

# Foundation Treatment, Reinforcement and Design Optimization for Oil Storage Tanks at TAZAMA Pipelines Limited (Ndola, Copperbelt Province, Zambia)

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**Abstract.** Addressing foundation soil consolidation and subsoil treatment/reinforcement pertaining to oil storage tanks is essential for ensuring their long-term structural stability and minimizing risks associated with ground movement. This study will specifically revolve around investigating Foundation Treatment, Reinforcement and Design Optimization for Oil Storage Tanks at TAZAMA Pipelines Limited Ndola Site, (a key player in the transportation of petroleum products between Zambia and Tanzania). Key content of article:

- Through systematic analysis of survey data of the target area, the engineering characteristics and distribution patterns of soft soil foundations in site area was analysed and appropriate foundation treatment and reinforcement methods of oil storage tanks within the area was taken into consideration.

- Demonstrated significance of applying chosen method of optimization to address the soil consolidation issues; i.e. presented through level for level analysis of application model.

- Considered a 50,000m<sup>3</sup> floating roof oil storage tank foundation for soil consolidation optimization, analysing practicality and feasibility of study.

The main author of this article served as a Civil Engineering Intern at TAZAMA Pipelines Limited.

**Keywords.** Oil Storage Tanks, Subsoil, Consolidation, Preloading, soft

## 1. Introduction:

TAZAMA Pipelines Limited is a company that operates a pipeline system for the transportation and storage of refined petroleum products. The company was established in 1968 as a joint venture between the governments of Tanzania and Zambia. TAZAMA's pipeline network plays a crucial role in supplying petroleum products to both countries, ensuring a reliable and efficient distribution system. [1,2]

### 1.1. Types of Oil Storage Tanks Used by TAZAMA Pipelines Limited:

Above-Ground Storage Tanks (ASTs): TAZAMA Pipelines Limited utilizes above-ground storage tanks for storing large quantities of oil. These tanks are typically constructed from steel and are designed to

meet specific industry standards for safety and environmental protection. ASTs are commonly used for storing crude oil, diesel, gasoline, and other petroleum products.

**Underground Storage Tanks (USTs):** In addition to above-ground storage tanks, TAZAMA Pipelines Limited does also employ underground storage tanks for certain applications. USTs are buried beneath the ground surface and are commonly used for storing fuel at vehicle fueling stations and specific onsite industrial facilities. These tanks require specialized monitoring systems to detect leaks and ensure compliance with regulatory requirements.

**Floating Roof Tanks:** TAZAMA Pipelines Limited also utilizes floating roof tanks for storing volatile petroleum products such as gasoline and fuel. Floating roof tanks feature a floating roof that moves up and down with the liquid level, reducing vapor emissions and minimizing the risk of fire or explosion. These tanks are designed to maintain product quality and safety during storage.

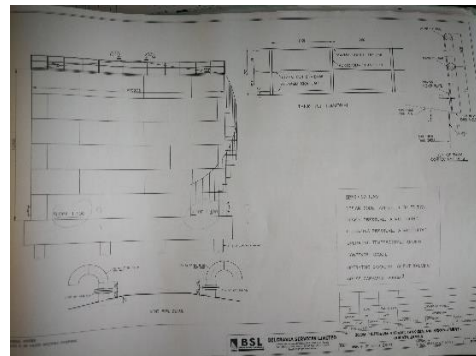
**Fixed Roof Tanks:** Fixed roof tanks are another type of storage tank that TAZAMA Pipelines Limited uses for storing oil products that do not require special vapor control measures. These tanks have a fixed roof that does not move with the liquid level, making them suitable for storing non-volatile liquids such as diesel or heavy fuel oil.

**Spherical Tanks:** TAZAMA also employs spherical tanks for storing liquefied petroleum gas (LPG) or other pressurized gases. Spherical tanks have a unique spherical shape that allows them to withstand high internal pressures while minimizing the surface area exposed to the environment.

Figure 1 – (A-E) Storage Tank Infrastructure at TAZAMA PIPELINES LIMITED Bwana Mkubwa Storage Depot, Ndola. (F) Author of Article on Site.



(A)



(B)



(C)



(D)



(E)



(F)

## 2. The City of Ndola, Copperbelt Province, Zambia

Ndola is one of the largest cities in the country. It is linked by road and rail to the capital, Lusaka, and to Livingstone and thus to Zimbabwe, as well as to Congo and Tanzania. Industries include a metallurgical plant, a sugar refinery, a tire factory, an auto-assembly plant, and various mine service industries. It is now the terminus of the Tazama fuel pipeline from Dar es Salaam, Tanzania. The town is home to the Copperbelt Museum and Northern Technical College (1964). Pop. (2000) 374,757; (2010 prelim.) 455,194. [3]

### 2.1. Soil Distribution of Bwana Mkubwa Area, Ndola.

The Bwana Mkubwa area in Ndola is known for its significant presence of soft soils, which can pose challenges for construction and infrastructure development. Soft soils are typically characterized by low shear strength, high compressibility, and high water content, making them prone to settlement and instability under load. [4, 5]

In the Bwana Mkubwa area specifically, the distribution of soft soils can vary depending on factors such as geological formations, soil composition, and historical land use practices. Areas with higher clay content or organic matter tend to exhibit softer soil properties compared to regions with more compacted or sandy soils. [4, 5]

Construction projects in the Bwana Mkubwa area need to account for the presence of soft soils through proper site investigation, soil testing, and engineering design measures. Techniques such as soil stabilization, deep foundations, or ground improvement may be employed to mitigate the challenges associated with soft soils and ensure the long-term stability of structures built in the area. [4, 5]

## 3. General Characteristics of Soft Soils

Soft soil (which comprise of silt, mucky soil, peat, and peaty soil) are referred to as fine particles with a natural porosity ratio greater than or equal to 1.0; a natural water content greater than the liquid limit. Such soils generally have a compression coefficient greater than 0.5MPa<sup>-1</sup> as well as an undrained shear strength of between than 20Kpa to 100Kpa. [6, 7, 8]

The compression coefficient, also known as the consolidation coefficient, is a key parameter used to quantify the rate at which soft soils consolidate under load. It represents the ability of the soil to decrease in volume over time due to applied stress. [6, 7, 8]

Undrained shear strength is another critical parameter used to assess the stability of soft soils under loading conditions where drainage is restricted or limited. It measures the resistance of the soil to shearing deformation when saturated with water. [6, 7, 8]

*3.1. Problematic Outcomes associated with Oil Storage Tank being Constructed on Soft Soil Foundations. (Figure 2 for Reference)*

1. **Settlement:** Soft soil foundations have a limited ability to support heavy loads without experiencing settlement. The weight of oil storage tanks can cause uneven settlement across the foundation, leading to structural issues such as tilting or cracking of the tank walls. Differential settlement can also result in operational problems, such as misalignment of piping systems or equipment within the tank. [9, 10, 11, 12, 13]
2. **Lateral Movement:** Soft soils have poor lateral resistance, which can result in excessive horizontal movement of the tank structure. This lateral movement can lead to deformation or buckling of the tank walls, compromising its structural integrity. [9, 10, 11, 12, 13]
3. **Slope Stability:** Soft soil foundations are more prone to slope instability, especially when subjected to cyclic loading from the weight of the oil stored in the tanks. Slope failures can occur around the perimeter of the tank foundation, posing a risk to both the tank structure and surrounding infrastructure. [9, 10, 11, 12, 13]
4. **Foundation Failure:** The low bearing capacity of soft soils increases the risk of foundation failure under the concentrated loads exerted by oil storage tanks. Foundation failure can manifest as excessive settlement beyond acceptable limits, leading to structural distress or even collapse of the tank system. [9, 10, 11, 12, 13]
5. **Seepage and Leakage:** Soft soil foundations may exhibit higher levels of permeability compared to firmer soils, increasing the potential for seepage and leakage around the tank base. This can compromise containment integrity and environmental safety by allowing oil spills or leaks into the surrounding ground or water bodies. Proper sealing and waterproofing measures must be implemented to prevent such incidents. [9, 10, 11, 12, 13]
6. **Maintenance Challenges:** Operating oil storage tanks on soft soil foundations can pose challenges in terms of maintenance and inspection activities. Uneven settlement or movement of the tank structure may hinder access for routine inspections or repairs, requiring specialized techniques or equipment for maintenance operations. [9, 10, 11, 12, 13]

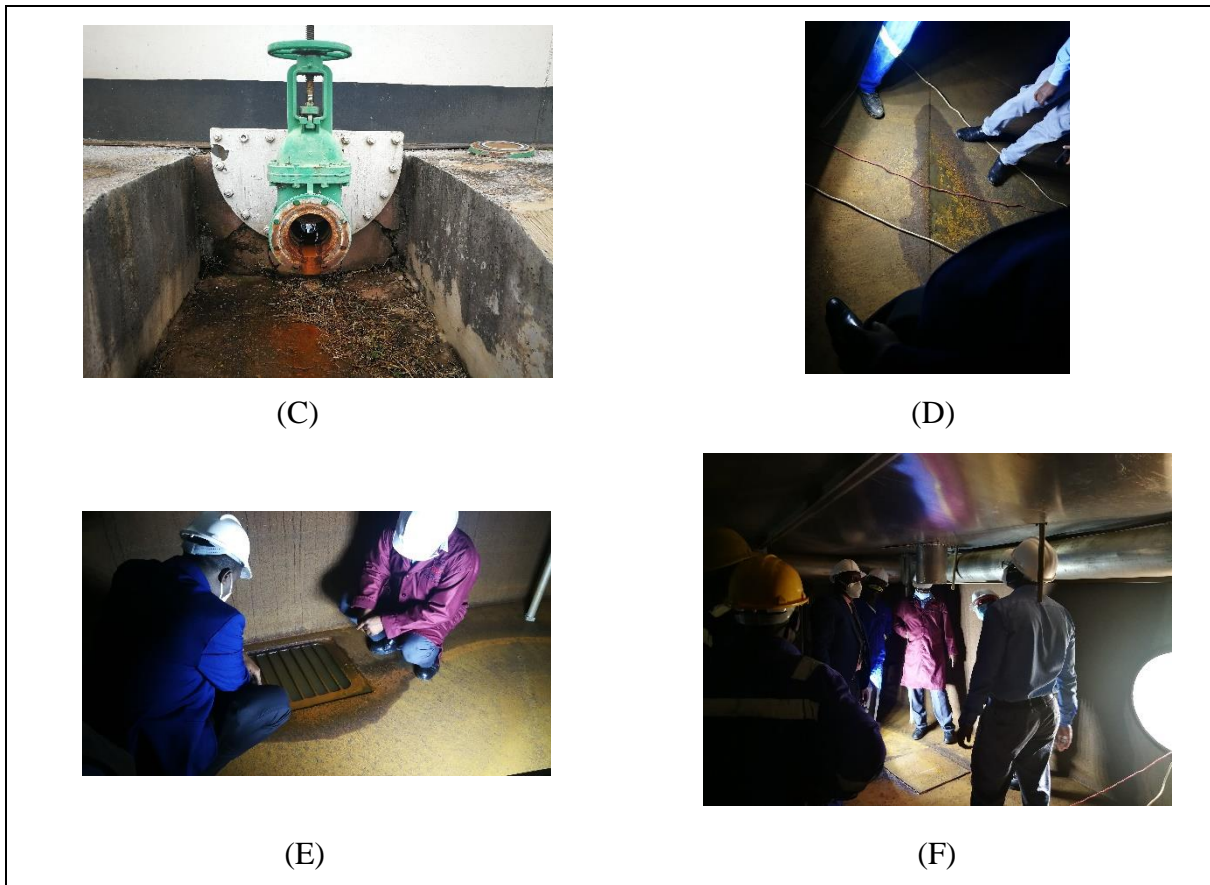
**Figure 2 – (A-F) Inspection by Management and Maintenance Team for Foundation Failure, Seepage/Leakage and Possible Internal Corrosion of Premium Tank 9.**



**(A)**



**(B)**



#### 4. Foundation Treatment and Reinforcement Methods Suitable For Oil Storage Tanks

Treatment / Reinforcement of a foundation is mainly implemented to improve both the hydraulic properties and shear resistance of the underlying subsoil's so that it will neither undergo excessive damaged nor excessive deformation (absolute settlement and differential settlement) under the load of the oil storage tank; Ensuring it's normal usage.

