation in soft clay is presented with the procedures in details using PLAXIS 2020 software is presented, and on the final part the comparison of the obtained results from the simulation with voottipruex results is investigated to assure that the next chapter (parametric study) is based on real and verified results.

3.1. DCM column

3.1.1. Geometry

This model is 10 m wide and 20 m long with 3 layers of soils, the column is 0.6 m in diameter, 8 m in depth and placed in the center of the geometry

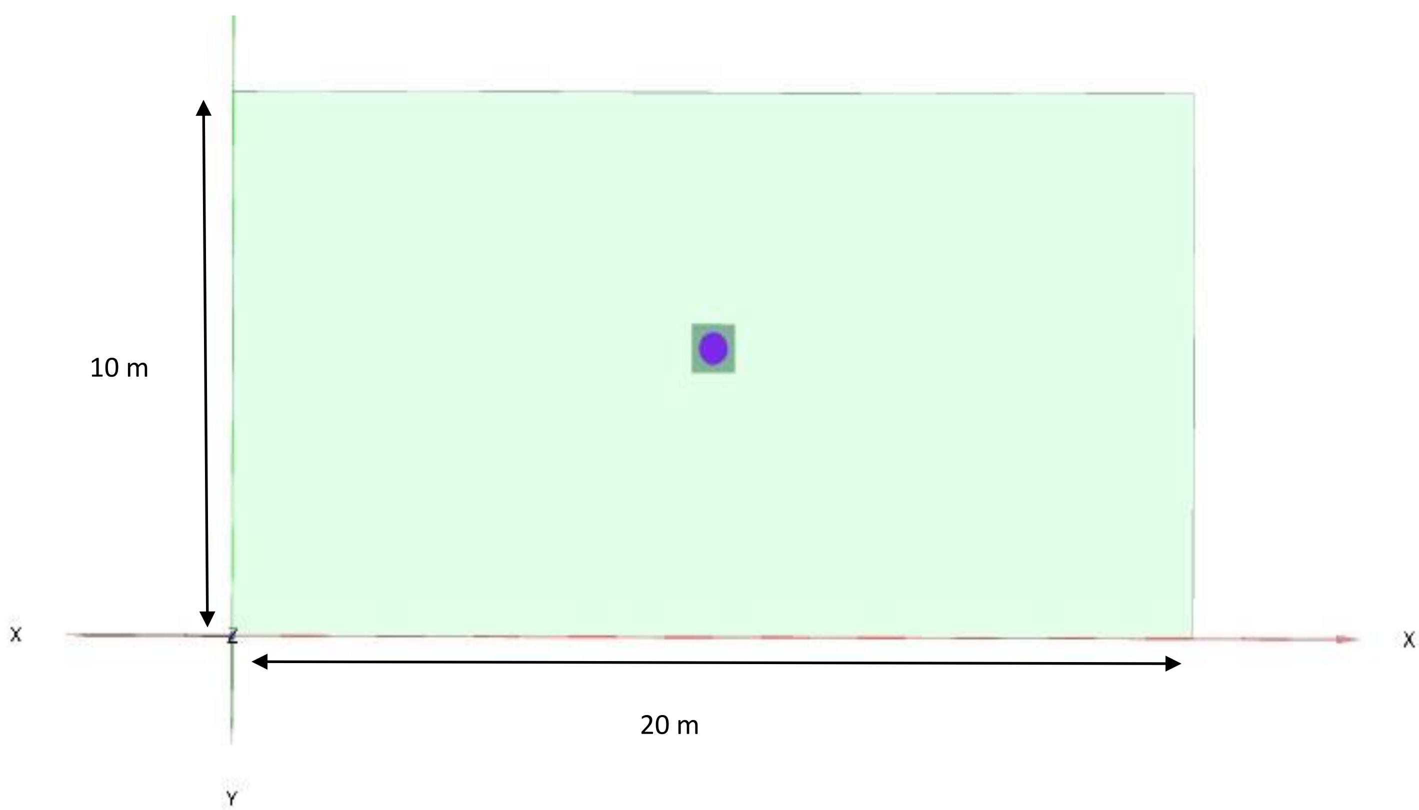


Figure 3.1 Top view of the model

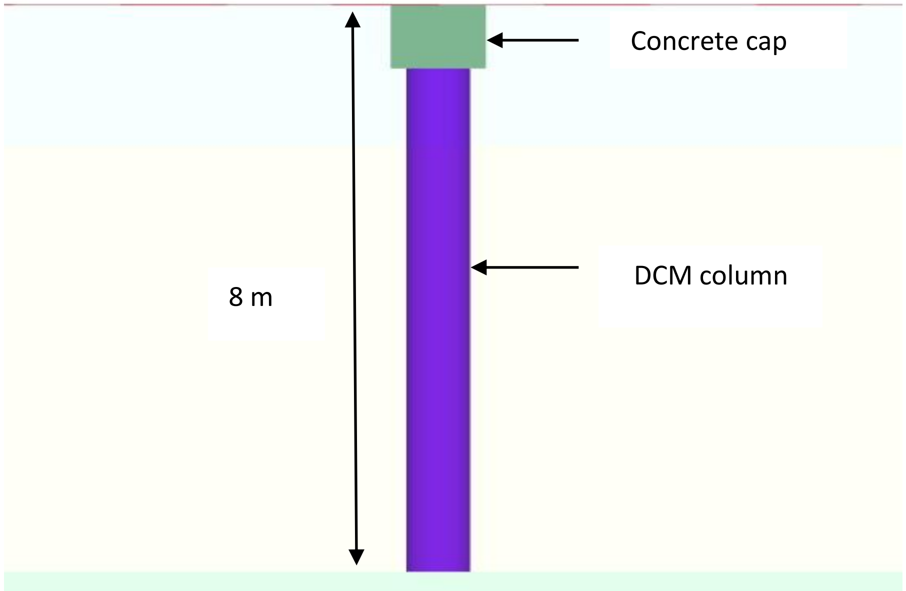


Figure 3.2 Cross section view of the DCM column

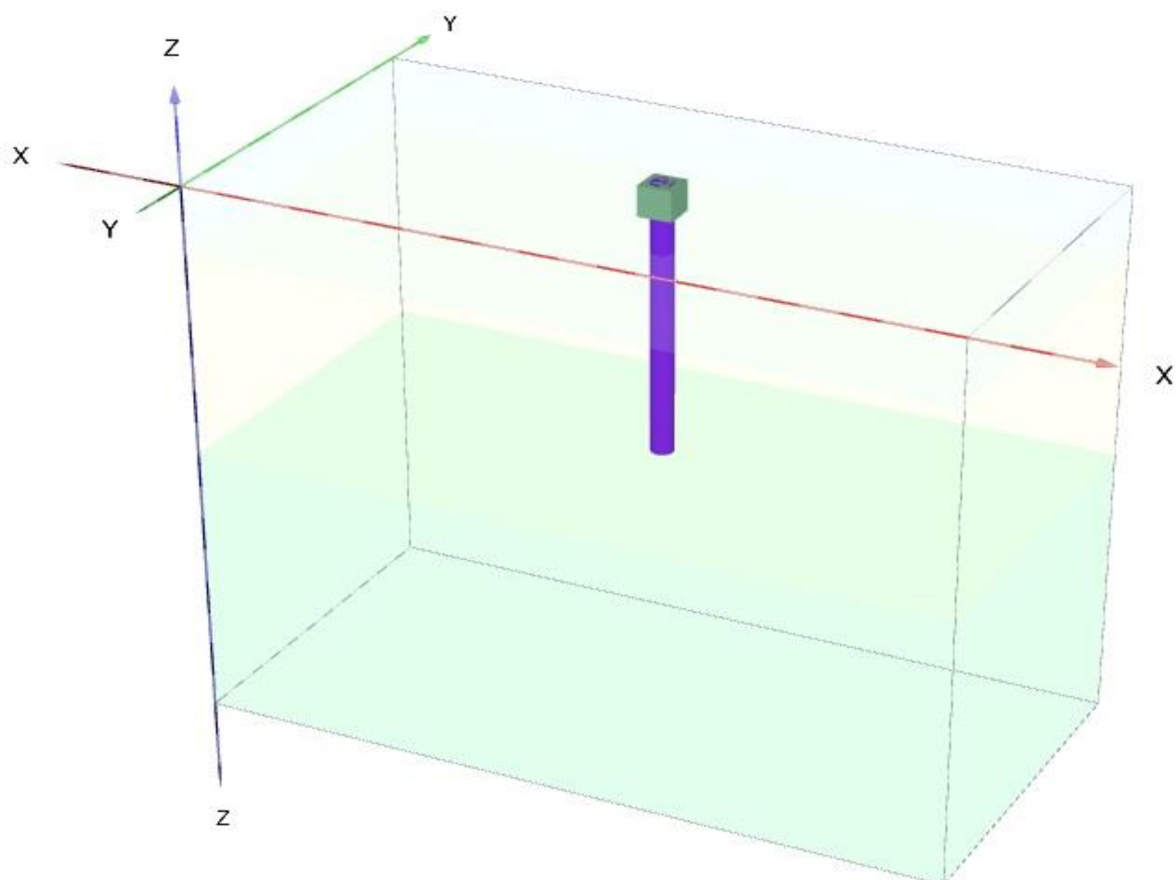


Figure 3.3 Perspective view of the DCM column

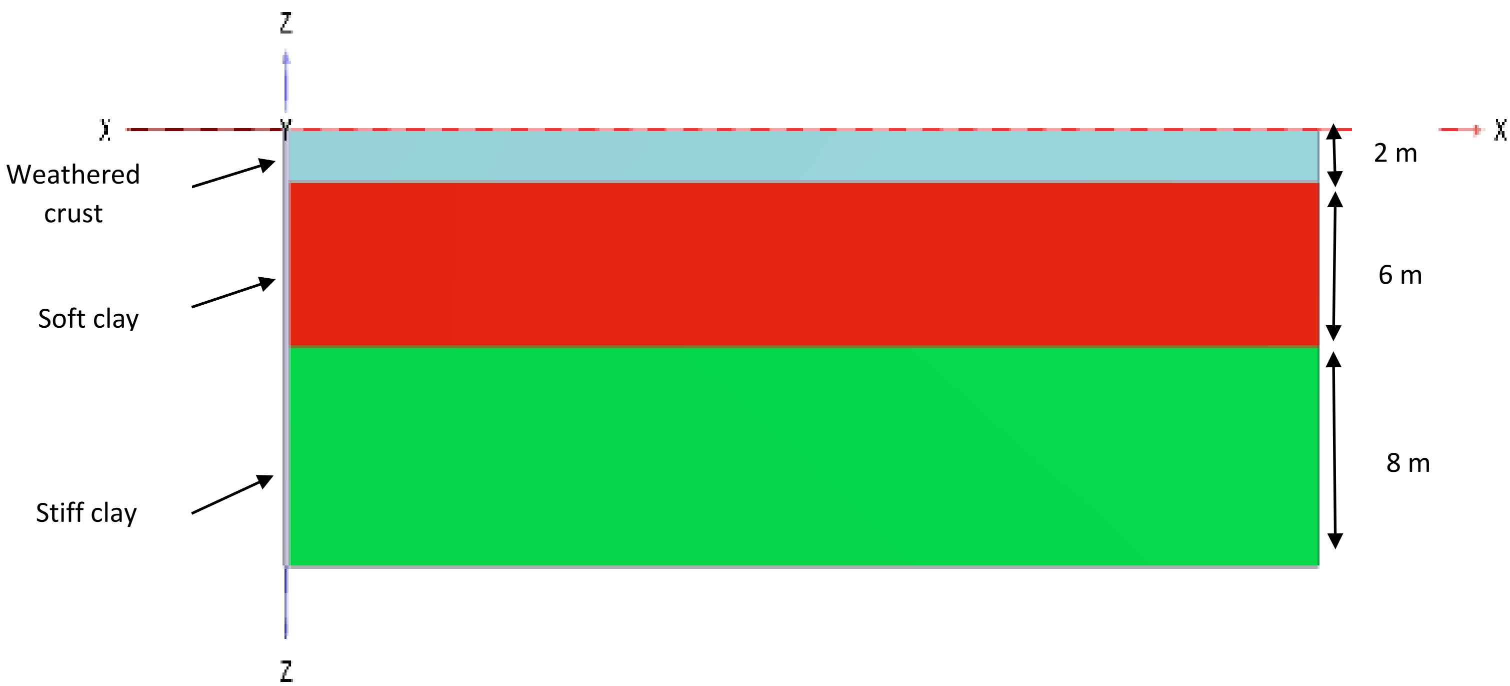


Figure 3.4 Layers stratification

3.1.2. Create new project

To create the geometry model, follow these steps:

1. Start a new project.
2. Enter an appropriate title for the project.
3. Define the limits for the soil contour as
   a. X-min = 0.0 and X-max = 20
   b. Y-min = 0.0 and Y-max = 10

3.1.3. Define the soil stratigraphy

In order to define the soil layers, a borehole needs to be added and material properties must be assigned. As all soil layers are horizontal, only a single borehole is needed.

