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RETROFIT DESIGN OF TILTED WATER TANK: A CASE STUDY AT A COAL POWER PLANT

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ABSTRACT: A large steel water tank installed at a coal power plant in Cilegon, West Java, Indonesia, faced stability and strength concerns due to significant tilting observed during a water load test. As a precautionary measure, the tank was emptied, and a thorough assessment was initiated to evaluate its fitness for purpose and to determine the strength and stability of both the tank and its foundation for long-term use. The site investigation identified uneven settlement and tilting of the foundation. To conduct a root cause analysis, finite element analysis was performed, with soil properties calibrated based on measured settlement. The mapped deformation of the tank's base was compared to industry standards such as API 653, EEMUA 159, and PIP STE02030. The analysis revealed that the failure resulted from an error in calculating the strength of the base soil during the design phase. Fortunately, the tank itself did not sustain significant damage, experiencing only rigid body displacement with minimal out-of-plane deformation, rendering repairs unnecessary. A proposed retrofit solution to enhance the strength of the soil beneath the tank is to implement soil improvement by concrete jet grouting. Once the soil characteristics have been improved, a comprehensive finite element analysis confirmed that both the steel water tank and the reinforced soil surrounding it will remain within acceptable stress and deformation levels for both short-term and long-term conditions. Field measurements further validate that the application of concrete jet grouting has effectively reduced the settlement potential of the tank.

Keywords: Tilted water tank, Retrofit, Soil improvement, Concrete jet grouting, Foundation

1. INTRODUCTION

Steel water tanks play a critical role in various applications, contributing to the infrastructure of diverse industries. Despite their significance, the potential for tank failure remains, often stemming from shifts in usage demand [1], material damage, or settlement [2]. Over time, settling tanks may become unstable or tilted, increasing the risk of failure. Foundation settlements are crucial for the integrity and functionality of these structures throughout their lifespan [3]. The uneven settlement, a common foundation deformation, poses a significant threat to infrastructure safety. Large tanks with uneven settlements are more vulnerable to failure during earthquakes, as this settlement increases structural seismic vulnerability proportionally [4]. Ensuring the safe use of such tanks necessitates retrofitting or strengthening measures to enhance both structural integrity and foundation stability.

The settlement and inadequate bearing capacity of steel tank foundations can be attributed to various factors, such as limited or incorrect soil investigation data. Since geotechnical investigations can only be conducted in a limited number of locations, relying solely on geotechnical investigation may not provide sufficient confirmation of variations in soil layers beneath the tank foundations [3].

Assessing the cause and impact of settlement is of utmost importance when determining whether a tank remains in a stable condition or necessitates retrofitting, either on the steel structure itself or on its foundation. A thorough assessment is vital to fill the information gaps that may have been overlooked during the initial design process and to identify the underlying cause of the tilting issue. With comprehensive data at hand, a retrofit design can be executed accurately and effectively, ensuring the appropriate measures are taken.

Conventionally, a practical retrofit option to remedy a foundation problem is underpinned by micro or large-diameter piles [5-7]. Alternatively, retrofit to improve foundation performance on soft soil can be achieved by soil improvement techniques, such as concrete grouting [8-10], deep soil mixing, and others. Retrofit by soil improvements has been successfully implemented. For instance, [9] investigates the use of cement injection to retrofit and enhance the foundation of a K10-type compressor, ultimately concluding that it effectively reduces vibrations while being cost-effective, as determined through numerical modeling. Meanwhile, [10] demonstrates that jet grouting offers a cost-effective and efficient means to improve the axial and lateral resistance of existing pile foundations.

Various soil improvement methods have been successfully implemented as a cost-effective alternative to conventional foundation systems for tanks. For instance, [11] demonstrates the successful use of dynamic compaction for loose sand to support fuel and STP. Dijkstra [12] introduces a CDC technique (Cofra Dynamic Compaction®) combined with soil replacement to support oil storage tanks. To enhance the mechanical properties of soft clay at an oil storage tank construction site, [13] presents soil improvement using CFA (continuous flight auger) piles before the tank's construction. Meanwhile, [14-16] conducts numerical analysis to evaluate the seismic performance of tank foundations improved with stone columns. These references offer examples of various soil improvement methods that can be effectively applied in new construction, where soil improvement is applied before tank construction or installation. However, in our study, focusing on retrofitting, soil improvement needs to be applied while considering the tank's existing placement. The challenge in retrofitting with the tank in place is the inability to perform retrofit directly to the soil or foundation under the center area of the tank due to the large size of the tank.