##### 4.1. Elaboration on objectives of Foundation Treatment / Reinforcement Methods

- Improving the shear strength of soil to avoid foundation failure

As shear stress increases within the local range of the foundation and reaches the shear strength of the soil, it can exceed the soil's bearing capacity, leading to shear failure where the soil loses its ability to support the foundation adequately. This can result in settlement, tilting, or even total collapse of the structure above. Therefore, certain measures must be taken to increase the shear strength of the foundation soil. [14]

- Improving compressional performance of the soil to avoid foundation settlement and foundation deformation.

Foundation settlement refers to the downward movement of the foundation due to various factors such as soil consolidation, inadequate soil bearing capacity, or uneven loading. This can lead to uneven stress distribution on the oil storage tank structure, potentially causing structural damage or failure. Deformation, on the other hand, involves changes in the shape or dimensions of the foundation under loading conditions. For oil storage tanks, excessive settlement or deformation can result in misalignment of piping systems, leakage issues, and compromised safety. Therefore proper foundation design, including adequate foundation reinforcement and monitoring systems are critical to ensure the long-term performance and safety of oil storage tank structures. [15, 16, 17]

- Improving the permeability of saturated soil to avoid saturation, ground water mounding and uplift forces

By enhancing the permeability of the soil surrounding the oil storage tanks, excess water can drain more efficiently, reducing the risk of soil saturation. This improved drainage capacity helps prevent the buildup of hydrostatic pressure within the soil mass, which in turn minimizes the potential for groundwater mounding beneath the oil storage tanks. Additionally, increased permeability aids in dissipating uplift forces that may be exerted on the oil storage tanks during periods of high groundwater levels or flooding events. [18, 19, 20]

#### 4.2. Foundation Treatment Methods Classification

Table 1. Foundation Treatment/ Reinforcement Methods Classification

#	Classification	Approach or Utilization of	Principle and Function	Scope of Application
1	Soil Replacement Method	Utilizes layers of Sand , Crushed Stone or Plain Soil	Dig out shallow soft soil (completely or partially) and replace it with high-strength materials such as sand and gravel to improve the bearing capacity of the bearing soil layers; reduce partial settlement.	Suitable for dealing with shallow and poor foundations, (generally only suitable for small and medium-sized oil storage tanks with lower loads.

2	Densification	<p>Rolling Method, Heavy Hammer Compaction Method, Strong Compaction Method, Vibration Compaction Method, Pile Compaction Method, Preloading Method</p>	<p>The rolling method and heavy hammer compaction methods fall under surface compaction treatment, while the rest of the listed methods belong to deep compaction treatment. The result of soil compaction is that the soil reaches a certain dry bulk density. Generally, the greater the compaction force, the better the reinforcement effect of the soil, and the higher the strength of the soil within the compression layer range of the foundation.</p>	<p>Suitable for sandy soil and cohesive soil with low water content. The optimal moisture content of the soil should be controlled using the dynamic compaction method. The preloading method can be used to preload the foundation by testing the leakage of water into the oil storage tank, but the loading speed must be controlled.</p>
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3	Drainage Treatment	Well point drainage method, Sump Pumping, Deep wells Dewatering Technique, Educator Wells Dewatering Technique, electro osmotic drainage method, Prefabricated Vertical Drain	By improving the drainage conditions of the foundation and applying preloading loads, accelerating the consolidation of the foundation soil and increasing its strength, the stability of the foundation is improved, and the settlement of the foundation is completed ahead of schedule.	Suitable for dealing with either saturated soft soil layers or thick soil layers. It however necessary to control the speed of preloading and the rate of foundation settlement.
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#### 4.3. Commonly Used Foundation Reinforcement Methods For Oil Storage Tanks

- Preloading in Foundation:

Before starting the proposed construction the weak soils are improved by applying pre loading technique. The magnitude of the pre load pressure usually rages from 1.2 to 1.3 times of the actual structural pressure or is slightly greater than the maximum pressure that is generated by the proposed structural load. Earth fills, water lowering, vacuum under impervious membrane are some of the techniques used for applying pre-load. Once the settlement under the pre load is completed, the preload is removed is removed and the construction of the structure is started. By the use of vertical sand drains the consolidation process can be increased which reduces the time of pre loading. [21]

- CFG Pile:

This technique involves driving piles made of a mixture of cement, fly ash, and gravel into the soft soil beneath the foundation. The cement provides strength and durability to the piles, while fly ash enhances workability and reduces permeability. Gravel is added to improve drainage and overall stability. Together, these materials create a reinforced foundation that distributes the load of the oil storage tank evenly, preventing settlement and potential structural failure. Additionally, this method helps to mitigate issues such as differential settlement and liquefaction in areas with soft soil conditions, providing a reliable foundation for the safe operation of oil storage tanks. [22, 23, 24]

- **Cement Deep Mixing (CDM):**

Cement Deep Mixing (CDM) is a method for improving the ground to a prescribed strength by mixing cement slurry with the soft soil in situ. Generally, the cement used is either ordinary portland cement or a mixture of portland cement and blast-furnace slag. The cement alone creates cementitious materials through hydration; and, although the reaction differs with the soil type, the calcium hydroxide liberated from the cement also undergoes a pozzolanic reaction with the soil to create cementitious materials. As the mixture ages, these cementitious materials gradually fill the void space between the soil particles, which results in higher strength and lower volume compressibility of soil. [25]

## **5. Optimization Method for Soft Soil Foundation Reinforcement - Oil Storage Tanks**

- **Grey System Theory:**

Grey System Theory (GST) is a mathematical approach that deals with systems characterized by uncertainty, vagueness, and lack of information. When it comes to soft soil reinforcement around oil storage tanks, GST can be utilized to analyze the complex interactions between the soil properties, tank structure, and environmental factors. By considering the uncertainties inherent in soil behavior and the dynamic nature of the tank loads, GST provides a framework to model and predict the performance of soil reinforcement techniques accurately. Through grey system modeling, engineers can optimize the design of reinforcement measures such as geogrids, soil nails, or micropiles to enhance the stability and load-bearing capacity of the tank foundation on soft soils. This methodology allows for a more robust and reliable approach to mitigating potential risks associated with soil settlement or instability in oil storage facilities. [26]

- **Fuzzy Mathematics Theory:**

Fuzzy mathematics theory is a branch of mathematics that deals with uncertainty and imprecision. In the context of oil storage tank foundation design on soft soil, fuzzy mathematics theory can be applied to address the uncertainties associated with soil properties, loading conditions, and other relevant factors. For instance Fuzzy logic can be used to model and quantify the uncertainty in soil properties such as shear strength, compressibility, and settlement characteristics. Instead of relying on precise values, fuzzy sets can represent these properties as linguistic variables (e.g., very soft, moderately stiff) with membership functions defining their degrees of belongingness to each category.[27, 28, 29]

Furthermore, Fuzzy optimization techniques can be employed to optimize the design parameters of foundation reinforcement measures for oil storage tanks on soft soils. By considering multiple conflicting objectives such as cost minimization, safety maximization, and construction feasibility as fuzzy goals, a fuzzy multi-objective optimization approach can identify the most robust foundation design under uncertain conditions. [27, 28, 29]

- **Analytical Hierarchy Process**

The Analytical Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology. In this civil engineering related context, AHP can be applied to prioritize and make decisions regarding various alternatives for reinforcing soft soil foundations of oil storage tanks. The follow would be the steps in doing so:

Step 1: Define the Problem

- The first step in applying AHP to oil storage tank soft soil foundation reinforcement is to clearly define the problem at hand. This involves identifying the key objectives, criteria, and alternatives related to reinforcing the foundation of the oil storage tank on soft soil. [30, 31, 32, 33]

Step 2: Establishing Criteria

- Next, a set of criteria must be established to evaluate the different alternatives for foundation reinforcement. These criteria could include factors such as cost, effectiveness, durability, ease of installation, environmental impact, and maintenance requirements. [30, 31, 32, 33]

Step 3: Develop a Hierarchy

- A hierarchical structure should be developed to organize the criteria and alternatives in a logical manner. The hierarchy typically consists of three levels: the goal (reinforcing soft soil

foundation), criteria (cost, effectiveness, etc.), and alternatives (different reinforcement methods). [30, 31, 32, 33]

Step 4: Pairwise Comparisons

- In this step, pairwise comparisons are made between each criterion and alternative based on their relative importance. Engineers assign numerical values representing the importance or preference of one criterion/alternative over another. These comparisons are used to derive priority weights for each criterion and alternative. [30, 31, 32, 33]

Step 5: Calculate Priority Weights

- Using mathematical calculations based on the pairwise comparison matrices, priority weights are calculated for each criterion and alternative. These weights indicate the relative importance of each criterion in achieving the overall goal of reinforcing the soft soil foundation effectively. [30, 31, 32, 33]

Step 6: Consistency Check

- A consistency check is performed to ensure that the pairwise comparisons are logical and consistent. If inconsistencies are found, adjustments may need to be made to maintain the validity of the analysis. [30, 31, 32, 33]

Step 7: Decision Making

- Based on the calculated priority weights, a final decision can be made regarding which alternative(s) for soft soil foundation reinforcement are most suitable for the specific conditions of an oil storage tank project. The alternative with the highest overall priority weight is typically chosen as the preferred solution. [30, 31, 32, 33]

## **6. Zambia Engineering Case Analysis for Proposed Optimization Method Simulation - Foundation Reinforcement of Floating Roof Oil Storage Tank of 50,000m<sup>3</sup> capacity.**

Specifications of the tank being analysed are:

- The design load of the oil storage tank is 220kPa
- The natural foundation bearing capacity is only 90kPa (which cannot meet the load requirements of the oil storage tank. Therefore, the foundation must be treated.)
- Diameter of Oil Storage Tank = 60 m
- Height of Oil Storage Tank = 19.35 m
- Weight of Oil Storage Tank = 900t
- Water filling weight: 47476.8t;
- Ring wall self-weight: 325.6t;
- Sand filling weight inside the ring wall: 11304t,
- After the completion of the oil tank, the structural load is 12529.6t;
- Total load: 60006.4t
- The bottom plate of the tank is 1m above the ground,
- The sand cushion layer below the ground is 1m thick;

### *6.1. Overview of Site Geological Conditions Extracted from Survey Record - (Multiple Underlying Soil Layers i,ii,iii .....)*

- i. Silty clay: average water content of 33.3%; compression coefficient of 0.621MPa<sup>-1</sup>; compression modulus of 3.775 MPa; highly compressible soil with a void ratio of 1.091; standard bearing capacity of 100kPa;
- ii. Clay containing Silt: average water content is 33.64%; the maximum attainable water content 44.9%; void ratio is 1.022; compression coefficient is 0.526MPa<sup>-1</sup>; compression modulus of 4.265 MPa; highly compressible soil, with average bearing capacity standard value of 90kPa.
- iii. Silty Sand: uniformly distributed with stable thickness; good permeability; relatively high bearing capacity of 140kPa.

- iv. Silty Clay: uniformly distributed with stable thickness; average water content of 26.8%; void ratio of 0.879; compression coefficient of 0.336 MPa<sup>-1</sup>; the compression modulus is 8.813 MPa; bearing capacity of 130 kPa.
- v. Fine Sand: good permeability; average bearing capacity of 210 kPa;
- vi. Fine Clay: uniformly distributed; bearing capacity of 300 kPa;
- vii. Fine Sand: good permeability; bearing capacity of 350 kPa

Table 2. Parameters of Soil Layers of Foundation

Soil Layer	1	2	3	4	5	6	7
Type of Soil	Silty Clay	Clay containing Silt	Silty Sand	Silty Clay	Fine Sand	Fine Clay	Fine Sand
Depth	0~2.5	2.5~4.5	4.5~5.5	5.5~7.5	7.5~26.5	26.5~31	31 ~
Thickness	1.5~2.5	0~3	1.0~3.5	1.0~3.0	19.0~20.0	2.0~3.0	>30
w%	33.26	33.61		32.91		20.21	
$\gamma(\text{kN}/\text{m}^3)$	18.57	19.71	18.81			18.98	
e	1.091	1.022		0.906			
$I_L/w_L$	1.11/35.31	1.305/30.37		0.98/24.23		0.29/26.58	
$I_P/w_P$	14.31/20.92	19.34/18.98		13.45/21.79		8.62/17.96	
$\alpha_{1-2}(\text{MPa}^{-1})$	0.62	0.526		0.336			
$F_s(\text{MPa})$	3.775	4.265		8.813			

$C_v(cm^2/s)10^3$	1.57	1.12					
C(kPa)	14.93	9.25					
$\phi(^{\circ})$	21.58	27.02					
K(cm/s)	$1.0 \times 10^{-6}$	$6.5 \times 10^{-7}$	$1.0 \times 10^{-5}$	$1.2 \times 10^{-6}$	$7.4 \times 10^{-3}$	$1.3 \times 10^{-6}$	$8.2 \times 10^{-3}$
$F_k(kPa)$	100	90	140	130	210	300	350

Based on the above parameters, the best methods for reinforcement would be :

- i. Cement Deep Mixing
- ii. CFG Pile
- iii. Drainage

## 6.2. Cement Deep Mixing

### 6.2.1 Design Calculation

- Pile Diameter and Length

Based on the geotechnical investigation report, building load requirements, and local construction experience for this type of project, the diameter of the cement deep mixing pile is chosen as 500mm. Taking into account the engineering geological conditions and construction factors, the (5th) layer comprising of fine sand is then selected as the bearing layer of the pile end that penetrates all through the above silt soil type layers. Effective pile length is set at 9 m.