1. Click the create borehole button and create a borehole at (0 0 0).
2. Add 3 layers with bottom levels at -2, -8, -16.
3. Set the Head in the borehole column to -16 m.

3.1.4. Create and assign the material data sets

A number of materials need to be defined for the different soil layers. The material properties are shown in the tables below.

Table 3.1: Parameters used in soft soil creep model

Parameters	Very soft clay to soft clay
Unit weight, γ (KN/m^3)	15
Modified compression index, k*	0.076
Modified swelling index, j*	0.028
Modified creep index, l*	0.007
Poisson’s ratio for unloading-reloading, Vur	0.15
Cohesion, c' (kPa)	2
Friction angle, Φ (degree)	23

Table 3.2: Parameters used in cap concrete

Parameters	Concrete
Material model	Linear elastic
Drainage type	Non-porous
Unit weight, γ (KN/m^3)	24
Young modulus E	26*10^6
Poisson’s ratio V(nu)	0.2

Table 3.3: Parameters used in Hardening soil model

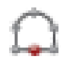
Parameters	Weathered crust	Stiff clay	DCM column
Unit weight, γ (KN/m^3)	17	20	16
Secant stiffness, E50ref (MPa)	17	20	35
Tangential stiffness, E_{oed}^{ref} (MPa)	13	25	35
Unloading and reloading stiffness, E_{ur}^{ref} (MPa)	62	95	240
Power of the stress-level dependency of the stiffness, m	1	0.9	0.4
Poisson’s ratio for unloading-reloading, Vur	0.2	0.2	0.2
Cohesion, c' (kPa)	15	30	350
Friction angle, Φ (degree)	27	23	40

1. Click the materials button  in the side toolbar.
2. Create a new data set under soil and interfaces set type.
3. Enter the specified parameters from the tables for each soil layer.
4. Click OK to close the window.
5. After closing the material sets window, click the ok button to close the modify soil layers window.
6. In the soil mode right-click each soil layer, select set material, and assign the proper materials.

3.1.5. Define the structural elements

The creation of: column, cap, point load, and the excavation area is described below.

Column

1. Select the Start designer button in the side toolbar 
2. Select Create polycurve 
3. Click on the middle of the drawing area.
4. In the General tabsheet select circular for the shape, the default orientation axes are valid.
5. In the Segments tabsheet, click on the Add segment, and set 0.3 for the radius and press ok.
6. Select the circle, left click on it and choose create then create surface 
7. Delete the circle and select the surface.
8. Click on Extrude object in the side toolbar  and select Extrude object.
9. Set the extrusion vector z to -8 m and press apply.
10. Delete the column top surface.
11. Select the column and assign the DCM column material to it.

Cap

1. Create a square surface of a 0.9 m to surround the pile top.
2. Extrude the new surface to a depth of -0.9 m.
3. Delete the top cap surface.
4. Select the cap and assign cap concrete material to it.

Point load

1. Click on create point from the side toolbar and select Create point load 
2. Place it on -0.7m from the left side of the cap top or enter its coordinates in the command line

3. In the model explorer click on point loads then click on pointload_1.
4. Enter the following values: Fx: 10 KN, Fy:0 KN, Fz: 0 KN.

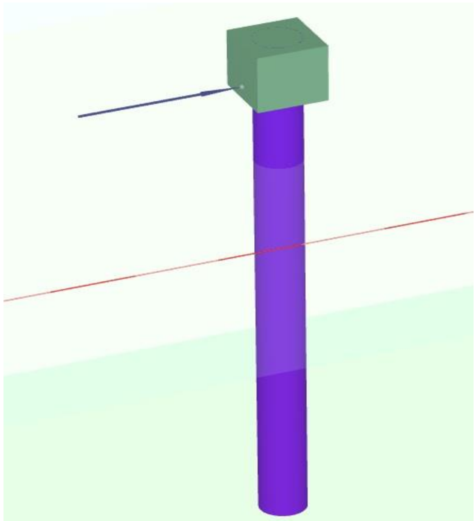


Figure 3.5 Point load modeling

Excavation volume

To be able to model the excavation in the staged construction its area must be created in Structures tab.

1. Create a trapezoidal surface with a -1 m depth and a 0.4 m space from the front side of the cap.
2. Extrude the surface with a 1.9 m in Y direction as shown in figure 3.6.
3. Delete the initial surface.

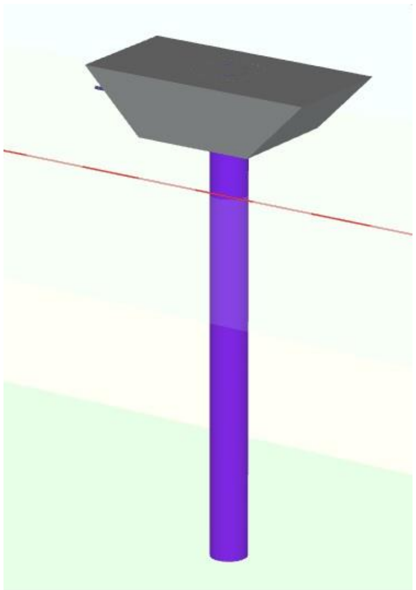


Figure 3.6 The excavation volume

3.1.6. Generate the mesh

In order to generate the mesh:

1. Click on the Mesh tab to proceed to the Mesh mode.
2. Click the Generate mesh button and click ok, the default parameters are valid.
3. Click on select points for curves and set nodes at the point load and at -1 m in the column.

3.1.7. Define the calculation

The calculation for this model will consist of 4 phases. These are the determination of initial conditions, the installation of the DCM column and 2 different load conditions.

1. Click on the Staged construction tab to proceed with the definition of the calculation phases.
2. Keep the calculation type of the Initial phase to K0 procedure. Ensure that all the structures and interfaces are switched off.
3. Add a new calculation phase and rename it as DCM column.
4. Activate the column, the cap, and deactivate the volume of the excavation.
5. In The phases window set the time interval to 1 day.
6. In the same window in deformation control parameters section reset the displacements to zero.
7. The other default parameters are valid.
8. Add a new phase and rename it 10 KN load.
9. Activate the point load of 10 kn.
10. In the phases window set the time interval to 1 day and reset the displacements to zero press ok.
11. Add the 4th phase and rename it 5 KN load.
12. In the model explorer extend the point loads option and change the 10 KN value to 5 KN.
13. In the phases window in general tab set the start from phase option to the 2nd phase (DCM column).
14. Set the time interval to 1 day.
15. Reset the displacements to zero and press ok.
16. Save the project and click on calculate button to start the calculation.

3.2. SDCM column

For the SDCM column we used the same DCM column model with some differences that are shown below.

Define the plate material as follow

Table 3.4 Parameters used in the plate material

Parameters	Plate
Unit weight, γ (KN/m^3)	98
Flexural rigidity EI (KN/m^2)	210*10^6

The rest of the parameters are kept to default.

3.2.1. Define the structural elements

1. In the same column add a 3 surfaces forming the letter H to model the steel H-beam as shown in Figure 3.7.
2. The H-beam used in this model is 200 mm in width and 6 m in length.
3. Extrude each surface to a depth of -6m.
4. Delete the 3 top initial surfaces.
5. Select the 3 new volumes right click on them and choose decompose into surfaces.
6. Select all the new surfaces, right click on them and choose create plate.
7. Assign the plate material to them, Figure 3.8.

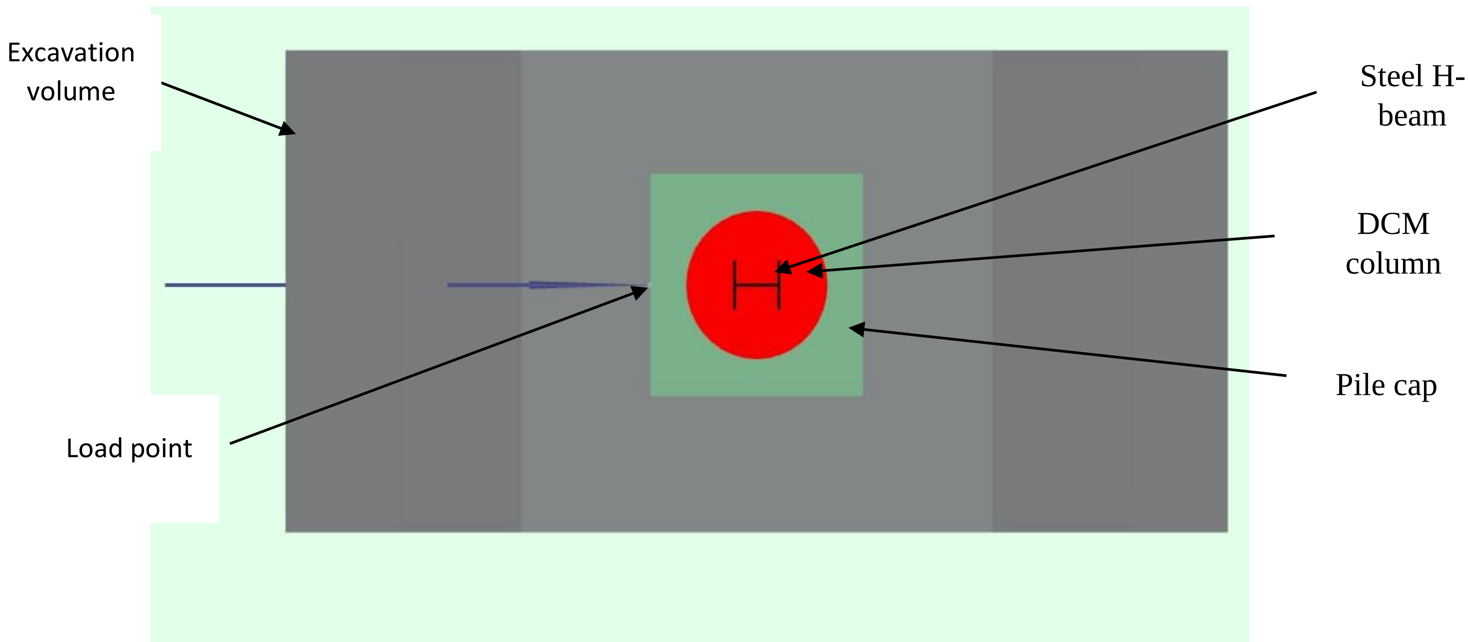


Figure 3.7 Top view of Steel H-beam

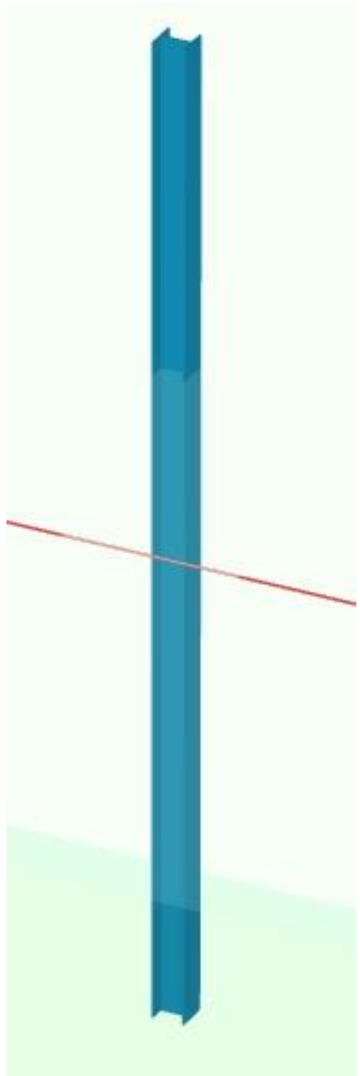


Figure 3.8 Perspective view of steel H-beam

3.2.2. Define the calculation

In this model the calculation will consist of 5 phases. These are the determination of initial conditions, the installation of the SDCM column and 3 different load conditions.