Concrete jet grouting stands out as a candidate for a highly effective retrofitting method for addressing foundations experiencing settlement issues or having inadequate bearing capacity. The process involves injecting a cementitious mixture into the soil beneath a structure, filling voids, and thoroughly mixing it with eroded soil to form a solid grout element once it hardens [8]. The anticipated outcome is improved soil properties, marked by a reduced settlement potential and increased bearing capacity. In this study, concrete jet grouting is implemented as the chosen retrofit method.

2. RESEARCH SIGNIFICANCE

The demand for large-sized tanks as industrial support facilities is consistently growing. Due to the escalating land prices, there is a need to construct more tanks in challenging soil conditions, specifically soft soil. Consequently, the development of construction methods and retrofitting techniques specifically tailored for tanks on soft soil becomes crucial. At present, soil reinforcement methods by concrete grouting as retrofitting techniques are not extensively employed. Therefore, this research aims to make a significant contribution to tank construction on soft soil, with a particular focus on the utilization of concrete grouting for retrofitting purposes.

3. METHODOLOGY

This case study involved five main steps: root cause analysis, assessment of the water tank's structural integrity, soil retrofitting design, final structural check, and implementation with monitoring.

The root cause analysis served a dual purpose. Firstly, it aimed to identify the issues that occurred and reveal their underlying causes. Another aspect of the analysis involved determining the actual soil parameters beneath the tank. Additionally, it sought to pinpoint a suitable method and accurate parameters for precise settlement estimation. This comprehensive approach aimed not only to uncover the root causes of the issues but also to refine the understanding of the soil conditions and enhance the accuracy of settlement predictions. To validate the accuracy of the method and parameters, analysis results were compared to settlement field measurement data obtained after the water load test. This step also included calibrating soil parameters to ensure a more precise analysis for the retrofit design.

The structural integrity of the tank was evaluated by examining the shape of its bottom settlement, following API 653 [17] procedure. This check is carried out to ascertain whether the existing tank structure is still in good condition and can accept the design water load. This procedure is in line with [3].

The retrofit design process uses calibrated soil properties as a basis by incorporating precisely determined parameters obtained in the earlier stages of the analysis. The retrofit design was carried out to maintain the stability of the tank and to prevent excessive additional differential settlement or tilting of the tanks.

Upon the completion of the entire design process, a conclusive step involves performing a final check using structural analysis software. This check considers the interaction between the tank structure and the stiffness of the soil. The primary goal of this analysis is to ascertain the condition of the tank structure following soil improvement. By conducting this evaluation, we gain insights into how the tank structure interacts with the altered soil conditions. This ensures a thorough understanding of the tank's post-improvement state. The analysis is integral to validating the effectiveness of the design and provides valuable information for further refinement if needed.

Following the completion of the analysis, the retrofit design was implemented, and monitoring was performed to validate the effectiveness of the retrofit measures.

4. DESCRIPTION OF THE WATER TANK

This study focuses on a steel water tank, constructed in 2022 at a steam power plant in Cilegon, West Java, Indonesia, serving as a firefighting water reservoir. The tank, depicted in Fig. 1, has a diameter of 18 m and a water height capacity of 19.6 m. Supported by a ring shallow foundation that encloses compacted soil. The -1.5 m deep ring foundation has a 1.5 m wide, 300 mm thick base. The steel tank's base is 8mm thick, with the wall thickness varying from 8mm at the top to 18mm at the bottom. The roof frame is supported by a central pole and the tank perimeter.