- Bearing Capacity of Single Pile

According to the geotechnical investigation report and the parameters of the cement deep mixing pile,  $\alpha=0.5$ . With this the standard value of the vertical bearing capacity of a single pile can be calculated as follows:

$$R_k^d = U_p \sum_{i=1}^n \bar{q}_{si} l_i + \alpha A_p q_p$$

$$= 1.57 \times (12 \times 1 + 9 \times 2.5 + 13 \times 1 + 12 \times 2 + 15 \times 2.5) + 0.4 \times 0.196$$

$$\times 180 = 185kN$$

Taking  $\eta=0.4$  the unconfined compressive strength of an indoor reinforced soil test with the same ratios as pile reinforcement soil of 90 days can be determined as follows:

$$f_{cu,k} = \frac{R_k^d}{\eta \times A_p} = \frac{185}{0.4 \times 196} = 2360kPa$$

With reference to the indoor mix ratio test data, the cement mixing ratio  $a_w$  can be taken as 18%.

- Composite Foundation

According to the required structural design requirements, the design loading  $f_{sp,k} \geq 220kPa$ , after substitution we get:

$$f_{sp,k} = m \frac{R_k^d}{A_p} + \beta(1 - m)f_{s,k}$$

The area replacement rate can be taken as  $m=0.208$ , we can then find the number of piles

$n = \frac{m \cdot A}{A_p} = 3307$ . When it comes down to construction, piles are generally used in groups with a common pile cap. A group may consist of two or three, or as many as ten to twelve piles depending on the design requirement. The load carrying capacity of a group of piles is given by: [34]

$(Q_u)_g = Nq_u n$ , where  $(Q_u)_g$  is Load carrying capacity of pile group; N is the number of piles;  $q_u$  is the allowable load per pile; n is the group efficiency. [34]

Its value for bearing or friction piles at sites where the soil strength increases with depth is found to be 1. For friction piles in soft clays the value on n is less than 1. The actual value of n depends on soil type, method of pile installation, and pile spacing. When piles are driven in loose, sandy soils, the soil is densified during driving, and  $n > 1$  in such cases. It has also been observed that if the spacing between piles is more than 2.5 times the pile diameter, the group efficiency is not reduced. Furthermore, the large pile to pile spacing will increase the overall cost of construction; meaning the reduction in load capacity due to the group effect can be estimated empirically. [34]

In such a case, the use of Feld's rule is probably the simplest. It states that the load capacity of each pile in a group is reduced by 1/16 on account of the nearest pile in each diagonal or straight row. [34]

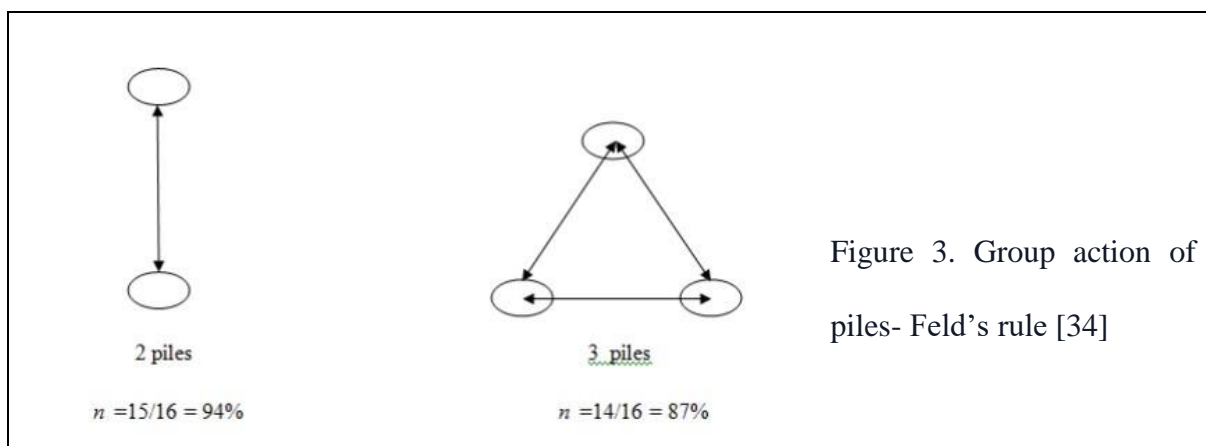


Figure 3. Group action of piles- Feld's rule [34]

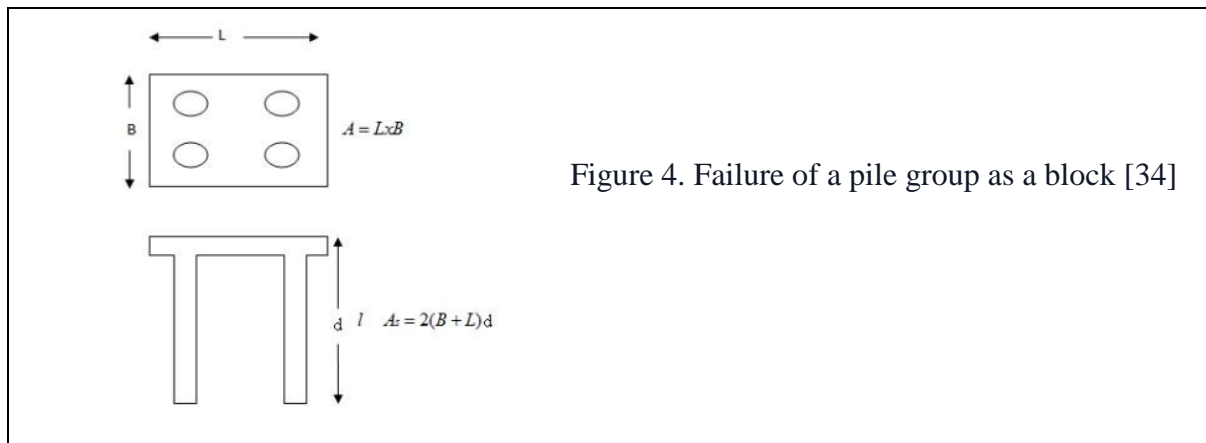


Figure 4. Failure of a pile group as a block [34]

A group of piles may fail as a block, i.e., by sinking into the soil and rupturing it at the periphery of the group Figure 4. To verify that the bearing capacity of the underlying layer foundation meets the requirements according to the principle of pile group action, we can solve:

$$f' = \frac{f_{sp,k}A + G - \bar{q}_s A_s - f_{s,k}(A - A_1)}{A_1} = 162.8\text{kPa} < 180\text{kPa}$$

### 6.2.2 Platform foundation settlement check

The Settlement of Reinforced area

$$S_1 = \frac{(p + p_0)}{2E_0} = 40\text{mm}$$

Subsidence settlement

$$S_2 = \psi_s \sum S'_i = 67\text{mm}$$

Total Settlement

$$S = S_1 + S_2 = 107\text{mm}$$

Meets settlement requirements and is feasible

### 6.2.3 Final Calculation and Design Result

- ❖ This plan designs a total of 3307 deep cement mixing piles with a pile diameter of 500mm and an effective pile length of 900m.
- ❖ Should utilise grade 32.5 ordinary Portland cement with a the cement mixing ratio of 18%,
- ❖ A pile cushion of 500mm should be made available for protection of pile head during mixing. Mixing should be carried out at 4 meter intervals for better effect.

### 6.3. CFG Pile Composite Foundation

#### 6.3.1 Design Calculation

##### Pile bearing capacity ( $R_K$ )

$$R_K = \frac{1}{r_{sp}} \left( V_p \sum_{i=1}^n q_{si} L_i + q_p A_p \right)$$

Where  $V_p$  is pile perimeter;  $q_{si}$  standard value of ultimate resistance of the  $i$ -th layer of soil on the sides of the pile;  $q_p$  standard value of the resistance of the pile end;  $L_i$  is the thickness of the  $i$ -th layer of soil.

##### Standard Value Bearing Capacity Of CFG Pile Composite Foundation:

$$f_{sp,k} = m \frac{R_K}{A_p} + \alpha \beta (1 - m) f_k$$

Where  $f_{sp,k}$  is the combined foundation bearing capacity in kPa;  $m$  is area replacement rate,;  $A_p$  is the cross sectional area of the pile in  $m^2$ ;  $f_k$  is the standard values of the natural foundations natural bearing capacity in kPa;  $\alpha$  is the ratio of the standard bearing capacity value of the reinforced pile to the standard bearing capacity value of the natural foundation;  $\beta$  is the pile-soil strength development coefficient usually between 0.75~1.0;  $R_K$  is the standard value for the bearing capacity of a single pile in kN.

#### 6.3.2 Calculation Parameter Selection

Table 3. CFG Pile Parameter Design Table

	$q_{si}$	$q_p$	$L_i$
First Layer	25	-	1
Second Layer	23	-	2.5
Third Layer	24	-	1
Fourth Layer	26	-	2
Fifth Layer	55	2150	8.5

#### 6.3.3 Final Calculation and Design Result

After calculation, results are as follows:

- ❖ Pile Length  $L=12m$
- ❖ Pile Diameter  $D=400mm$
- ❖ Pile Tip Elevation  $1m$
- ❖ Standard Value For The Bearing Capacity Of A Single Pile  $R_K= 350kN$
- ❖ Area Replacement Rate  $m=0.05$
- ❖ Standard Value for Composite Foundation Bearing Capacity  $f_{sp,k}= 220kPa$ .

### 6.4. Preloading in Foundation

#### 6.4.1 Calculation Principle

##### Degree of Consolidation

Using the Redulic-Terzagh consolidation theory, we can solve:

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2} + C_h \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right)$$

Where are  $C_v$  and  $C_h$  are vertical and horizontal joint coefficients respectively. If only vertical consolidation is to be considered, we can use the first portion of the equation as follows:

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2}$$

Where  $u$  is the excess pore water pressure and  $C_v$  is vertical consolidation coefficient.

The average radial consolidation degree of the foundation  $\bar{U}_r$  can be calculated using the Terzaghi method as follows:

$$\bar{U}_r = \frac{8}{\pi^2} e^{-\frac{\pi^2 T_v}{4}}$$

Where  $T_v$  is the consolidation time factor;  $T_v = \frac{C_v t}{H^2}$  with  $t$  being consolidation time.

In actual engineering, the load is often gradually increased in stages, hence appropriate algorithms such as Terzaghi correction method and Zeng Guoxi's algorithm are considered. Furthermore, in order to simplify the actual loads into multi-level constant velocity loadings, the following formula is commonly used:

$$\bar{U}_t = \sum_1^n \frac{q_n}{\sum \Delta p} \left[ (T_n - T_{n-1}) - \frac{\alpha}{\beta} - e^{\beta t} (e^{\beta T_n} - e^{\beta T_{n-1}}) \right]$$

$\bar{U}_t$  is the Average consolidation degree of foundation under multi-level constant velocity loadings;  $q_n$  is the load loading rate;  $\sum \Delta p$  is the accumulated value of load;  $T_{n-1}$  and  $T_n$  are the loading start and end times;

For sand soil layers 5 and 7 are with good permeability, it is not necessary to use vertical drained consolidation to deal with this part of the foundation as these are horizontally permeable. In light of this the values  $\alpha$  and  $\beta$ , using the Terzaghi method, are  $\alpha = \frac{8}{\pi^2}$  and  $\beta = \frac{\pi^2 C_v}{4H^2}$  respectively.

#### 6.4.2 Estimation of Foundation Strength Growth

Can be estimated utilises two main methods of computation designed by Zeng Guoxi which are ;

- i. Shear strength of any point in the foundation at any time

$$\tau_f = \tau_{f0} + \Delta\tau_{fc} - \Delta\tau_{f\tau}$$

Where  $\tau_f$  is the natural shear strength of a certain point in the foundation before loading (can be determined experimentally through unconfined compression strength tests and triaxial undrained triaxial shear testing);  $\Delta\tau_{fc}$  is the increase in shear strength due to consolidation;  $\Delta\tau_{f\tau}$  is the shear strength attenuation due to shear creep.