1. Click on the Staged construction tab to proceed with the definition of the calculation phases.
2. Keep the calculation type of the Initial phase to K0 procedure. Ensure that all the structures and interfaces are switched off.
3.  Add a new calculation phase and rename it as SDCM column.
4. Activate the column, the cap, the plates, and deactivate the volume of the excavation.
5. In The phases window set the time interval to 1 day.
6. In the same window in deformation control parameters section reset the displacements to zero.

7. The other default parameters are valid.

8. Add a new phase and rename it 120 KN load.

9. Set the point load value to 120 KN.

10. In the phases windows set the time interval to 1 day.

11. Reset the displacements to zero and press ok.

12. Add a new phase and rename it 30 KN load.

13. Set the value of the point load to 30 KN.

17. In the phases window in general tab set the start from phase option to the 2nd phase (SDCM column).

14. Set the time interval to 1 day.

15. Reset the displacements to zero.

16. Add a new phase and rename it 60 KN load.

17. Set the value of the point load to 60 KN.

18. In the phases window in general tab set the start from phase option to the 2nd phase (SDCM column).

19. Set the time interval to 1 day.

20. Reset the displacements to zero.

21. Save the project.

22. Click on calculate button to start the calculation.

3.3. The excavation model

This model represents an excavation supported by a wall of DCM columns, the wall is 4.6 m long and consists of 9 columns from the previous model with a depth of 11 m and an overlapping of 0.1 m.

3.3.1. Geometry

This model is 60 m wide and 30 m long, it consists of a 3 three layers with a depth of 16 m like the previous model, the excavations are going to be realized to a depth of 5 m.

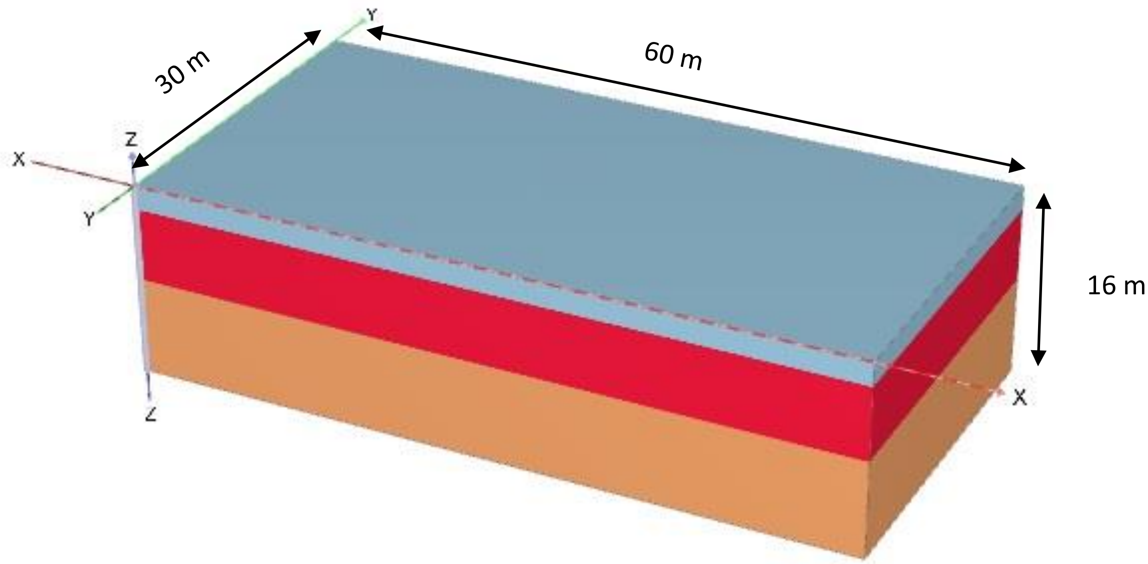


Figure 3.9 Perspective view of the geometry

3.3.2. Create a new project

To create the geometry model, follow these steps:

1. Start a new project.
2. Enter an appropriate title for the project.
3. Define the limits for the soil contour as
   - **a.** X-min = 0.0 and X-max = 60
   - **b.** Y-min = 0.0 and Y-max = 30

3.3.3. Define the soil stratigraphy

As the previous model to define the soil layers, a borehole needs to be added and material properties must be assigned. All soil layers are horizontal, so only a single borehole is needed.

1. Click the create borehole  button and create a borehole at (0 0 0).
2. Add 3 layers with bottom levels at -2, -8, and -16m.
3. Set the Head in the borehole column to -16 m.

3.3.4. Create and assign the material data sets

The materials used in this model are the same as the ones defined for the previous columns model, they should be added and found in the global materials sets.

3.3.5. Define the structural elements

The creation of the DCM wall, and the excavation area is described below

1. Select the Start designer button in the side toolbar
2. Select Create polycurve
3. Click on the point of (12, 27, 0).
4. In the General tabsheet select circular for the shape, the default orientation axes (x-axis, y-axis) are valid for this polycurve.
5. In the Segments tabsheet, click on the Add segment, and set 0.3 for the radius and press ok.
6. Select the circle, left click on it and choose create then create surface
7. Delete the circle and select the surface.
8. Click on Extrude object in the side toolbar and select Extrude object.
9. Set the extrusion vector z to -11 m and press apply.
10. Delete the column top surface.
11. Select the column and assign the DCM column material to it.
12. Select the column and click on create array in the side toolbar.
13. In shape option select 1D, in Y direction.
14. Set the distance between columns to 0.5m to create the overlapping of 0.1m between columns.
15. The same procedure is applied with each new column.
16. Repeat the 15th step until you reach a number of 9 columns with a length of 4.6 m.
17. Create a surface on (27.3 12 0, 27.3 16.6 0, 32.3 16.6 0, 32.3 12 0).
18. Extrude the new surface to a depth of 1 m.
19. Repeat the 18th step until you reach 5 m.
20. After the 5 volumes are realized delete the top surface.

3.3.6. Generate the mesh

In order to generate the mesh:

1. Click on the Mesh tab to proceed to the Mesh mode.
2. Click the Generate mesh button and click ok, the default parameters are valid.

3.3.7. Define the calculation

The calculation consists of 7 phases. The initial phase consists of the generation of the initial stresses using the K0 procedure. The next phase consists of the installation of the DCM wall, then the next 5 phases are for each 1 m of the excavation.

1. Click on the Staged construction tab to proceed with the definition of the calculation phases.
2. Keep the calculation type of the Initial phase to K0 procedure. Ensure that all the structures and interfaces are switched off.
3.  Add a new calculation phase and rename it as DCM wall.
4. Activate all the 9 columns,
5. In The phases window set the time interval to 1 day.
6. In the same window in deformation control parameters section reset the displacements to zero.
7. The other default parameters are valid.
8.  Add a new phase and rename it first excavation volume.
9. Deactivate the first volume (1m) of the excavation.
10. In The phases window set the time interval to 1 day.
11. Reset the displacements to zero, to avoid any unnecessary displacement before the excavation due to the installation of the wall.
12. Repeat the last phase for the remaining 4 phases and deactivate 1 m for each one.
13. Do not reset the displacements to zero for the last 4 phases.
14. Save the project and click on calculate button  to start the calculation.

The final model is shown in the figure 3.10.

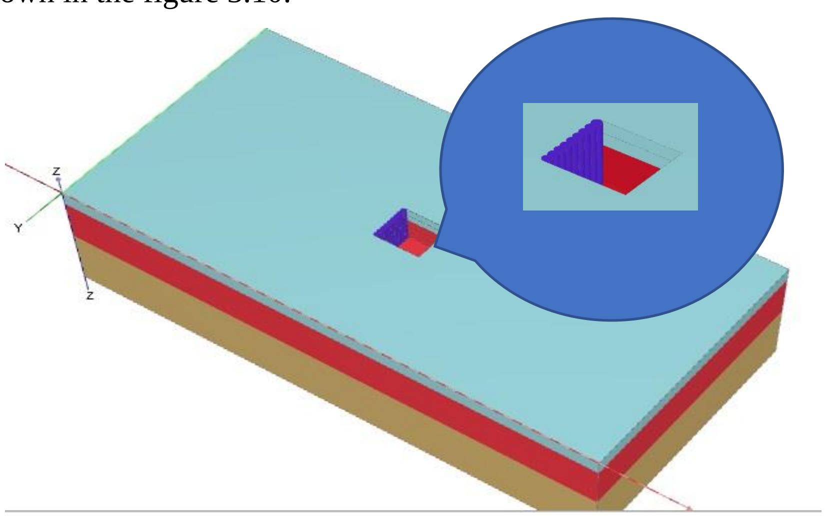


Figure 3.10 Perspective view of the final model

3.4. Model validation (Simulated results compared with experimental data)

This section is about the validation and comparison of the results obtained from the simulated model in the previous part, and the results of our reference model (voottipruex et al., 2019)

3.4.1. Columns

3.4.1.1. Lateral load tests

Figure 3.12 presents lateral load versus lateral displacement curves for individual DCM and SDCM columns obtained from the experimental model (voottipruex et al., 2019) and our simulated model. The curves clearly show that the SDCM column has much higher stiffness than the DCM column due to the very high stiffness of the steel H-beam. The lateral load-lateral displacement curve reported in a similar study by (Jamsawang et al. 2011) is plotted in Fig 3.11 for comparison.

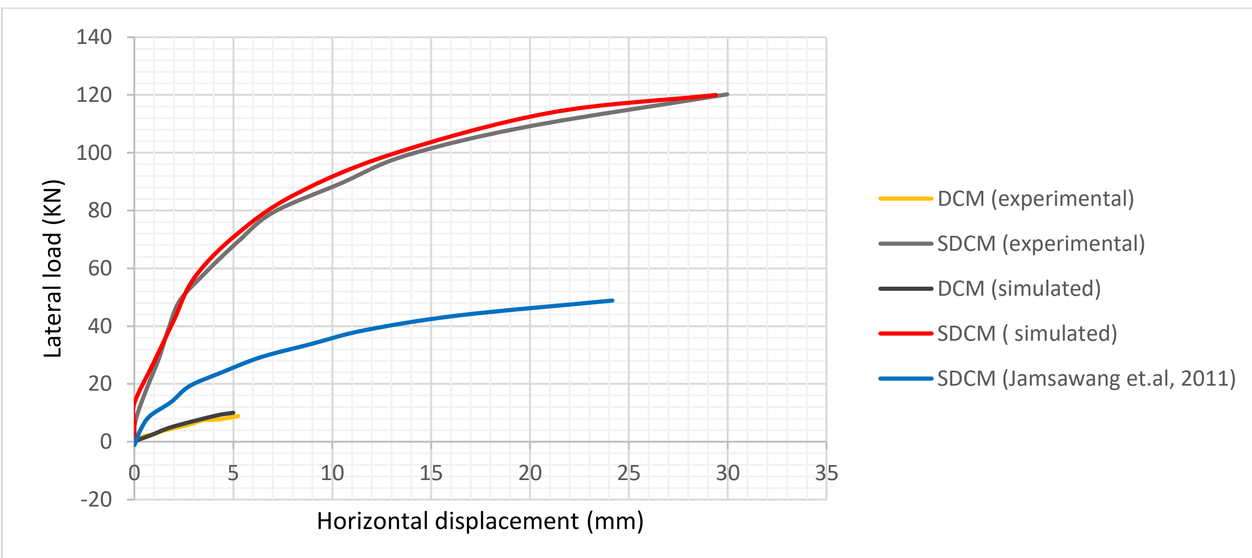


Figure 3.11 Experimental and simulated lateral load and lateral displacement curves.

3.4.1.2. Load-lateral displacement versus depth curve

Figures 3.12 and 3.13 show the lateral displacement versus depth (below excavated base) curves for DCM and SDCM columns, respectively. The maximum lateral displacement occurred at the excavated base for both the DCM and SDCM columns.