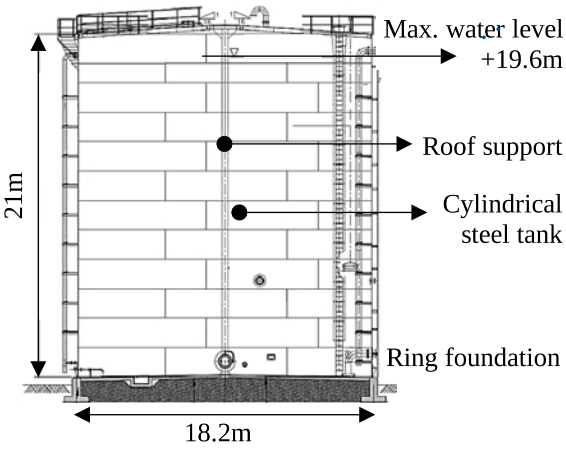

Fig.1 Firefighting - steel water tank at Cilegon

5. THE WATER TEST INCIDENT

Upon completion of construction, a water load test was conducted. Daily settlement monitoring measurements were taken around the tank perimeter during the test, and the results are detailed in Table 1. The observed maximum settlement of 73 mm and maximum differential settlement of 72 mm raised safety concerns, prompting the tank to be emptied for further assessment.

Table 1 Monitored settlement during loading test

Perimeter point location	Monitored Settlement (mm)				
	Day 1	Day 2	Day 3	Day 4	Day 5
0°	0	-2	1	0	1
45°	-2	-2	-2	-2	-3
90°	-26	-27	-28	-28	-28
135°	-48	-51	-51	-52	-53
180°	-62	-64	-71	-71	-73
225°	-64	-67	-69	-69	-71
270°	-45	-47	-48	-48	-50
315°	-15	-16	-16	-17	-16

6. ASSESSMENT AND DESIGN CRITERIA

The structural criteria for the steel water tank against the operational loads based on API 650 [18], API 653 [17], EEMUA 159 [19], and PIP STE02030 [20] are as follows.

1. According to API 650 [18], the allowable stress limit for tank shell elements with A283M quality (f_y = 205 MPa, f_u = 380 MPa) when operational (holding water) is 154 MPa.
2. According to API 653 [17], the maximum out-of-plane settlement (S_{max}) limit for the planar tilt water tank category is defined as Eq. (1).

$$S_{max}=\frac{L^2\times Y\times 11}{2(E\times H)} \quad [17] \qquad (1)$$

where:
S_{max} = max. out of plane settlement (m)
L = arc length between measuring points (m)
Y = material yield stress of wall shell (MPa)
E = Young's modulus of wall shell (MPa)
H = tank height of wall shell (m)

3. According to EEMUA159 [19], the allowable planar tilt is 0.5% of the tank shell height.
4. According to API 653 [17] and PIP STE03020 [20], the allowable circumferential differential settlement is L/450.
5. According to EEMUA159 [19] and PIP STE03020 [20], the allowable center-to-edge differential settlement (sagging) is 200-400 mm for a tank with a diameter of around 20 m.

These standards collectively contribute to the comprehensive design and evaluation of steel water tanks, ensuring they meet safety and reliability requirements.

7. ROOT CAUSE ANALYSIS

Geotechnical data plays a crucial role in the root cause analysis, involving the verification and calibration of the data. Root cause analysis includes geotechnical data collection and verification, as well as calibration of soil properties and analysis methods.

7.1 Geotechnical Data Verification

The initial foundation design for the tank was based on soil investigation data taken approximately 30 m away from the tank site. This data indicated the presence of competent soil with an *NSPT* value exceeding 50 at a depth of 1.5 m and below. However, after conducting a load test and observing subsequent differential settlement of the tank, it became imperative to gather soil data directly at the tank location. The additional soil investigations, presented in Fig.2, unveiled competent soils at varying depths, ranging from 6.5 to 11.5 m below the surface.