- ii. Shear strength of any point in the foundation at any time

$$\tau_f = \eta(\tau_{f0} + \Delta\tau_{fc})$$

Where  $\eta$  is the reduction coefficient that takes into account the effects of shear creep and other factors on strength, recommended value of  $\eta$  is 0.75 ~ 0.9.

For ease of calculation, the above can be used, however in most cases, shear strength is calculated using the following formula:

$$\tau_f = \sigma' \tan \varphi'$$

Where  $\sigma'$  is the normal effective compressive stress on the shear plane;  $\varphi'$  is the effective internal friction angle of the soil. For maximum effective principal stress, the following equation can be used:

$$\tau_f = \sigma' \frac{\sin \varphi' \cos \varphi'}{1 + \sin \varphi'} = K \sigma'$$

Therefore as a result, the strength increased due to foundation consolidation is:

$$\Delta \tau_{fc} = K \cdot \Delta \sigma'_1 = K(\Delta \sigma_1 - \Delta u) = K \Delta \sigma_1 \left(1 - \frac{\Delta u}{\Delta \sigma_1}\right) = KU \Delta \sigma_1$$

With further substitution we can get:

$$\tau_f = \eta [\tau_{f0} + K \Delta \sigma_1 - \Delta u] \quad \text{or} \quad \tau_f = \eta [\tau_{f0} + K \cdot U \cdot \Delta \sigma_1]$$

Where  $K$  or  $\frac{\sin \varphi' \cos \varphi'}{1 + \sin \varphi'}$ ;  $\Delta u$  are the pore water pressure at a certain point in the foundation caused by the load increment, measured on site;  $\sigma_1$  is the maximum principal stress increment at a certain point in the foundation caused by the load, calculated according to the elastic theory formula;  $U$  is the degree of consolidation at a certain point in the foundation,

### 6.4.3 Foundation Stability Calculation

Calculation of foundation stability is generally simplified into a plane problem, and the arc sliding surface method is used to perform the overall calculation. This method is commonly used to assess the potential for soil movement and failure, particularly in deep excavations or foundation pits in soft soil areas. It takes into account various factors such as soil properties, groundwater conditions, external loads, and geometry of the excavation to model the behavior of the soil mass accurately. [35, 36, 37]

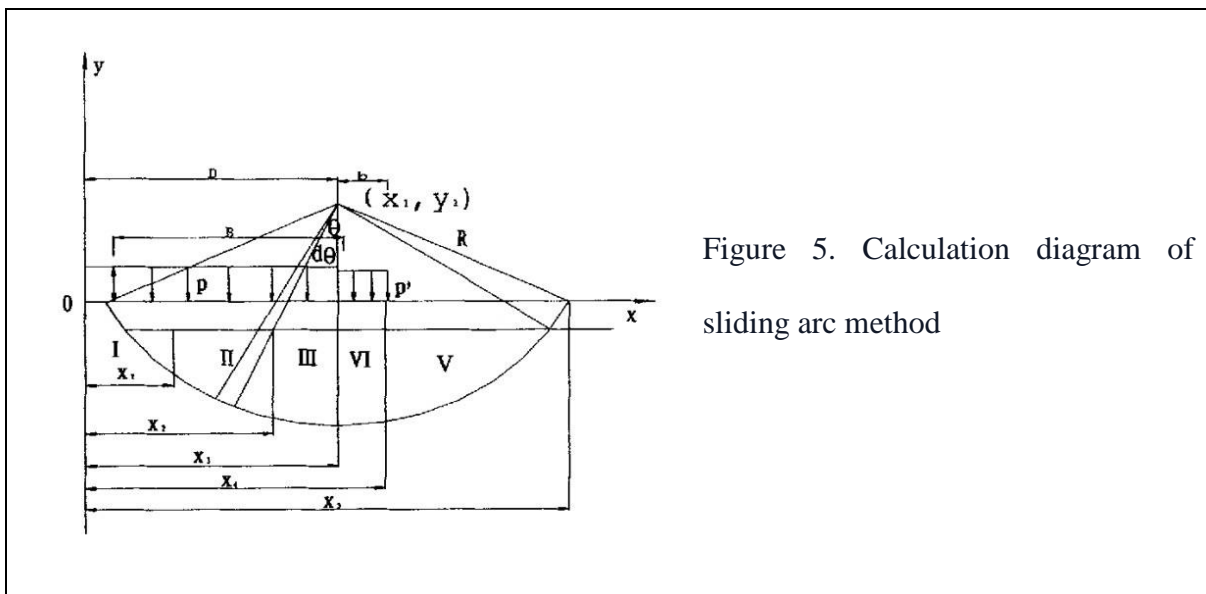


Figure 5. Calculation diagram of sliding arc method

### Anti-slip moment calculation

Hard Shell Layer Anti Slip Moment is  $M_{anti} = R_i^2(\tau_0 + \tau'_0)\theta_0$ . Where  $\tau_0$  is the Average shear strength of the hard shell soil layer in the tank;  $\tau'_0$  is the Average shear strength of the hard shell layer soil layer outside the tank;  $\theta_0$  is the central angle corresponding to the part of the hard shell layer cut by the sliding arc.

The anti-slip moment of the soft soil layers (Zones I, II, III, IV) below the hard shell layer can be found using:

$$\tau_{fi} = \tau_{02} + \lambda_{iz}$$

Take the anti-slip moment of zone II as an example. The change of foundation soil shear strength with depth in this area is:

$$\tau_{f2} = \tau_{02} + \lambda_{2z}$$

$$z = R_j \cos \theta - y_i$$

$$\theta'_2 = \sin^{-1} \frac{D - x_2}{R_j}$$

$$\theta'_1 = \sin^{-1} \frac{D - x_1}{R_j}$$

Therefore we can plug and play to get:

$$\begin{aligned} M_{0anti} &= \int_{\theta'_1}^{\theta'_2} R_j d\theta \cdot \tau_f \cdot R_f = R_j^2 \int_{\theta'_2}^{\theta'_1} [\tau_{02} + \lambda_2(R_j \cos \theta - y_i)] d\theta \\ &= R_j^2 \left[ (\tau_{02} + \lambda_2 y_i) \left\{ \sin^{-1} \frac{D - x_1}{R_j} - \sin^{-1} \frac{D - x_2}{R_j} \right\} + \lambda_2 (x_2 - x_1) \right] \end{aligned}$$

The other zones can also be calculated in the same manner. Any anti-slip moment caused by back pressure loads originating from surrounding rubble can be found using:

$$M_{anti} = \frac{1}{2} p' b^2$$

Where  $p'$  is the back pressure loading in (kPa) ;  $b$  is the width of load in (m).

In regards to sliding moment,  $M_{sliding} = \frac{1}{2} p B^2$ , where  $p$  is the load of tank (kPa),  $B$  is the Width of sliding arc cutting tank bottom.

### Rate of Settlement Calculation

Loading Phase:

$$S_t = \frac{m_s S_c (U_t - U_{t_{i-1}})}{t - t_{i-1}}$$

End of Loading Phase

$$S_t = \frac{m_s S_c (U_t - U_{ti})}{t - t_i}$$

$S_t$  is the rate of settlement;  $S_c$  is the consolidation settlement under total load;  $m_s$  is the empirical coefficient for settlement.

### Calculation of Settlement

The overall process of geotechnical settlement is made up of three main components occur at different stages:

- Immediate settlement (also known as elastic settlement)  $S_d$
- Consolidation settlement (or primary settlement)  $S_c$
- Creep settlement (or secondary settlement).  $S_s$

Settlement can be calculated through the following formula:

$$S_\infty = S_d + S_c$$

$$S_c = \sum_1^n \frac{e_{0i} - e_{1i}}{1 + e_{0i}} \Delta h_i$$

For settlement occurring at different times during the loading process, through the following formula:

$$S_t = \left[ (\Psi_s - 1) \frac{p_t}{\sum \Delta p} + \bar{U}_t \right] S_c$$

### 6.4.4 Final Calculation and Design Result

Table 4. Table of Calculation Results

Stage		1	2	3	4	5	6
Item Being Calculated		1	2	3	4	5	6
Load Increment per Level kPa		46.5	50	50	50	30	15
Cumulative Load kPa		46.5	96.5	146.5	196.5	226.5	241.5
Starting time of each level $t_{i-1}$ (days)		0	41	63	93	126	159
Ending time of each level $t_1$ (days)		30	49	73	105	136	161
Offload time (days)		11	14	20	21	23	4
Loading rate (kPa/d)		2	6.5	6.5	6.5	6.5	6.5
Loading rate (kpa/d)		2	6.5	6.5	6.5	6.5	6.5
$U_t$	t=35	12.5					
	t=45	22.3					
	t=53	22.7	1.28				
$U_t$	t=63	23.9	3.01				
	t=71	24.1	3.21	1.28			
	t=81	25.0	4.26	3.01			
	t=89	25.1	4.41	3.21	1.28		
	t=99	25.8	5.16	4.26	3.01		
	t=117	25.9	5.27	4.41	3.21	1.28	

		t=130	26.4	5.81	5.16	4.26	3.01	
		t=138	27.4	6.84	6.60	4.515	4.26	3.01
		t=148	27.6	7.08	6.94	6.74	4.81	2.33
	$T_i$ Total Degree of Consolidation		15.5	28.5	40.1	53.3	67.2	74.4
i	Total degree of consolidation at the end of stage		22.3	32.3	44.7	58.2	72.5	77.4
	Total degree of consolidation at the end of current stage		79.7	67.3	71.1	75	78.3	77.4
	Increased intensity		13.7	19.8	27.4	35.7	44.4	47.4
	Rate of Settlement mm/d		1.75	4.74	5.19	5.42	5.51	5.52
i	Rate of Settlement at the End of Stage		1.38	1.76	2.16	2.36	2.47	2.79
Stability	Whole Structure	Arc Method	5.24	3.16	2.52	2.19	2.19	2.09
		Skempton Method	3.54	2.44	2.06	1.87	1.76	1.71
	Section 0.28	Arc Method	2.74	1.88	1.56	1.39	1.28	1.22
		Skempton Method	2.18	1.73	1.52	1.43	1.36	1.34

## 7. Foundation Optimization Analysis

Commonly used methods for optimization and evaluation of soft soil foundation reinforcement schemes for oil storage tanks include analytic hierarchy process, fuzzy mathematics theory and the gray system theory amongst others. For this particular engineering situation analysis, the analytic hierarchy process was used.

The AHP process involves deriving priority vectors that represent the relative importance of different elements within a decision-making framework. Here's a step-by-step breakdown to help clarify the concept: [38, 39]

### Step One: Pairwise Comparisons and Judgment Matrices:

In AHP, decision-makers compare elements pairwise to establish their preferences or priorities.

These comparisons are typically captured in a judgment matrix, where each element represents the preference of one alternative over another. [38, 39]

### Step Two: Deriving Priority Vectors:

To obtain a priority vector from the judgment matrix, normalization is performed. Normalization involves dividing each element in a column by the sum of all elements in that column. After normalization, averaging the values in each row yields the priority vector. [38, 39]

### Step Three: Eigenvector Precision Calculation:

The process of raising the judgment matrix to consecutive powers and obtaining "another priority vector" is related to eigenvalues and eigenvectors. By calculating the eigenvector corresponding to the maximum eigenvalue of the judgment matrix, you arrive at a final expression of preferences between elements. The eigenvector with the highest eigenvalue signifies the most critical priorities or preferences within the decision framework. [38, 39]

### Significance of Eigenvector Precision:

The eigenvector matching the maximum eigenvalue provides a precise representation of priorities as it encapsulates both the relative importance and interdependencies among alternatives. This precision ensures that decisions are based on comprehensive assessments that consider not only individual preferences but also how they interact within the decision hierarchy. [38, 39]

Figure 6 shows a summary of the AHP process and Figure 7 Shows the Analytical Hierarchy Process Model that was established after carefully analyzing the interrelationship between relevant factors.