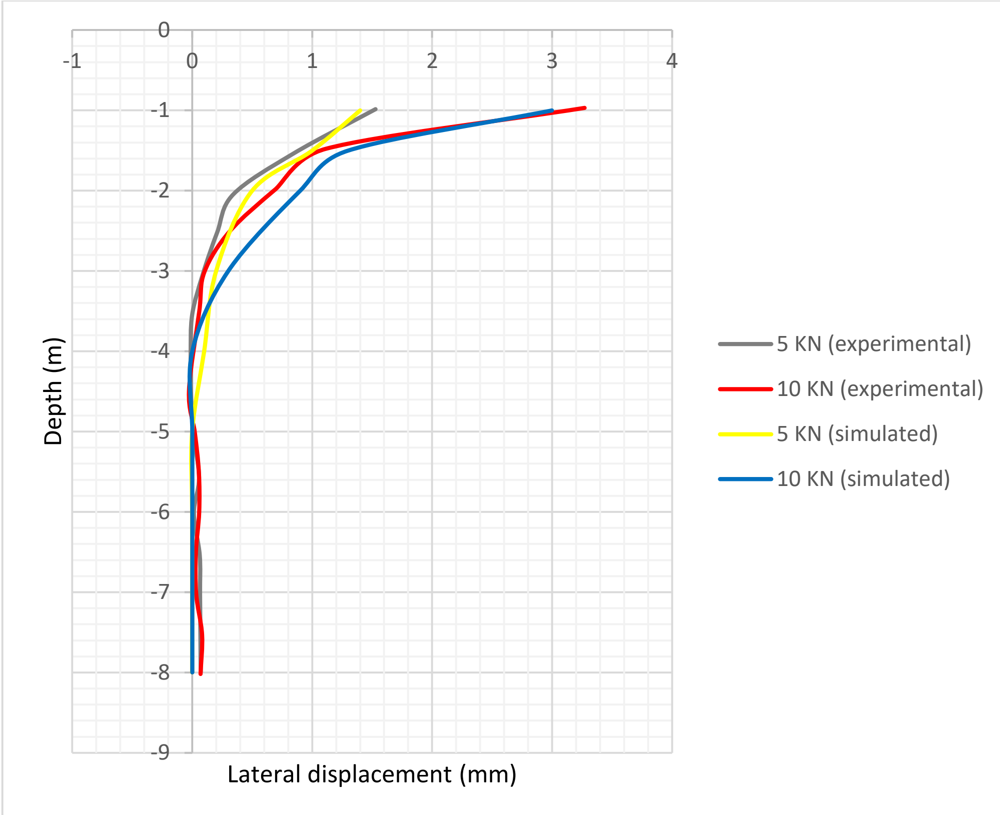


Figure 3.12 Measured and simulated lateral displacement versus depth for DCM column

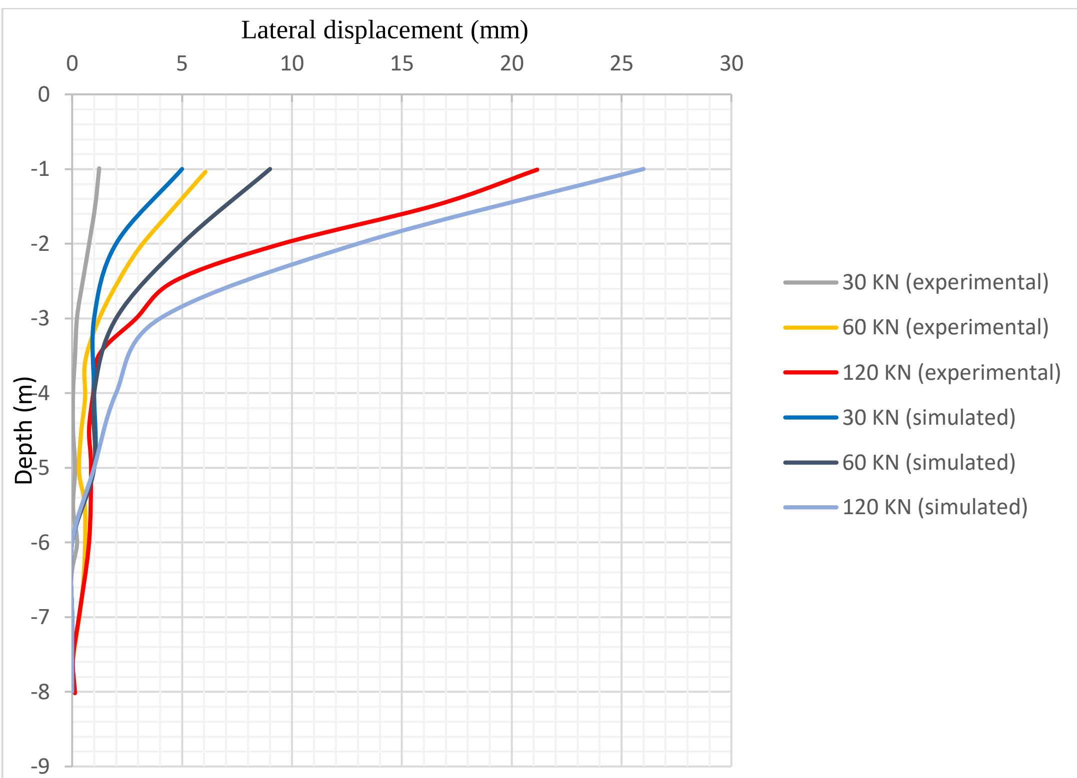


Figure 3.13 Measured and simulated lateral displacement versus depth for SDCM column

3.4.2. DCM wall under deep excavation

Figure 3.14 shows the measured lateral displacement for DCM wall after excavation

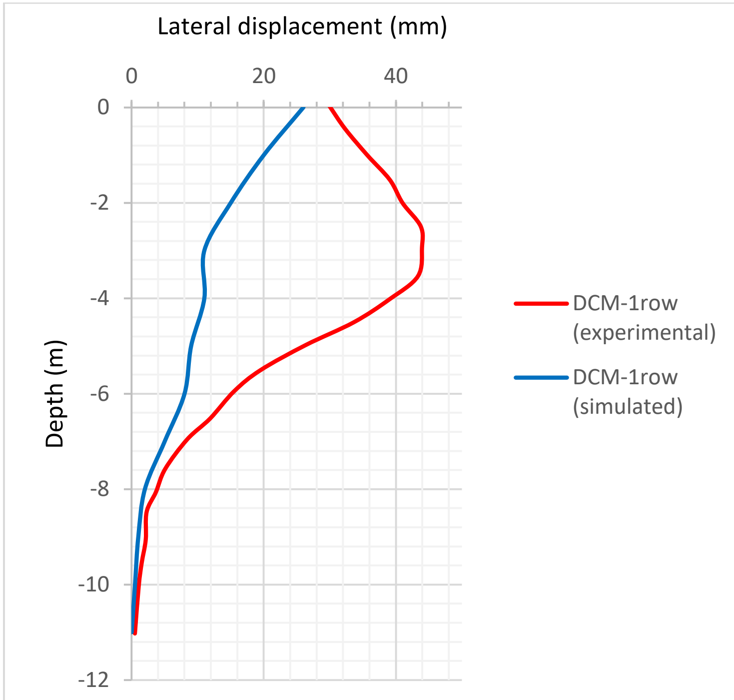


Figure 3.14 Lateral displacement of DCM wall after excavation

3.5. Conclusion

In this chapter the simulation of (voottipruex et al, 2019) was done using PLAXIS software with all the details and different steps.

The simulated model has given good results compared to those obtained from the experimental model of (voottipruex et al, 2019) and the different parametric studies of the next chapter will be done according to this verified model.

The slight differences of results could be due to the PLAXIS software versions difference and also to the simulation procedure.

CHAPTER IV Parametric study

4. Introduction

After having the validation results of the previous chapter from our model in comparison with the experimental model of (voottipruex et al., 2019), in this chapter the study of DCM walls with new concepts represented by the addition of more rows and the stiffening of the DCM wall by the adding of steel beams inside the columns was conducted, to see the effects of the new changes on its behavior, and also as some solutions to improve the effectiveness of this method.

4.1. DCM wall with 2 rows

A second row of DCM columns was added forming a new wall with an overlapping of 0.1 m between the rows as shown in Figures 4.1, and 4.2.

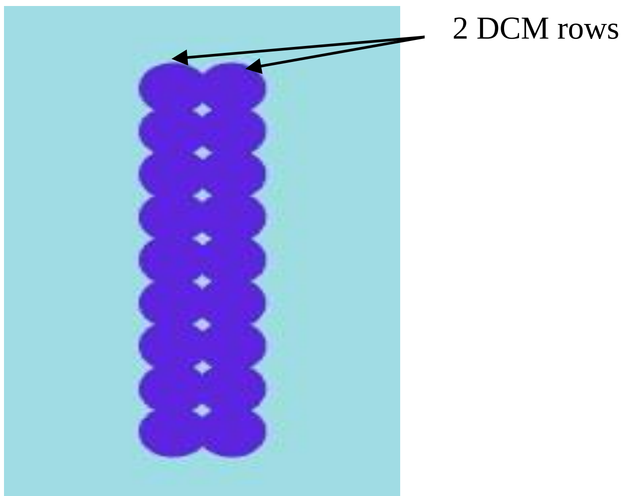


Figure 4.1 Top view of DCM wall with 2 rows

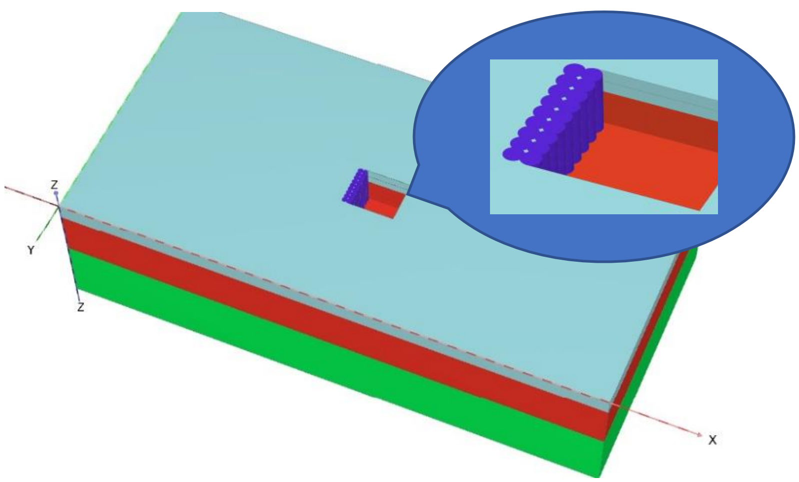


Figure 4.2 Perspective view of DCM wall with 2 rows

The obtained results from the realization of a second DCM row show a reduction in lateral displacement by 11 mm on the surface and also per depth until -8 m compared with the previous 1 row due to the increased rigidity of the wall Figure 4.3.