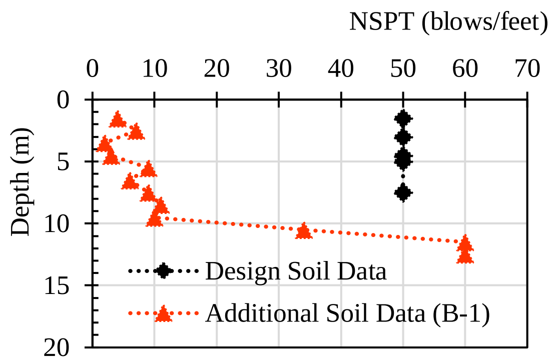

Fig.2 Existing and additional soil data

The upper layers primarily consisted of soft soil, with a thin layer of medium soil showcasing *NSPT* values between 4 and 18. Upon reviewing the soil data, it was determined that the design soil data originated from the original soil area, while additional soil data were collected from the reclaimed area. The demarcation between these two areas was inconclusive. Consequently, the designer solely relied on the available design soil data, assuming the tank footing was on the original soil area, opting for a shallow circular footing presumed to be adequate.

7.2 Calibration of Soil Properties

As mentioned, the presence of a soft soil layer beneath the ring foundation has caused the tank to settle excessively during the water load test. To simulate the actual event, back analysis was carried out utilizing PLAXIS 2D finite element software [21]. As a simplification, the analysis was carried out in the axisymmetric assumption. Fig.3 shows the axisymmetric soil model under the tank.

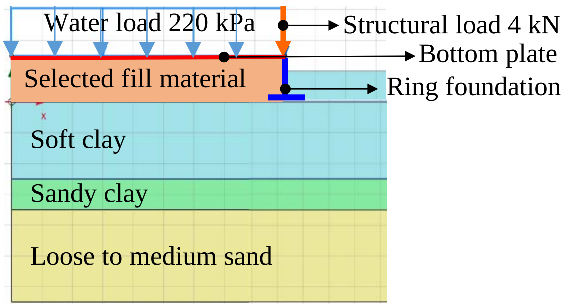

Fig.3 Root cause analysis axisymmetric model

During the load test simulation, a surcharge load of 220 kPa is applied to the soil to represent the water load. The settlement magnitudes at various points along the tank perimeter were analyzed and compared with the measurements presented in Table 1. These results serve as the basis for calibrating the soil properties used in the PLAXIS 2D [21] model. Calibration is necessary because soil property values are typically estimated using empirical equations based on soil investigation data. Although widely used in geotechnical engineering, these empirical functions do not provide an exact correlation but instead have a range of variations.

The calibration process involved using a trial-and-error method to achieve an acceptable difference between the settlement values obtained from analysis and those measured in the field. The soil properties that require calibration are specifically the ones that directly affect settlement, such as Young's modulus and shear modulus of the soil. As a starting point, the following correlation proposed by [22] was utilized to estimate the initial values: $E = 766\ NSPT$ for sand and $E = (250 – 500)\ C_u$, with $C_u = (5\text{-}6)\ NSPT$ for clay. These values were also compared with the typical values suggested by [23]. Additionally, a Poisson's ratio of 0.3 was adopted. Concrete ring foundation and steel tank base are included in the model as elastic plate materials.

8. STEEL STRUCTURE ASSESSMENT AFTER THE LOAD TEST

There is a real concern that the steel tank experienced structural damage after enduring differential settlement during the water load test.

According to API 653 [17], tank settlement can be classified as uniform settlement, rigid body tilting (planar tilt), or settlement in a non-planar pattern. Based on the measured settlement, the settlement values are not uniform, therefore need to establish if the settlement is in a planar or non-planar pattern. If we can establish that the settlement pattern is planar, then structural damage is not a concern since the tank moved in a rigid body mode. To check whether the settlement mode is planar or non-planar, API 653 [17] procedure is followed.

For valid application of the procedure, API 653 [17] defines the minimum number of measurement points needed based on tank diameter as $N = D/10$, where N is the minimum number of measurement points needed with not less than 8 points. The radius distance of each point is not less than 32 ft (9.75m) and D is the diameter of the tank (m). API 653 [17] characterizes the settlement of a planar tilt tank as a cosine curve. The settlement elevations are determined based on the polar coordinates of points along the tank perimeter, following Eq. (2).

$$Elev = a + b\cos(\theta + c) \quad [17] \qquad (2)$$

The values of a, b, and c can be determined through trial and error to obtain an R value, as computed by Eq. (3), that is equal to or greater than 0.9. This threshold is considered valid for the stiff tilt plane settlement type.

$$R^2 = \frac{S_{yy} - S_{SE}}{S_{yy}} \quad [17] \qquad (3)$$

where S_{yy} is the sum of the squares of the differences between the measured average height and the height of the point under consideration and S_{SE} is the sum of the squares of the differences between the measured and estimated heights.