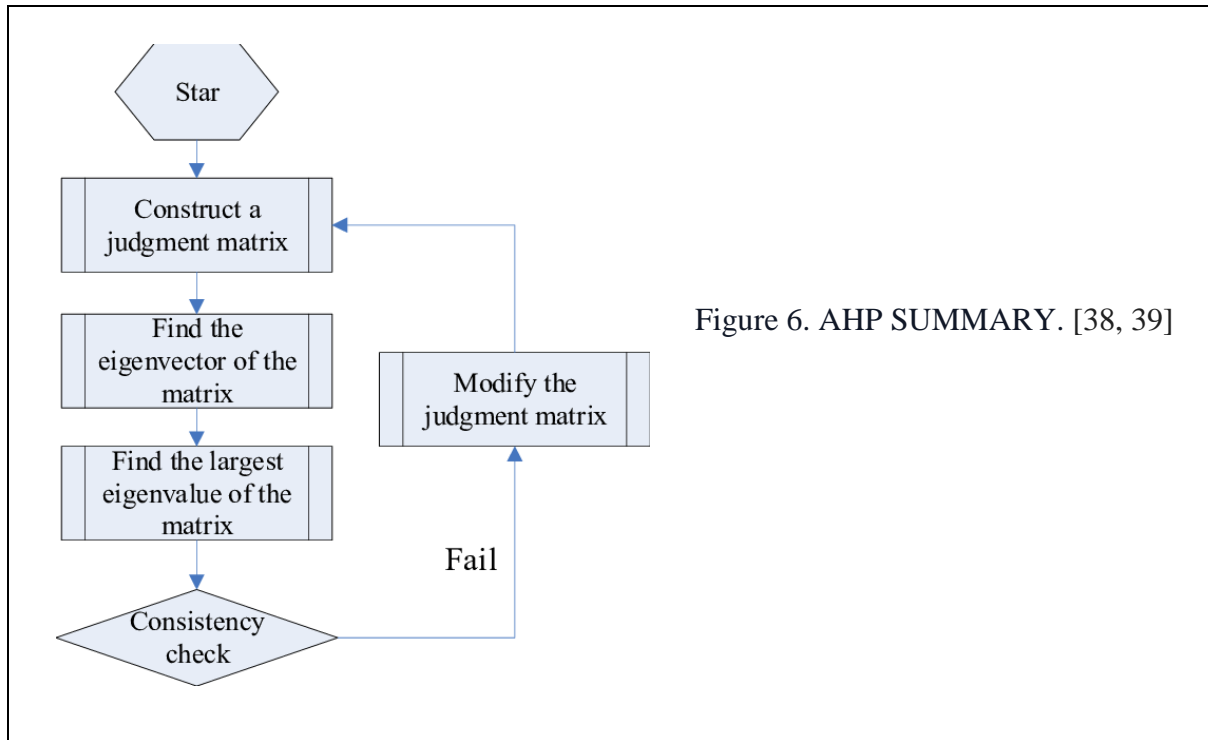
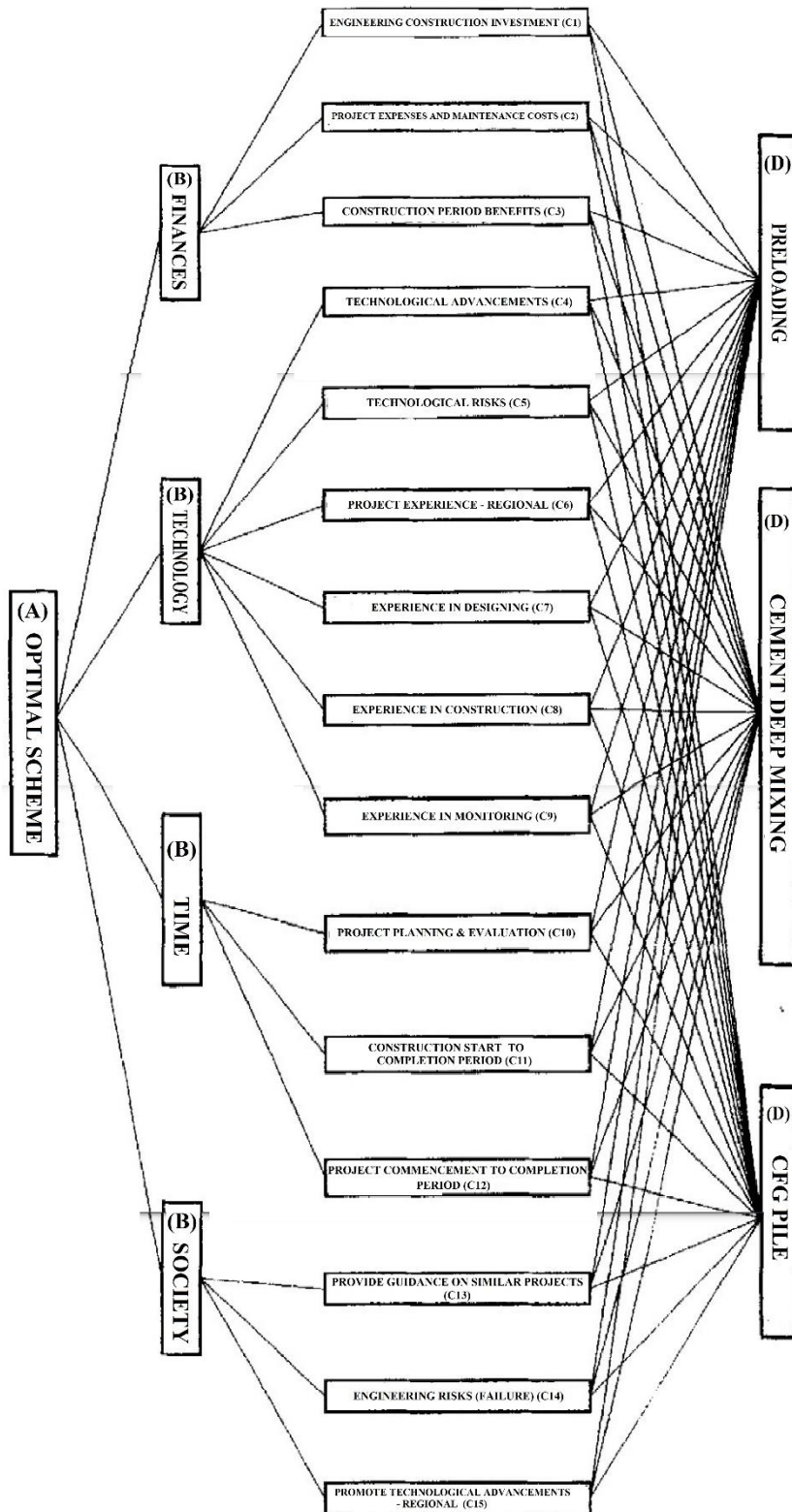


Figure 6. AHP SUMMARY. [38, 39]

Figure 7. ANALYTICAL HEIRACHY PROCESS MODEL



### 7.1. Optimal Scheme Selection Procedures

- 1) The judgment matrix of B towards A (The second level towards the highest level)

Table 5. B's judgment matrix towards A

A	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	B <sub>4</sub>
B <sub>1</sub>	1	10/3	5/2	10/3
B <sub>2</sub>	3/10	1	3/4	1
B <sub>3</sub>	2/5	4/3	1	4/3
B <sub>4</sub>	3/10	1	3/4	1

The judgment matrices of other levels can also be represented in a similar manner.

- 2) Sorting

Calculate the eigenvector precision of the judgment matrix for B towards A :

W=(0.3599, 0.1920, 0.2560, 0.1920)

- 3) Consistency Check

Find the principal eigenvalue or the maximum magnitude eigenvalue,  $\lambda_{max} \approx 4.201$ , then

$$CI = \frac{\lambda_{max} - n}{n - 1} = 0.067$$

Since the order is 4, RI = 0.9 so

$CR = \frac{CI}{RI} = 0.074 < 0.10$  (This shows that Judgment Matrix AB meets Consistency)

Hence  $W_{B-A} = (0.3599, 0.1920, 0.2560, 0.1920)$  is Level B's single sorting for A.

The single sorting of other levels can be carried out in a similar manner.

### 7.2. Overall Sorting of Levels

Table 6. B-C Overall Sorting

	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	B <sub>4</sub>	Level C Overall Sorting
W	0.3599	0.1920	0.2560	0.1920	
C <sub>1</sub>	0.6524	0	0	0	0.3549
C <sub>2</sub>	0.2124	0	0	0	0.143
C <sub>3</sub>	0.1352	0	0	0	0.0962
C <sub>4</sub>	0	0.2111	0	0	0.0342
C <sub>5</sub>	0	0.1889	0	0	0.0342
C <sub>6</sub>	0	0.1423	0	0	0.0225
C <sub>7</sub>	0	0.1577	0	0	0.0225
C <sub>8</sub>	0	0.2111	0	0	0.0342
C <sub>9</sub>	0	0.0889	0	0	0.0143
C <sub>10</sub>	0	0	0.2314	0	0.0395

C <sub>11</sub>	0	0	0.2314	0	0.0395
C <sub>12</sub>	0	0	0.5372	0	0.168
C <sub>13</sub>	0	0	0	0.2864	0.045
C <sub>14</sub>	0	0	0	0.4000	0.0532
C <sub>15</sub>	0	0	0	0.3136	0.0451

Table 7. C-D Overall Sorting

	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>5</sub>	C <sub>6</sub>	C <sub>7</sub>	C <sub>8</sub>
W <sub>i</sub>	0.3549	0.143	0.0962	0.0342	0.0342	0.0225	0.0225	0.0342
D <sub>1</sub>	0.6	0.1521	0.125	0.500	0.1521	0.2462	0.2462	0.2462
D <sub>2</sub>	0.20	0.2462	0.375	0.375	0.2461	0.6017	0.6017	0.6017
D <sub>3</sub>	0.20	0.6017	0.500	0.500	0.6017	0.1521	0.1521	0.1521

Table 8. C-D Overall Sorting

	C <sub>9</sub>	C <sub>10</sub>	C <sub>11</sub>	C <sub>12</sub>	C <sub>13</sub>	C <sub>14</sub>	C <sub>15</sub>	W
W <sub>i</sub>	0.0143	0.0395	0.0395	0.168	0.0451	0.0532	0.0451	
D <sub>1</sub>	0.2462	0.2951	0.2946	0.2104	0.5012	0.2104	0.5012	0.5012
D <sub>2</sub>	0.6017	0.2951	0.6008	0.2541	0.1423	0.2541	0.1423	0.2355
D <sub>3</sub>	0.1521	0.4199	0.2946	0.5319	0.3565	0.5319	0.3565	0.2635

Consistency Check

$CR - \frac{CI}{RI} = 0.0321 < 0.10$  (This shows that Overall Sorting of C-D meets Consistency)

Upon observation, The Option D1 (Preloading in Foundation) has a greater weight hence is deemed the optimal scheme. Following in suit is the Cement Deep Mixing, after which CFG Pile Composite Foundation comes third in rank.

**8. Analysis of Project Implementation and Monitoring Results.**

*8.1. Observation results and analysis of ring beam subsidence*

After optimization, this project finally adopted the preloading in foundation method which meets the desired requirements. The following was observed:

Figure 8. Layout Plan of Monitoring Points

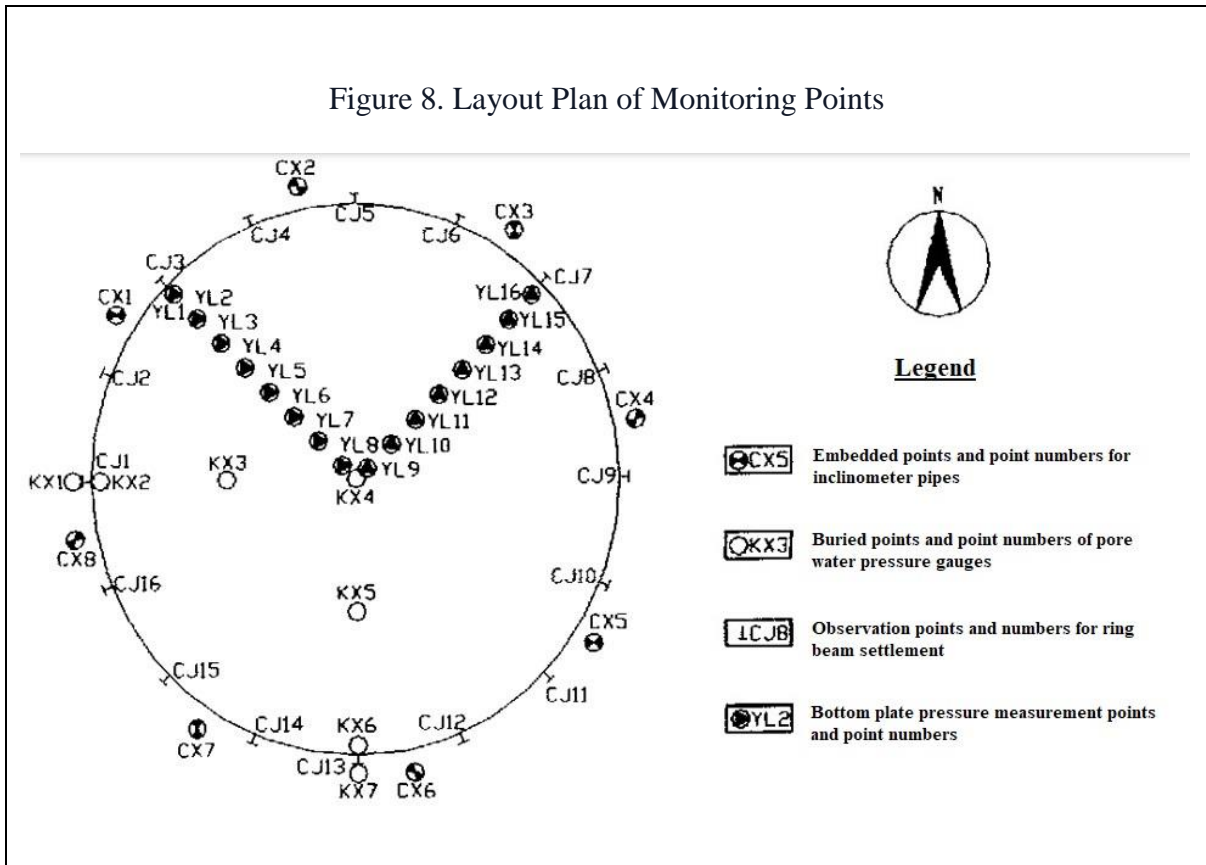
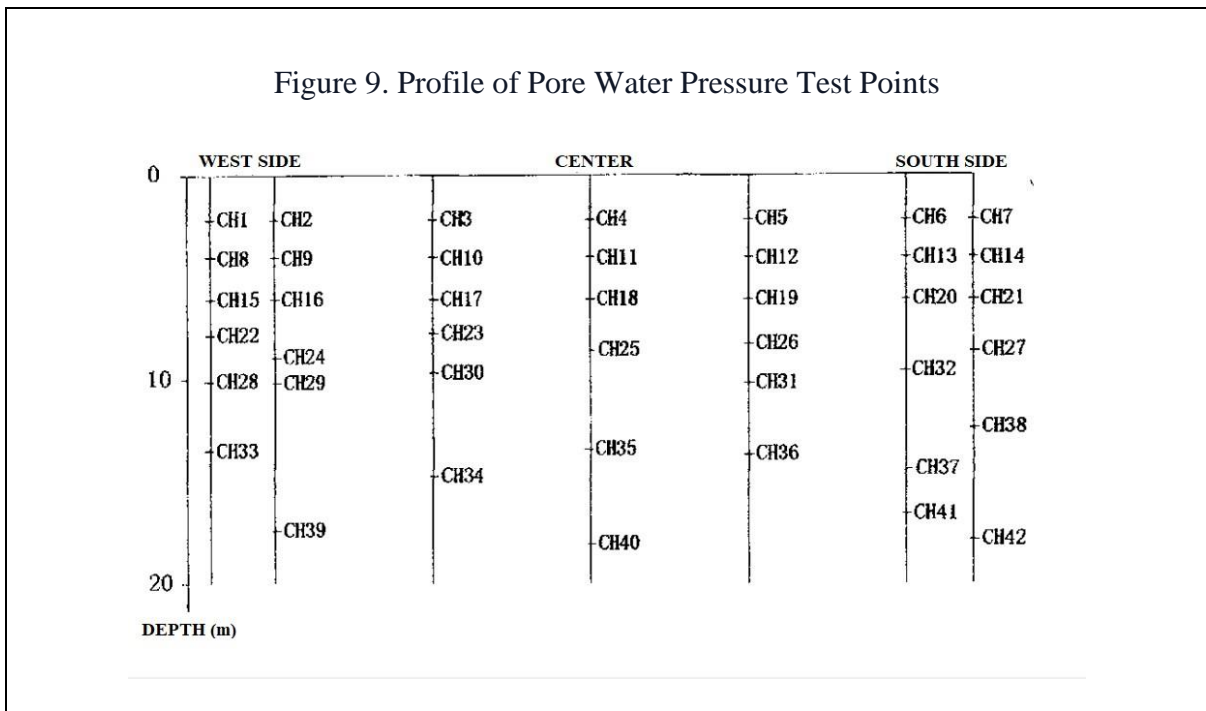
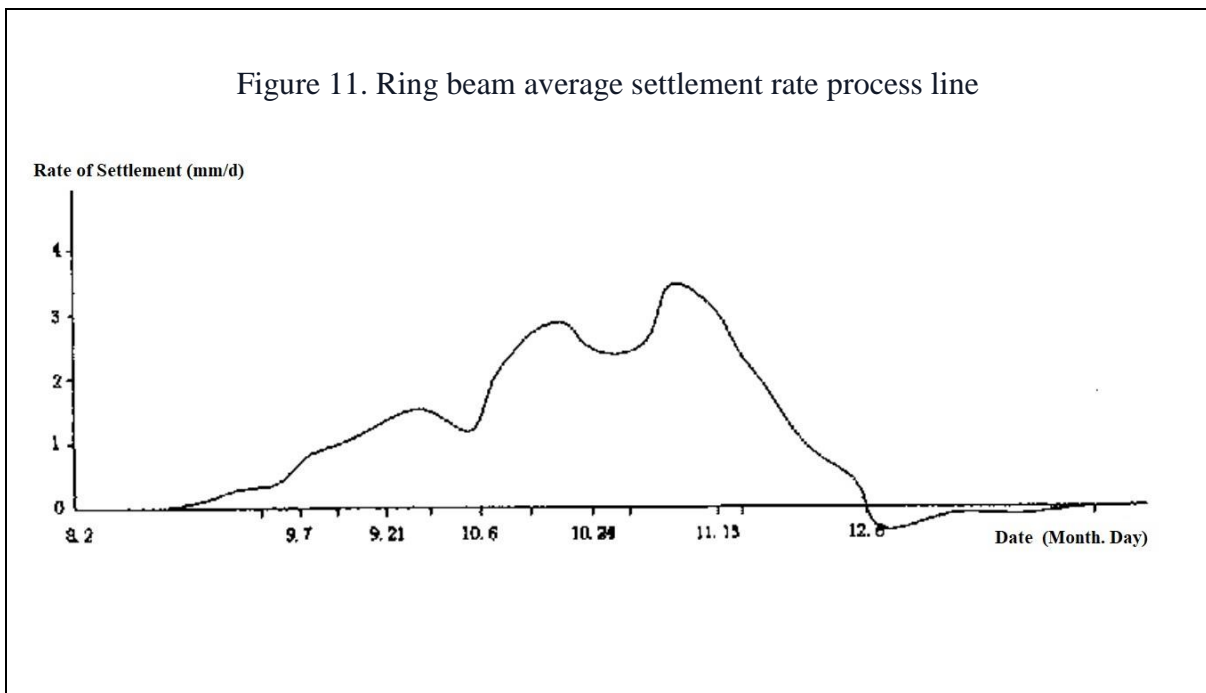
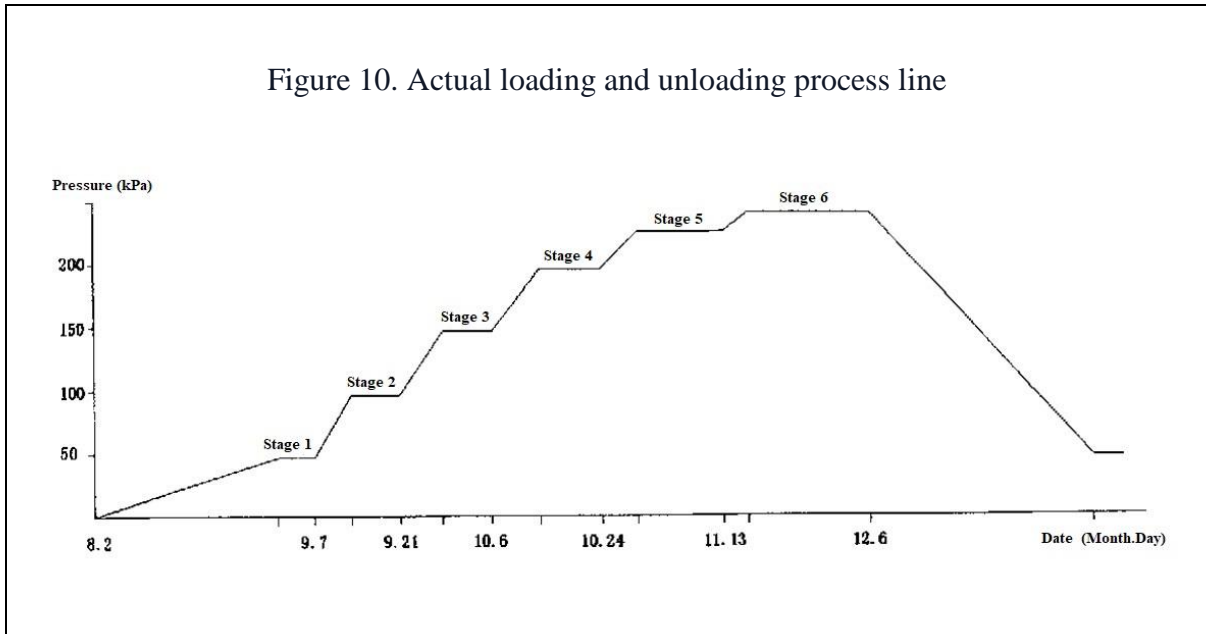


Figure 9. Profile of Pore Water Pressure Test Points

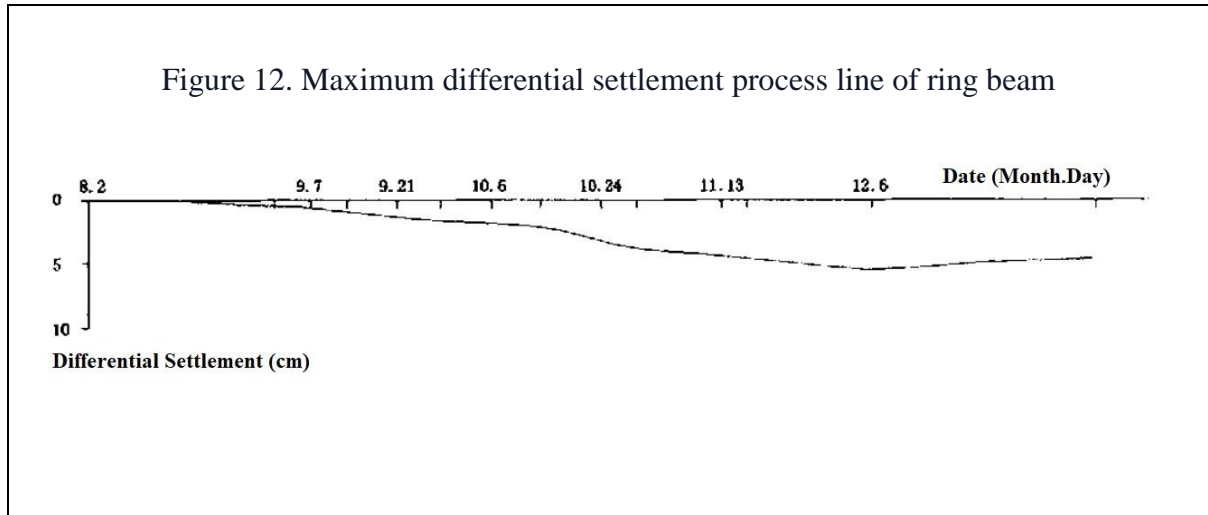


From the actual loading and unloading process lines in Figure 10 below, it can be seen that the actual loading days are fewer than the calculated ones. This is because the horizontal circumferential structure of the silt interlayer in the soil was not considered during the calculations.