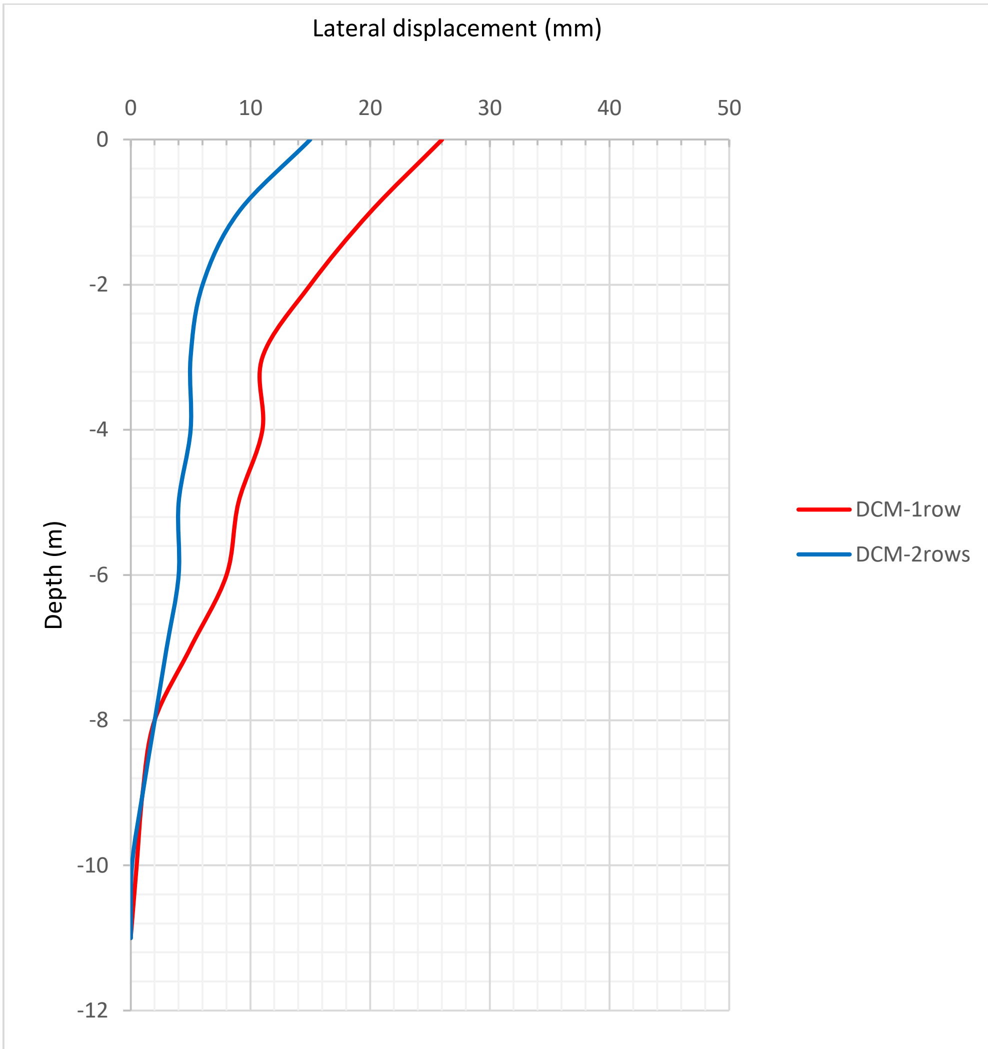


Figure 4.3 Simulated lateral displacement vs depth curves for DCM walls (2 rows)

4.2. DCM wall of 0.8 m diameter

For this study the diameter of the columns has been increased by 0.2 m, from 0.6 m to 0.8 m to address the concept of the diameter size effect on the wall, only 7 columns were used to form the DCM wall with an overlapping of 0.1 m as shown in figure 4.4

However, the diameter of 0.4 m was studied as well but the results were a complete failure, and the 0.8 m model showed good results

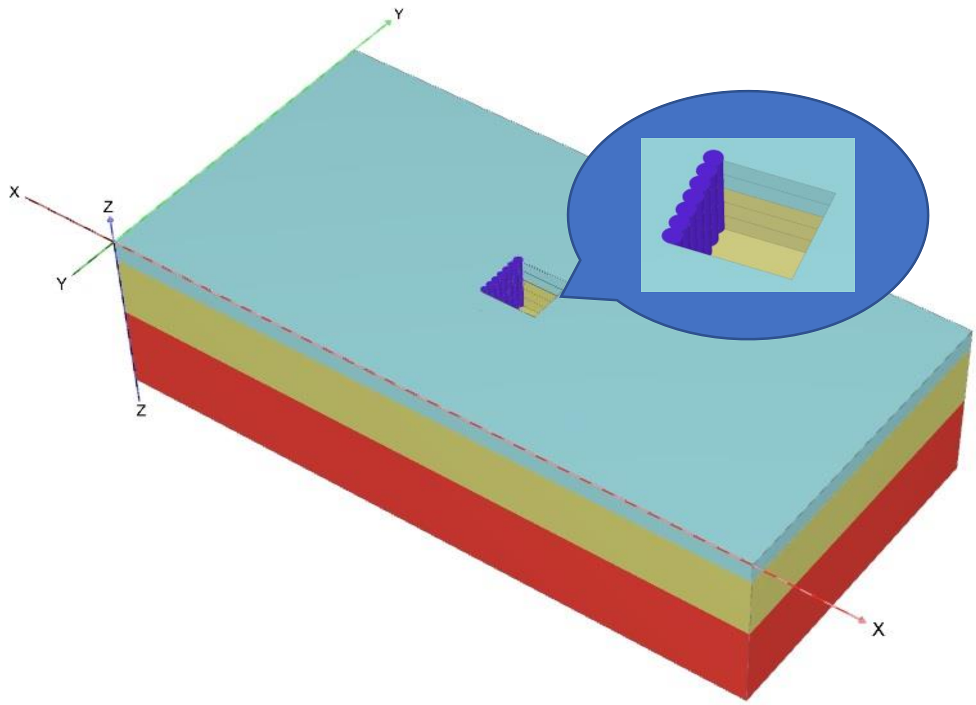


Figure 4.4 Perspective view of DCM wall with 0.8 m diameter

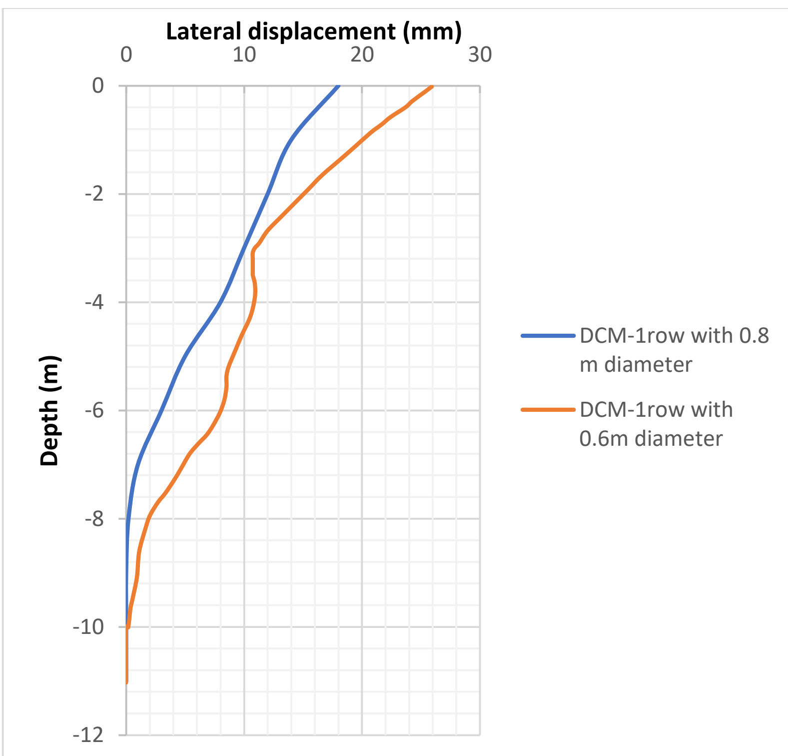


Figure 4.5 simulated Lateral displacement vs depth curve for DCM wall-1row with 0.8 m diameter vs 0.6m

The results of the Figure 4.5 show clearly a reduction of lateral displacement at the surface by 8 mm in comparison with the first model of 0.6 m diameter, the displacement were null at -8 m which means that the passive earth pressure is present at this level, and the diameter increase affected positively the whole wall rigidity.

4.3. DCM wall of 1 m diameter

Due to the last lateral displacement reduction because of the diameter increasing, the diameter of 1 m is presented in this study to compare this one with the previous 2, in order to decide what diameter is best for the DCM 1 row model, only 5 columns were used as shown in figure 4.6.

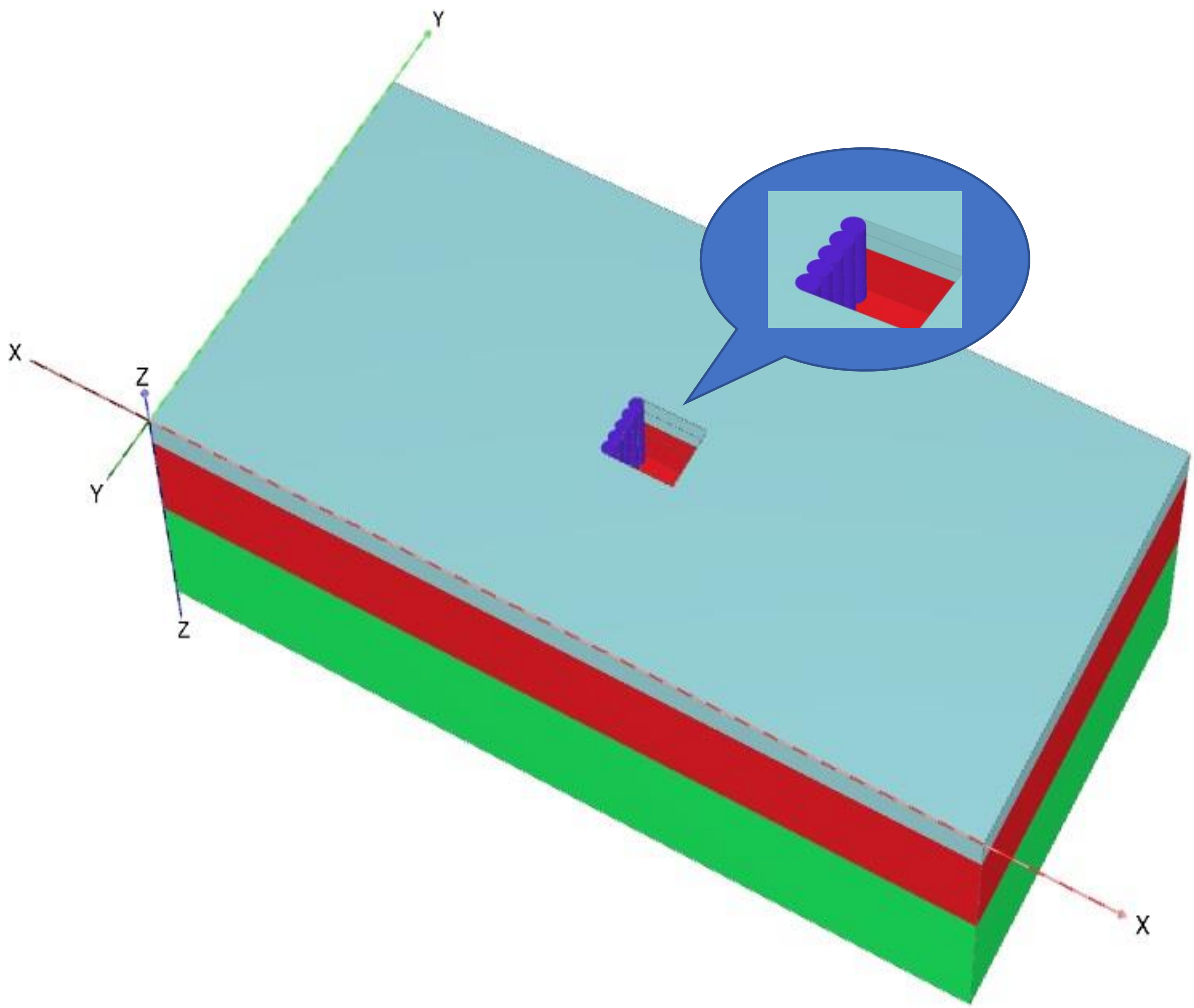


Figure 4.6 Perspective view of DCM wall with 1 m diameter

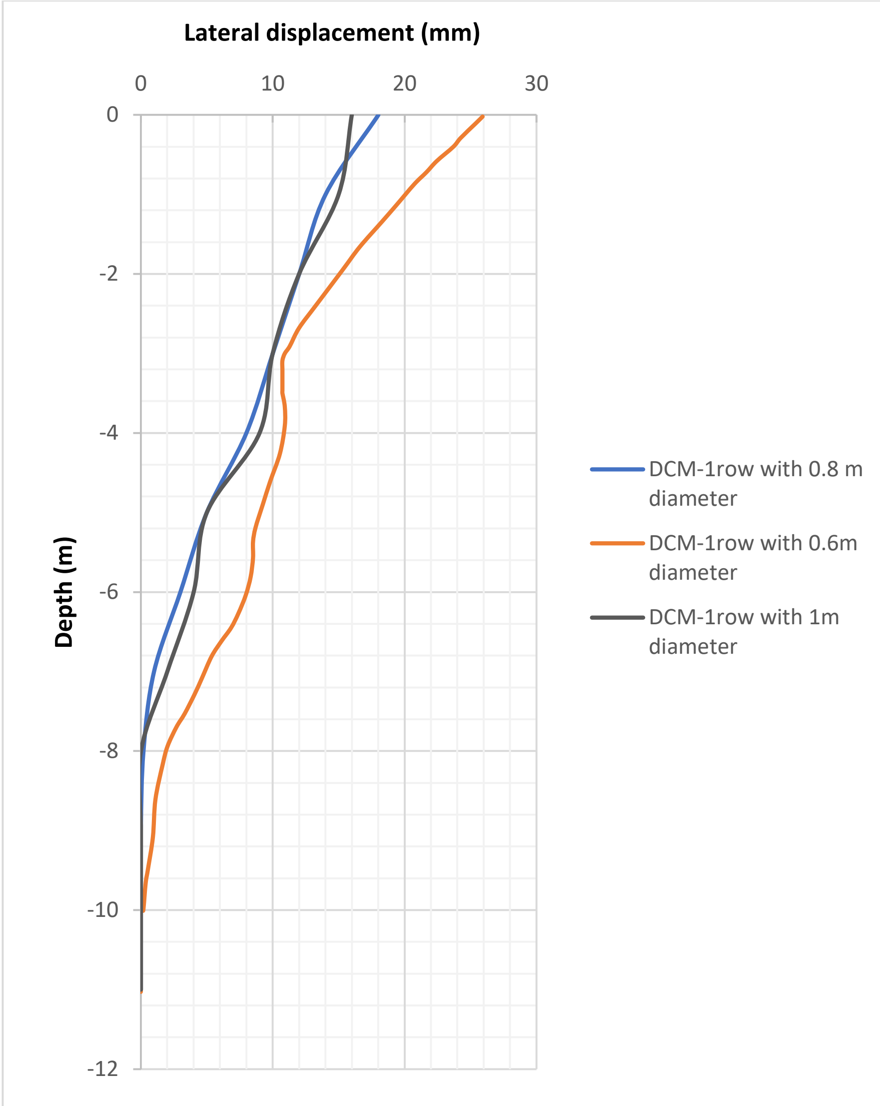


Figure 4.7 Simulated Lateral displacement vs depth curve for DCM wall-1row with 0.6 m diameter vs 0.8 m vs 1 m

The obtained results did not show a real improvement of the wall and were almost like the 0.8 m model which means that the wall reached its full rigidity with the 0.8 m diameter model, and any other improvement would a waste of resources.

4.4. DCM wall with a length of – 13 m

For this concept the column length was increased by 2 m reaching -13 m to study the effect of the embedding on the overall wall behavior

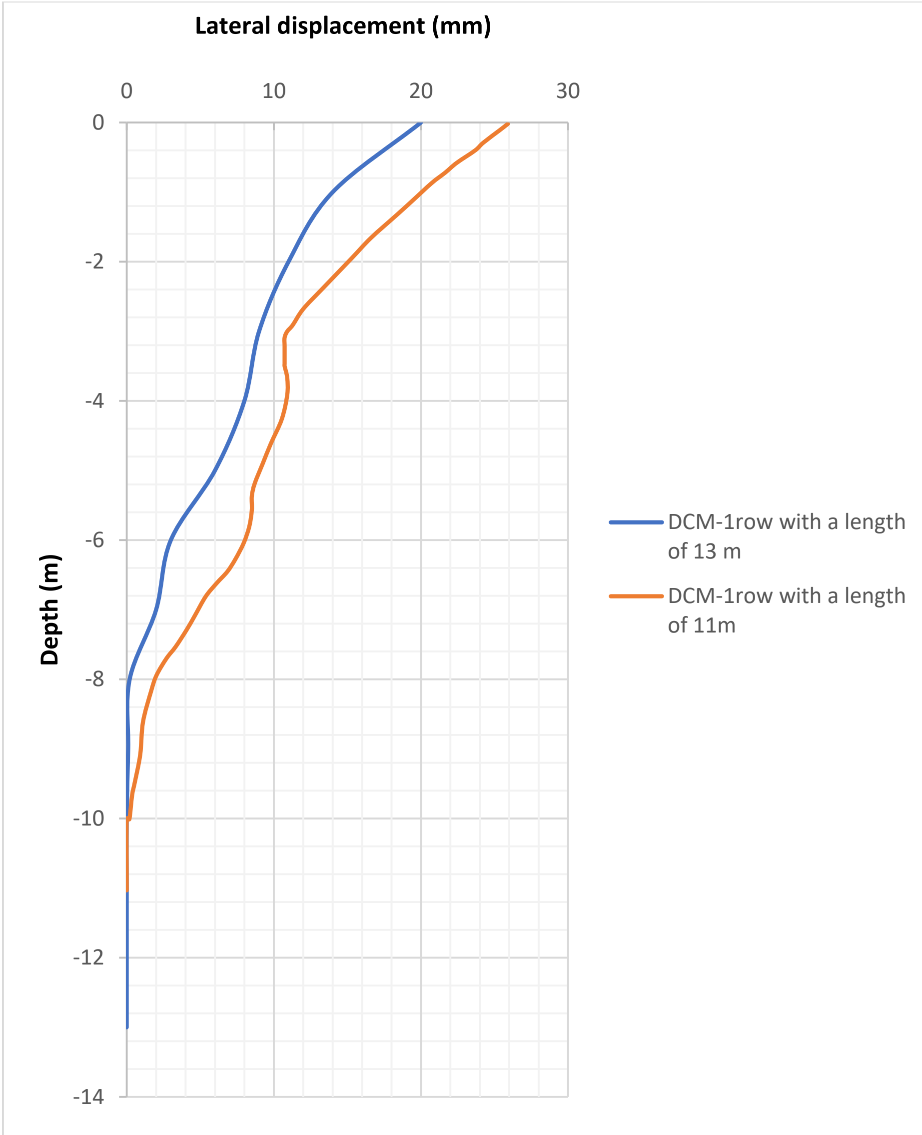


Figure 4.8 Simulated lateral displacement vs depth curve for DCM wall-1row with a length of 13 m

The results of Figure 4.8 show a reduction on the surface displacements, but the significant thing is that the displacements where null at just -9 m in comparison with the model of 11 m in length were it was null at around 10 m, and this is due to the increase of the embedding length of the column, it gave the wall complete rigidity especially at the third soil layer.

4.5. DCM wall with 3 rows

The addition of another row with same 0.1 m overlapping was investigated to see the effect of multiple rows on the behavior of the wall, as shown in Figures 4.9 and 4.10.

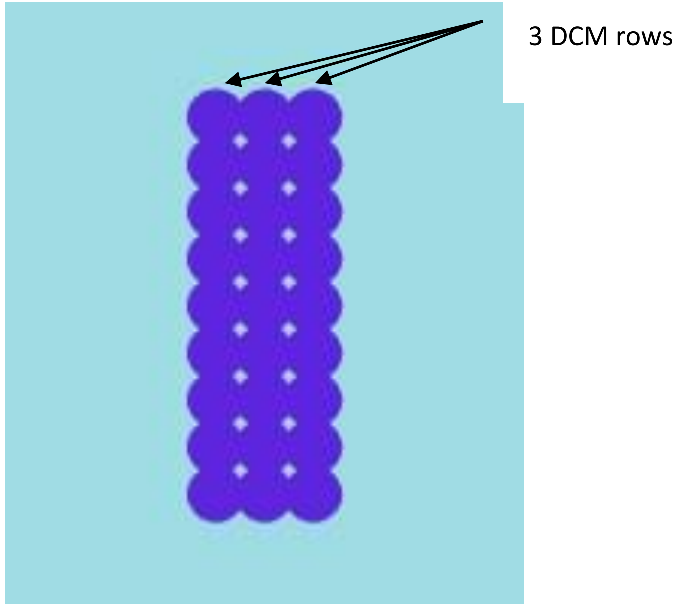


Figure 4.9 Top view of DCM wall with 3 rows

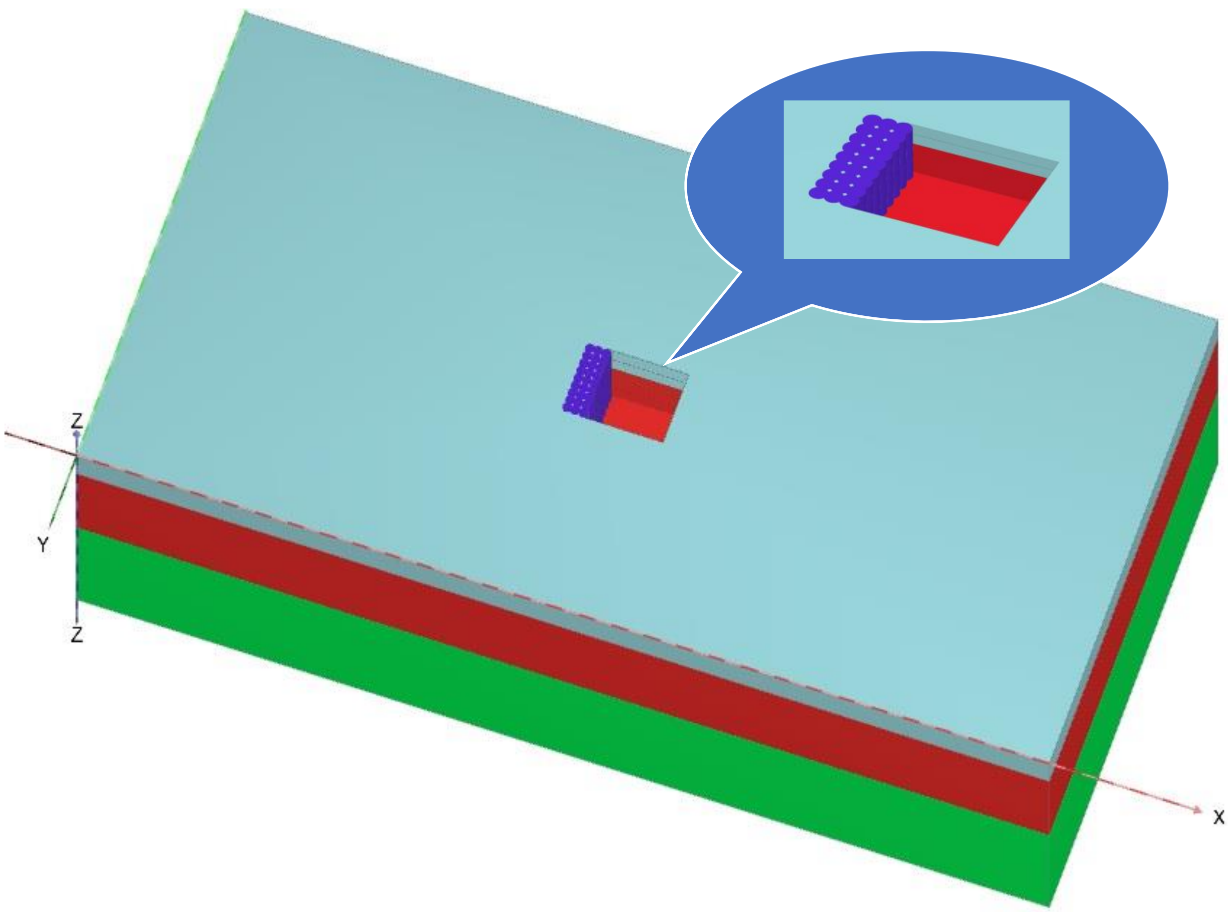


Figure 4.10 Perspective view of DCM wall with 3 rows

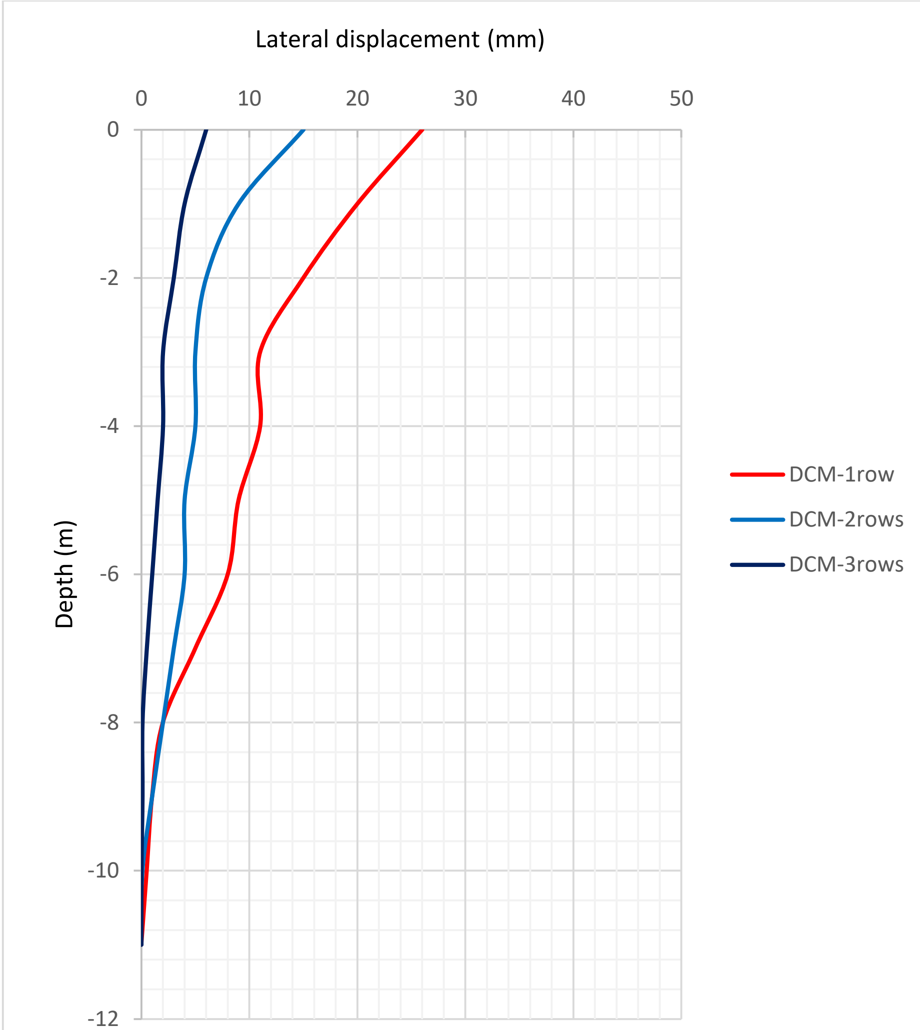


Figure 4.11 Simulated lateral displacement vs depth curves for DCM walls (3 rows)