It can be seen from the average settlement rate process line of the ring beam (Figure 11 above) that each grade is like the initial load. During the period, the settlement rate showed an overall increasing trend, and the settlement rate in most graded loading and non-loading sections showed a significant decreasing trend. It can be seen that in order to ensure the stability of the foundation soil in the later stage of water filling, it is of great significance to appropriately extend the load-stop time. At the beginning of the water release and unloading section, the settlement rate appears negative, indicating

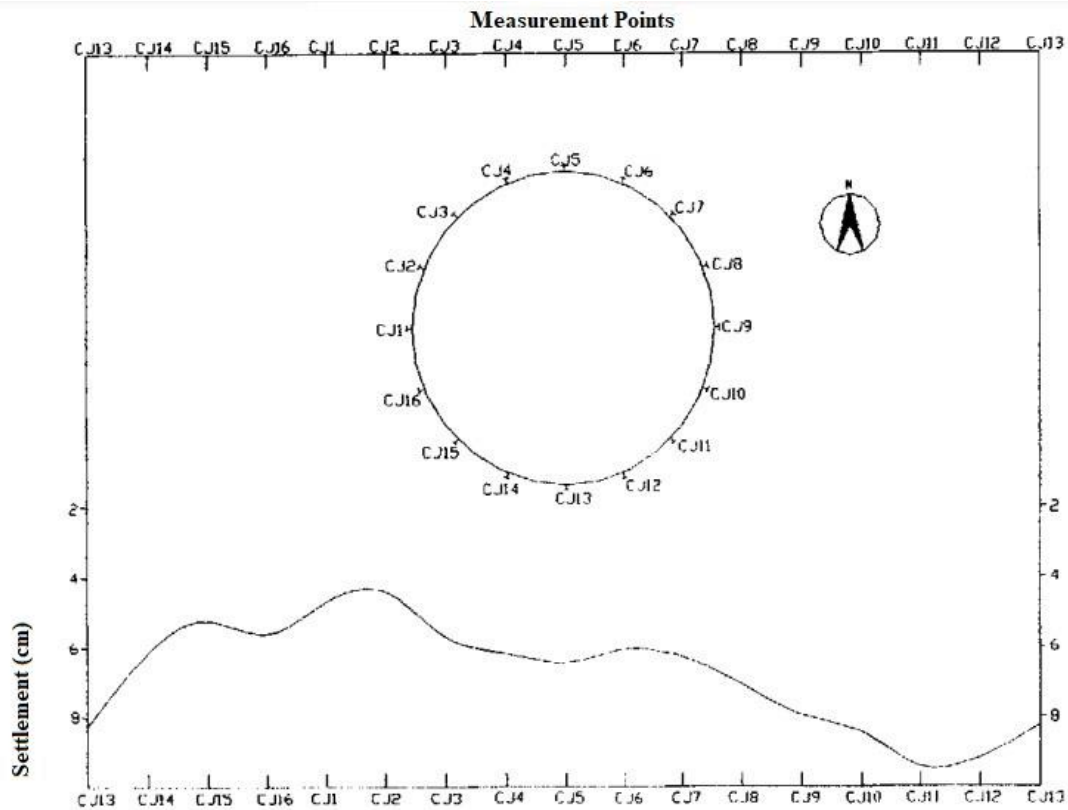
that the foundation soil has rebounded. Since the unloading is densely graded and the unloading rate is basically unchanged, the rebound rate appears from large to small, and the final rate is zero. The rebound is stable.



It can be seen from the maximum differential process line of the ring beam (figure 12 above) that the maximum settlement point CJ11 and the minimum settlement point cJ2 is similar. It also gradually increases with the increase of load with no sudden abrupt change. After the load is unloaded and the elastic force is released, the differential settlement slightly decreases.

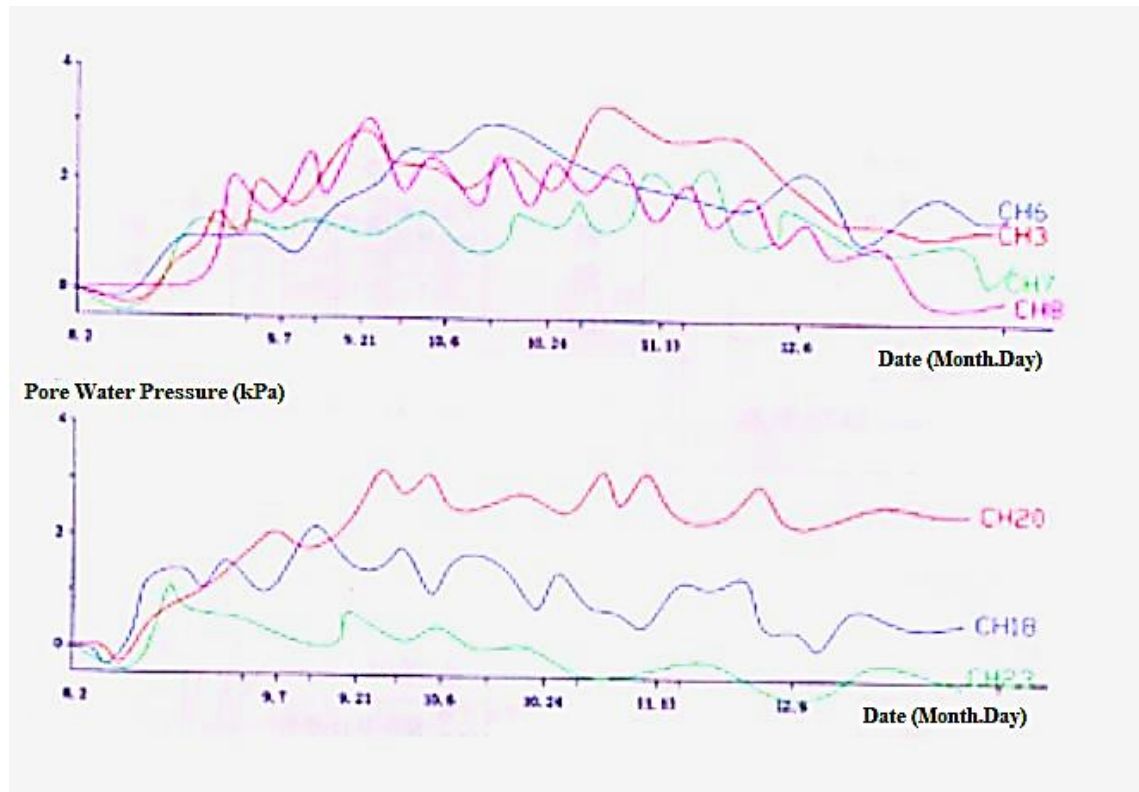
From the expanded diagram of the maximum settlement of each of the measuring points of the ring beam (as shown in Figure 13 below), it can be seen that during the entire water filling process, the overall inclination and deflection of the tank surface tends to increase with the increase of load, which is basically a sinusoidal curve with no uneven. This is because the distribution of the inner layer in the tank area is relatively uniform. Each measuring point is basically within the same plane, with slight local deflection, but no experiencing of bending failure phenomenon in the ring beam. According to the analysis and calculation results, the maximum overall inclination of the plane is 1.6 %, which is far below the control index requirements. The deflection occurs near the maximum settlement point CJ11, with a value of 0.98 %, which is also far below the control index requirements.

Figure 13. Expanded diagram of the maximum settlement at each measuring point of the ring beam



8.2. Pore water pressure monitoring results and analysis

Figure 14. Process line of pore water pressure change



The pore water pressure change process line is drawn from the actual measurement results (Figures 14 above). The results show that the amplitude of the change in excess static pore water pressure at each buried measurement point is not significant, but there are significant differences among different points, which are related to the distribution of soil layers, stress distribution, and drainage conditions of the soil layers. In addition, the increase and dissipation of excess static pore water pressure during the loading process occur simultaneously, and the measured values reflect the result of their simultaneous action; The pore water pressure variation values of  $\beta$  at each measuring point, namely the ratio of the excess pore water pressure increment  $\Delta u$  to the load increment  $\Delta p$ , are all lower than the control indicators.

The change in pore water pressure  $\beta$  value is used to determine whether the foundation soil can undergo plastic failure under load. One important indicator is to limit the value of  $\beta$  to ensure that the effective stress corresponding to the measurement point increases with the increase of load, so as to stabilize the foundation soil and increase its strength.

In addition, it can be seen from the pore pressure change process line that after water filling and loading at all levels, the pore water pressure dissipates quickly and the relationship between the curve and the loading process line is good, indicating that the vertical drainage path of the foundation soil is shorter and the horizontal drainage conditions are better.

8.3. Analysis and Result Monitoring of horizontal displacement of foundation soil

Figure 15. Process line of tank foundation soil horizontal displacement

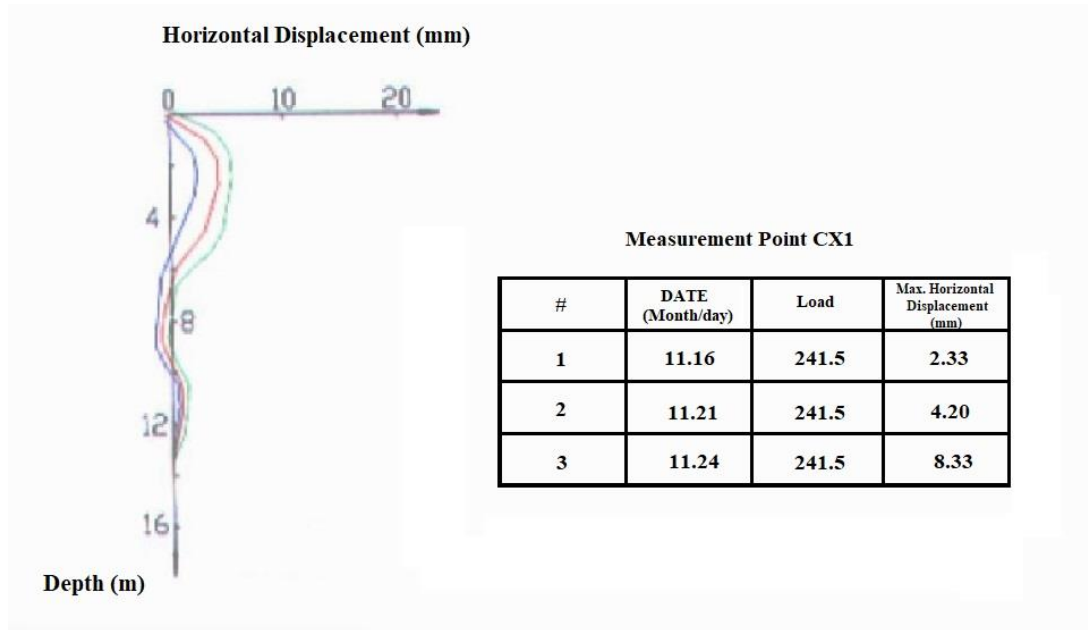
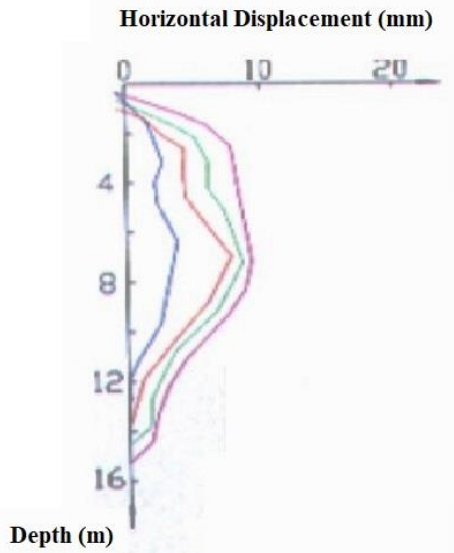


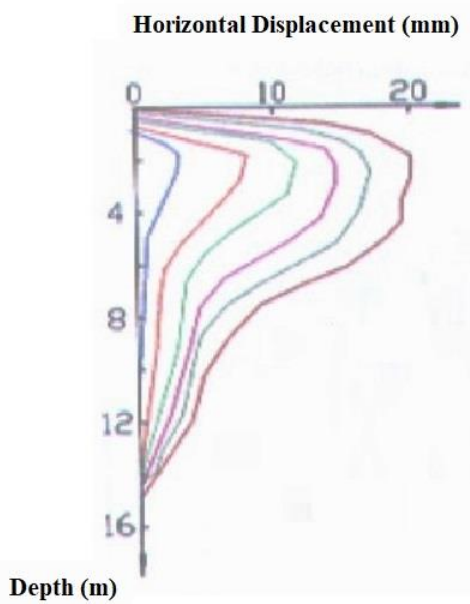
Figure 16. Process line of tank foundation soil horizontal displacement



Measurement Point CX3

#	DATE (Month/day)	Load	Max. Horizontal Displacement (mm)
1	11.7	226.5	3.67
2	11.16	241.5	7.70
3	11.21	241.5	9.34
4	11.24	241.5	10.30