Figure 4.11 shows an even more reduction in lateral displacement by 6 mm on the surface and 0 mm on the depth of -8 m compared to the previous 2 rows, the displacement curve is almost linear indicating that the wall has gained sufficient rigidity in all its layers to act like a homogeneous element.

4.6. SDCM columns wall

For this concept the SDCM columns are used instead of the DCM to form a stiffened 1 row wall to see the effects of the steel beams on the wall behavior and resistance.

4.6.1. SDCM-alternate

The steel beams are alternated for this model as shown in Figures 4.12 and 4.13.

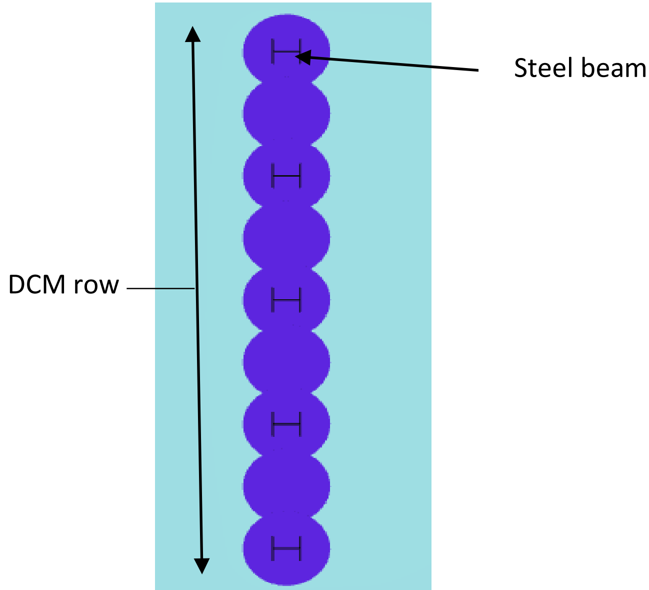


Figure 4.12 Top view of the SDCM-alternate wall

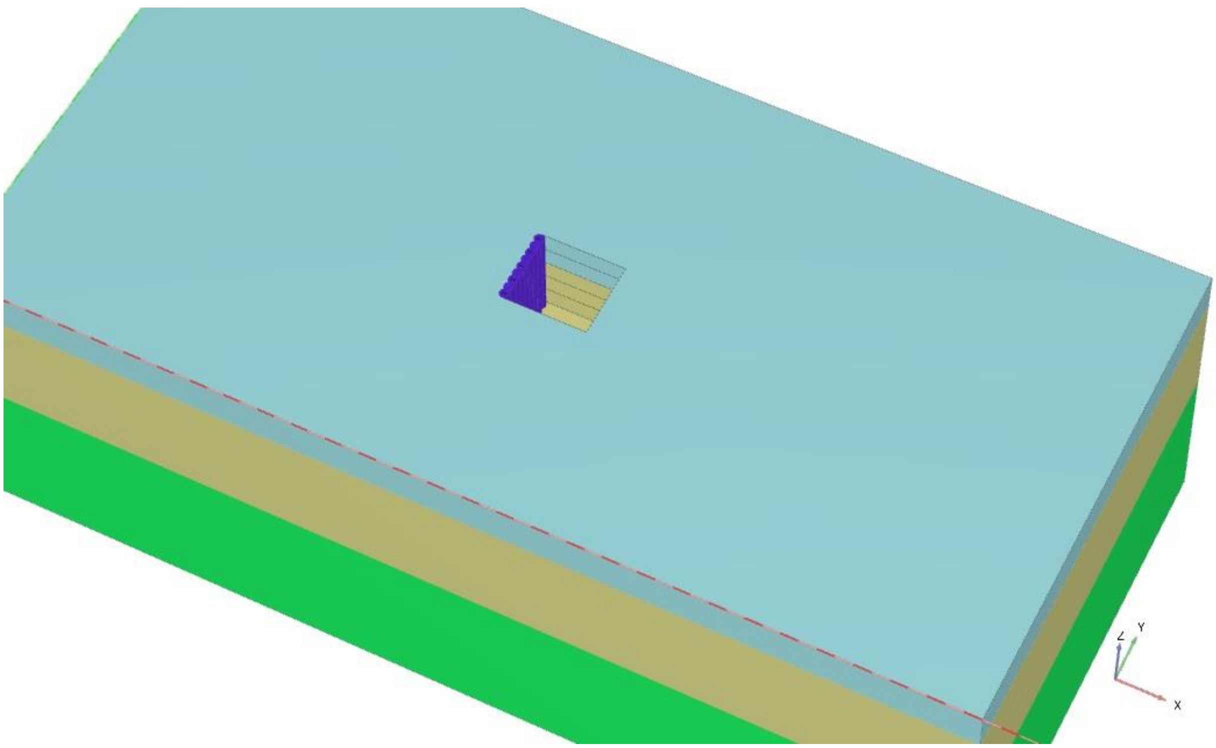


Figure 4.13 Perspective view of the SDCM-alternate wall

The stiffening of the wall with alternated steel beams show clearly that the lateral displacement was reduced by almost 9 mm on the surface part compared with the 1 row DCM wall proving the increasing of wall rigidity due to the addition of the steel beams as shown in Figure 4.14.

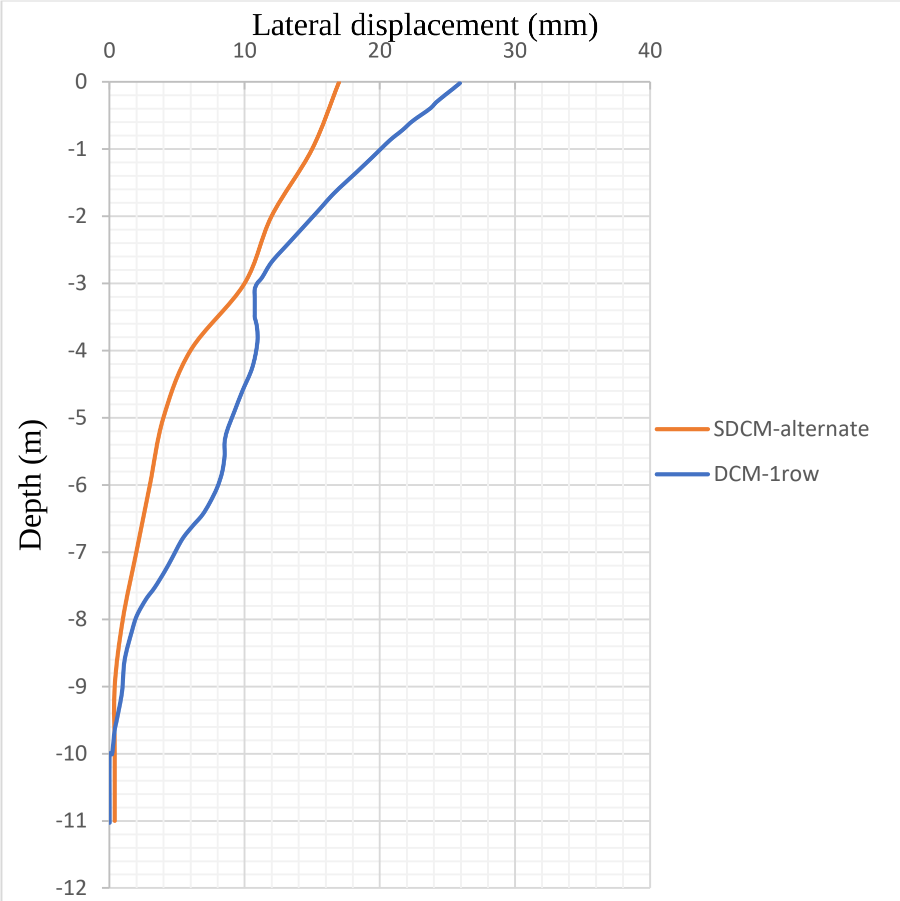


Figure 4.14 Simulated lateral displacement vs depth curve for the SDCM-alternate wall and DCM-1row

4.6.2. SDCM alternate with connectors

For this study 4 connectors were added for each steel beam, 2 on each side and were placed at -1.5 m and -4.5 m to assure the friction between the steel beam and the DCM column binder, the material used for the connectors is the same as the steel beam as shown in figures 4.15 and 4.16.