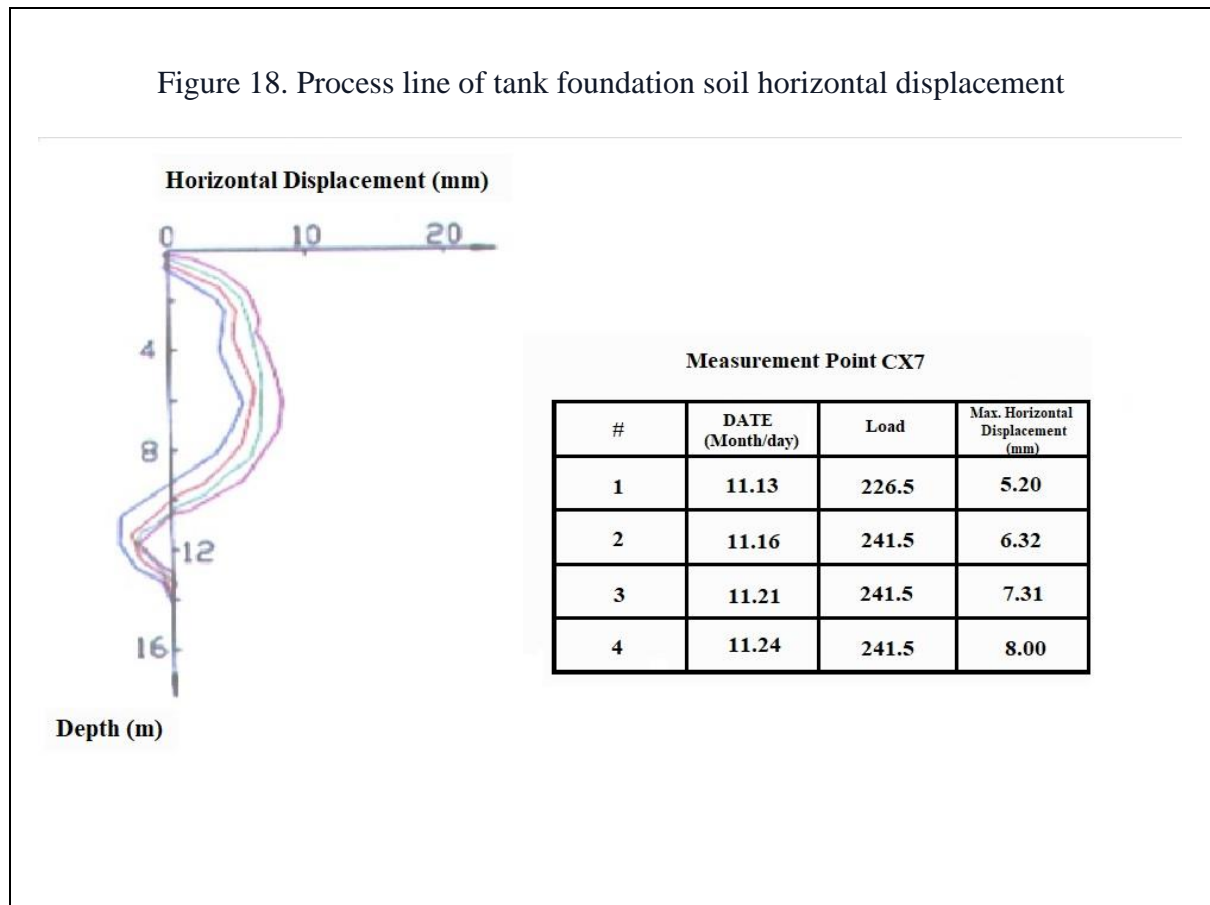
Figure 17. Process line of tank foundation soil horizontal displacement



Measurement Point CX5

#	DATE (Month/day)	Load	Max. Horizontal Displacement (mm)
1	10.29	196.5	3.20
2	11.7	226.5	8.20
3	11.13	226.5	11.67
4	11.16	241.5	14.34
5	11.21	241.5	17.00
6	11.24	241.5	20.20

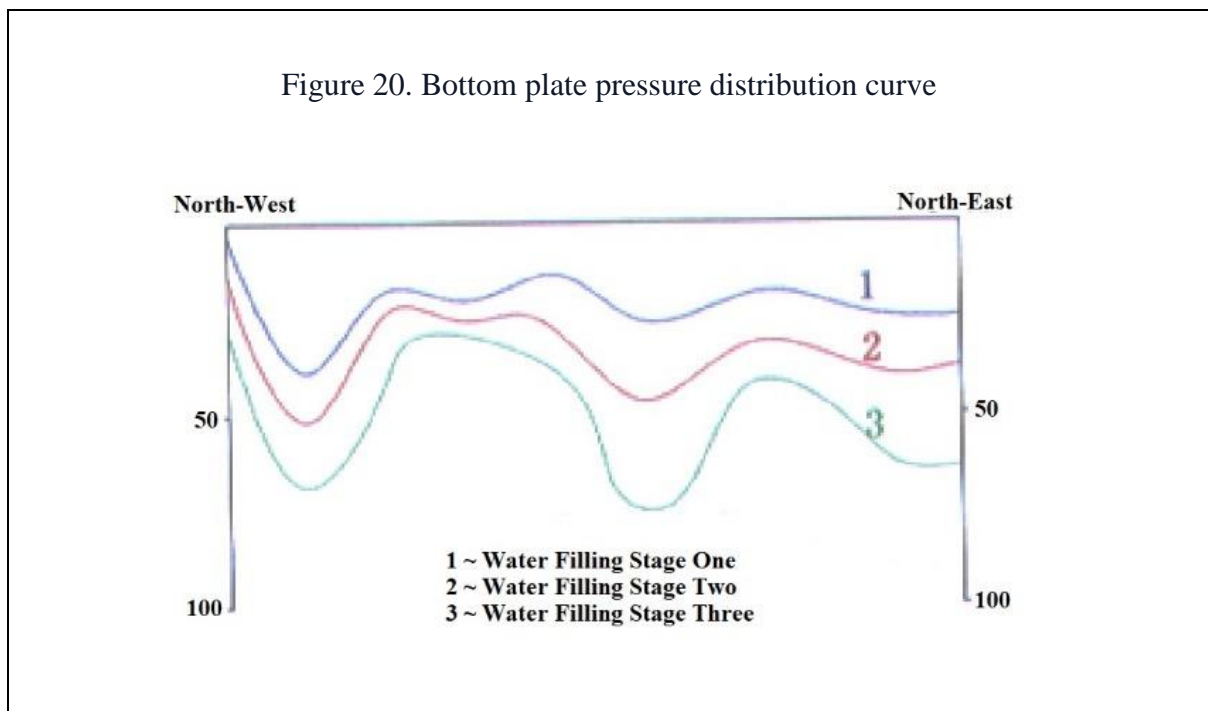
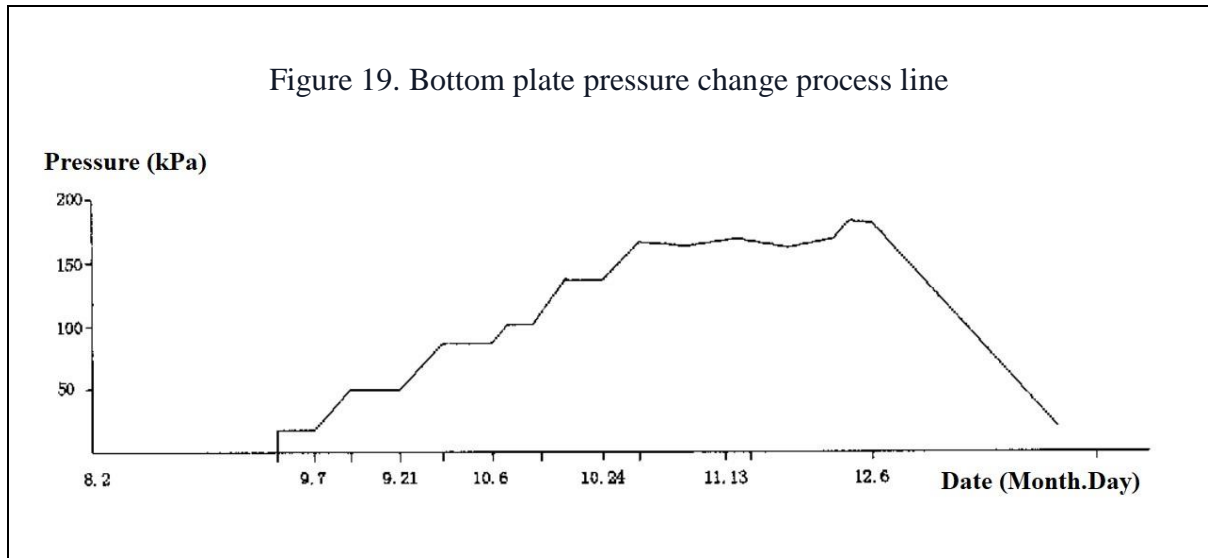
Figure 18. Process line of tank foundation soil horizontal displacement



For the inclinometer pipes arranged outside the tank, a portable inclinometer was used for test purposes and requirements at different stages. Through use of the instrument for observation, horizontal displacement process lines of the tank’s foundation soil was plotted (Figures 15, 16, 17, 18 ) and analysis was as follows:

- The horizontal displacement of each measuring point is small, and the horizontal displacement of the soil layer is 15.0m above the ring surface. Within the range, the most horizontal displacement occurs in the relatively weak silt and clay soil layers. This is due to its poor water permeability, slow drainage and consolidation, and plastic deformation under loading.
- The maximum horizontal displacement rate amongst the measuring points occurs at point CX4, which is 1.50mm/d, meeting the control index requirements.
- The inclinometer tubes close to the surface that were set up around the ring beam at varying degrees showed that the surface soil was denser. This is probably related to the frequent passing of machinery. In addition, the lower cohesive soil interlayer was relatively weak owing to stress distribution being responsible for this phenomenon;
- All in all, the horizontal displacement rate is small in the early stage of water filling, but the horizontal displacement rate increases slightly in the later stage of water filling and loading. During the unloading and water release period, the horizontal displacement rate tends to decrease as the foundation soil rebounds.

8.4. Monitoring and analysis of oil storage tank bottom plate pressure



- The pressure at each point on the bottom plate of the oil storage tank increases in correlation with the increase of the load resulting from the water filling process. Additionally it was noted that the average measured pressure is initially smaller than the corresponding load from water-filling. This shows that factors such as structural rigidity, cushion strength and density have an impact on the distribution and recording of pressure under the bottom plate.
- The pressure distribution on the bottom plate of the oil tank is uneven, as shown in Figure 20, with maximum pressure distribution occurring around the central region of the oil storage tank.

## 9. Conclusion

### 9.1. *Opinion on the Researching of foundation soil and their basic properties*

The study of the basic properties of foundation soil is the most basic and important task in the design of oil storage tank foundations. Before designing the oil storage tank foundation, the basic properties of the soil must be carefully studied. These basic properties should include the geological history of the oil storage tank area, the natural strength of the foundation soil, the seepage properties of the soil, pore water pressure parameters, and various triaxial compression test indicators, characteristics and stress paths, etc. The basic properties of these soils are crucial to the selection of the type of reinforcement for oil tank foundations in soft soil areas.

### 9.2. *Opinion on the Reinforcement Scheme Selection for the oil storage tank foundation*

Through the analysis of the overall engineering geological conditions of the area, the soft soil foundation mainly composed of general clay soil composed of surface clay and underlying silt or silty clay. Bearing in mind that the foundation comprised of alternating cohesive soil and sand layers, the preloading in foundation method was selected after optimization and comparison of various schemes. Generally speaking, this is the most optimal schemes as oil storage tanks need to be filled with water and tested for any leakages after installation. Hence this provides convenient conditions for the use of water-filled preloading foundation treatment solutions.

### 9.3. *Opinions on the design and execution of the preloading in foundation method*

- In areas whose underlying soil has well-draining soils, artificial methods of consolidation can have a negative effect.
- Future related calculations and analysis of the stress, deformation, stability and other issues of the soft soil foundations of oil storage tank can be compiled through the consolidation related finite element methods, so that complex practical engineering calculation problems can be realized through computers.
- During the water-filling preloading process, information such as settlement, pore water pressure changes and the depth level of the foundation soil should be considered. Then based on their results, loading plans can be adjusted in a timely manner.

### 9.4. *Opinions on the Application of optimization analysis method in the selection of oil storage tank foundation reinforcement and treatment schemes.*

Highly recommended because at present there are many feasible plans based on engineering geological conditions, actual engineering conditions etc. The use theories such as analytic hierarchy process and fuzzy mathematics to optimize and evaluate the plans in order to select the optimal one is a big boost, especially for third world countries.

## 10. Data Availability Statement

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

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