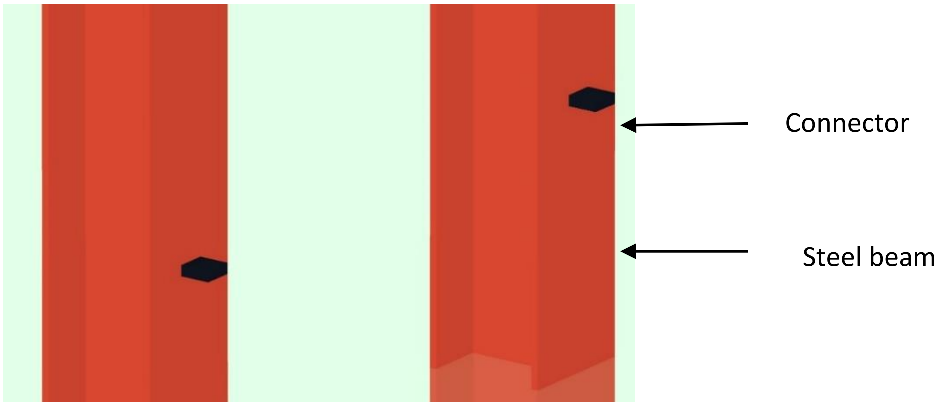


Figure 4.15 Connectors attached to the columns

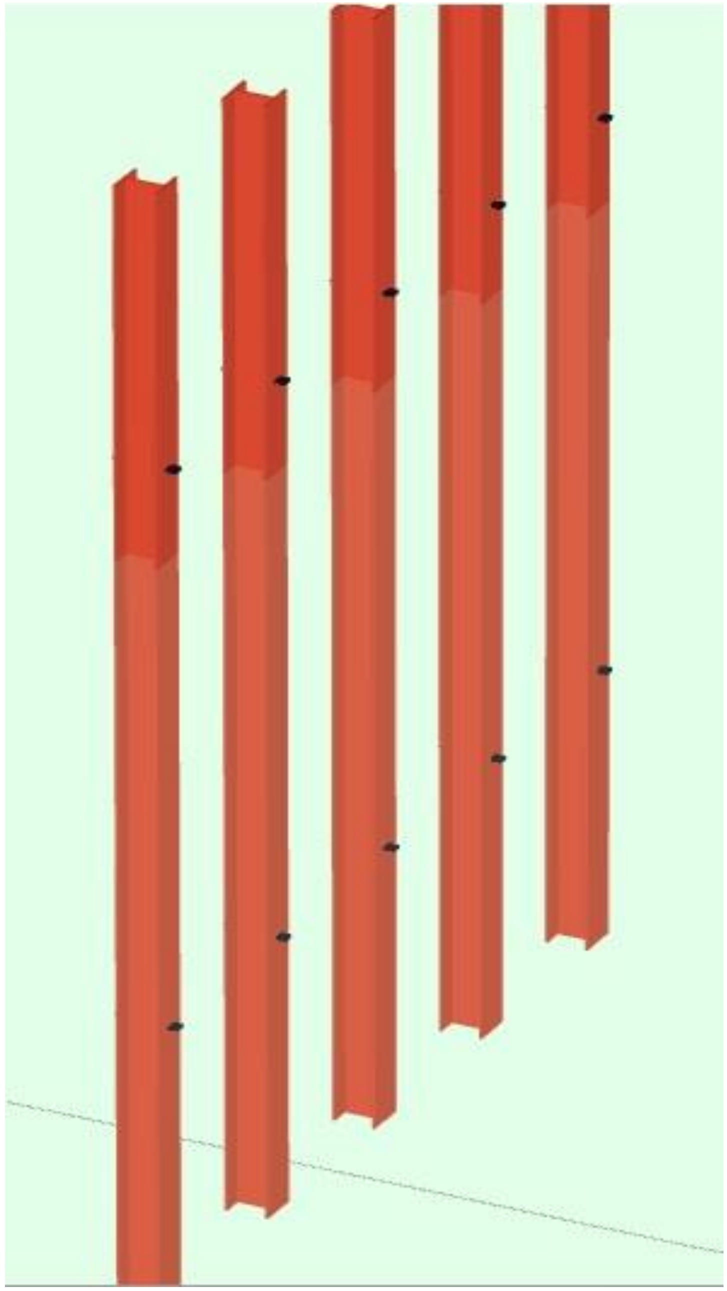


Figure 4.16 General view of the connectors

The results of this study were the same as the previous SDCM alternate model with no changes, and this is due to PLAXIS software because it supposes that the DCM binder and the steel beam are already attached and automatically assuring the friction and the adhesion of them, so this concept of adding connectors is not ideal or necessary when dealing with PLAXIS software, however this does not mean that the results of the real realization will be the same, the only way to be sure is by comparing the results of the simulation with real realization results.

4.6.3. SDCM-all

The same previous model was used with the addition of steel beams to all columns in the wall as shown in Figures 4.17, 4.18

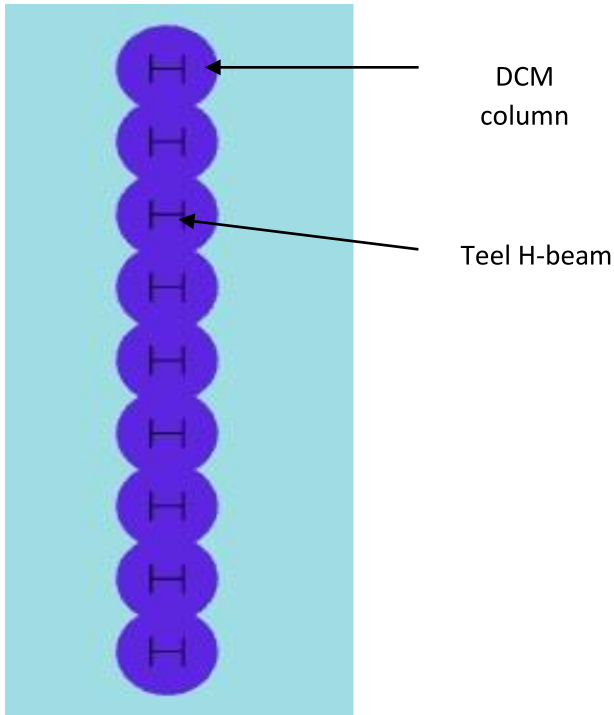


Figure 4.17 Top view of the SDCM-all wall

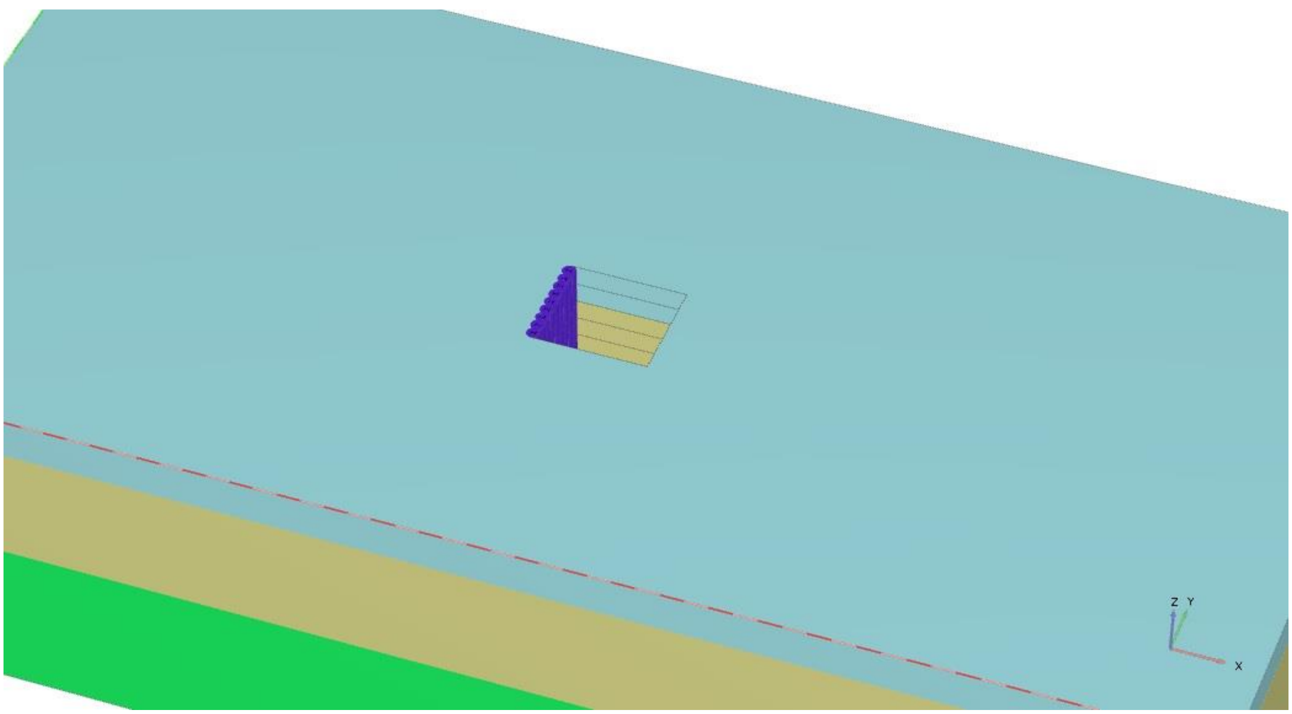


Figure 4.18 Perspective view of the SDCM-all wall

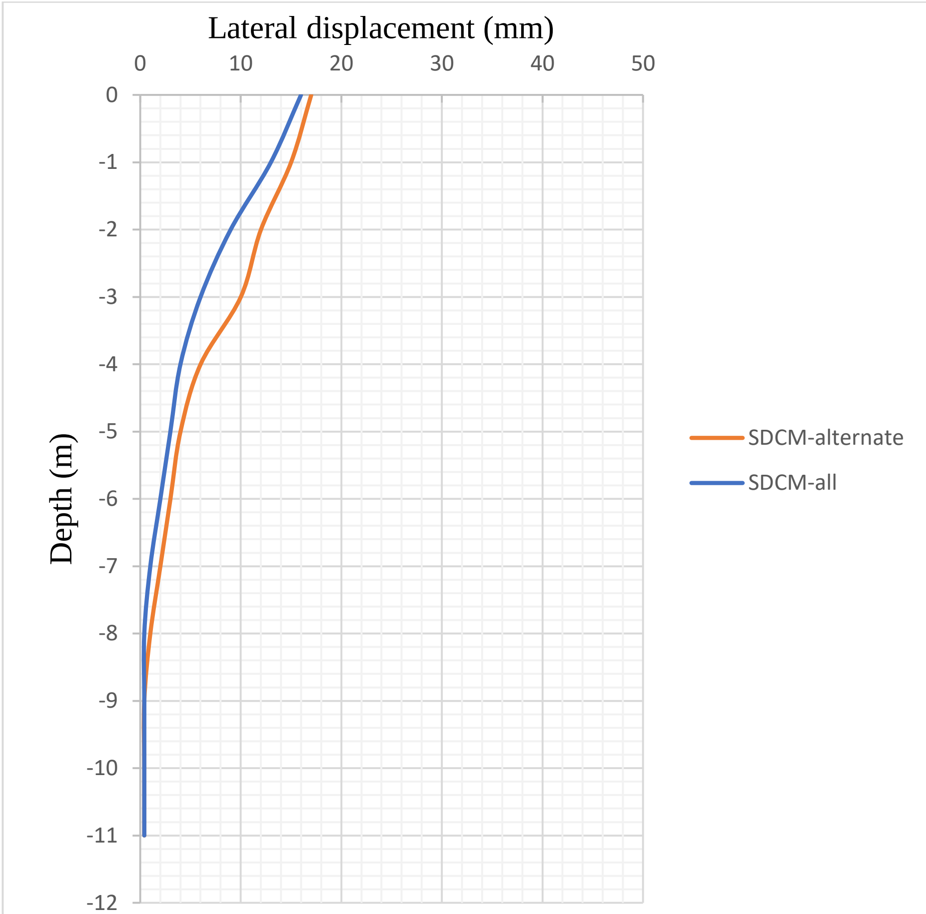


Figure 4.19 Simulated lateral displacement vs depth curve for the SDCM-all wall

Figure 4.19 shows a slight reduction in the displacement on the surface and also per depth where it became 0 at -8 m compared to the SDCM-alternate indicating that the number of steel beams has a positive impact on the wall behavior which could be used as yet another option to increase the wall resistance and rigidity without adding more rows

4.7. Conclusion

This chapter presented the effect of some changes on the concept and modifications to make this technique more effective without exhausting the economic resources, we can conclude the studies in the following points

- The DCM wall with one row had the most surface displacements reaching up to 2 mm

- DCM wall with one row can be ameliorated either by increasing the length of the columns and assuring good embedding or enlarging the diameter starting from 0.6 m
- DCM wall also has another good concept which is the addition of more rows, like in the case of 3 rows where the lateral displacements was down to only 6 mm, but it may influence the economic side because it requires a lot of materials
- The increasing of the cross section area proved its efficiency by reducing the lateral displacements on the surface by 8 mm for the 0.8 m model and 10 mm for the 1 m model In comparison with the 0.6 m model.
- Assuring good embedding by increasing the length of the DCM wall has positive impact of the rigidity of wall where it was null at -8 m compared with the previous models at 10 m
- SDCM alternate and all did not show big difference in terms of lateral displacements however the effect was mostly decreased under the surface and null at -8 m
- The SDCM alternate model may be the best approach for this model to preserve the economic resources and assure good rigidity and reliability.

General Conclusion

Earthworks and excavations represent the first major phase of any construction project to build the appropriate type of foundation, the success of this phase depends on the approach and method used to assure the stability, each field and soil types demand different requirements meaning one method cannot be used in every situation and the right decision is decided by the geotechnical studies and tests.

Deep Soil Mixing method was investigated in this work as a solution to assure the stability during and after the excavations, first the results were validated, then different parametric studies were tested in order to decide the best concept that offers both the stability translated by the minimum displacements, and lower cost.

The following points represent the conclusion of this work:

- Deep soil mixing method proved its efficiency when applied on soft soils.
- The parametric studies show that any change of the concept of the DCM walls either by adding more rows like in the cases of 2 and 3 rows or stiffening the wall by injecting steel beams into the columns like the alternate and all models, has a great impact on the behavior of the wall during and after the excavation.
- The increase of the cross section area and the length of the columns by assuring good embedding has positive effect on the wall behavior
- SDCM-all exhibited better performance than DCM-1 row, DCM-2 rows, and SDCM-alternate. whereas SDCM alternate is only better than the DCM-1 row.
- The addition of more rows or the stiffening of the wall with steel beams are great solutions when the normal approach has not given the desired results.

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