Furthermore, API 653 [17] defines out-of-plane deflection, S_i for point-i according to Eq. (4).

$$S_i = U_i - \left(\frac{U_{i-1} + U_{i+1}}{2}\right) \quad [17] \qquad (4)$$

The out-of-plane settlement, U_i, for point i can be determined by comparing the measured settlement value with the settlement elevation derived from the cosine curve. If the elevation measurement in the field is higher than the corresponding value on the cosine curve, the difference will be positive (+). Conversely, if it is lower, the difference will be negative (-).

9. RETROFIT BY SOIL IMPROVEMENT

Once it has been determined that the settlement issue is due to inadequate soil-bearing capacity, the subsequent step is to devise a retrofit design. The primary objective of this retrofit is to mitigate soil settlement and minimize any further tilting of the tank in the future.

As addressed in Section 1, the examination of the congested site conditions has led to the consideration of soil improvement retrofit methods. Given the constraints imposed by restricted space and the overall progress of the project, it is imperative to proceed with the retrofit of the tank's foundation in its existing location. The relocation of the tank prior to commencing the retrofit is deemed impractical. Therefore, the chosen method for improvement is the cement jet grouting technique. The selection of cement grouting is grounded in practical considerations, the ease of implementation, ensuring safety in terms of tank stability, and its suitability for the prevailing soil conditions in the field.

In the retrofit design, the quality of the grout mixture and the targeted grouting area underwent testing under various scenarios, with soil strength and settlement analysis conducted using PLAXIS 2D [21] software. Given the tank's current position, minimizing grouting directly beneath the tank was deemed necessary due to the considerable challenges associated with its implementation. Despite this constraint, it is anticipated that effective results can still be achieved by relying on the confinement effects of the grouted soil under the tank perimeter area to reinforce the soil beneath it. Furthermore, the introduction of grout material in the perimeter area is expected to increase soil volume, subsequently leading to soil compaction beneath the tank. Therefore, the grouting is expected to fulfill three purposes: directly improving soil properties of the area under the perimeter of the tank, aiding in soil compaction, and confining the soft soil under the central area of the tank.

10. FEM ANALYSIS OF THE TANK ON IMPROVED SOIL

The last stage in the design process involves verifying whether the tank structure meets the design criteria when exposed to deformation caused by foundation settlement. The analysis was performed by SAP2000 software [24], with the following assumptions:

1. Structural elements of roof trusses and columns are modeled as frame elements. The wall, base shell, and roof elements are modeled as thin shell elements.
2. The load calculated in the analysis includes self-weight of structural elements, water loads up to 21 m (at the base and walls of the tank), and live load on the roof (0.96 kN/m^2).
3. Soil support is modeled as spring with stiffness adjusted such that the settlement values from PLAXIS 2D [21] analysis can be reproduced as closely as possible.

The purpose of the FEM analysis is to verify the safety and serviceability of the tank during the intended service life of the tank considering the improved soil condition.

11. RESULTS AND DISCUSSION

The analysis results, commencing with soil properties calibration, followed by a steel tank check, retrofit design, and steel stress check after retrofit, are presented in the following subsections. The last subsection details the implementations of the retrofit design and the post-retrofit test.

11.1 Results of Calibration of Soil Properties

The soil properties were calibrated by a trial-and-error process with the target to match observed soil settlement with analysis. After the trial-and-error process, the analysis results indicated a soil settlement of 175 mm at the center of the tank and 10 mm at the perimeter. These analysis results are comparable to the average settlement value measured in the field. The final calibrated soil parameters are presented in Table 2.

Table 2 Calibrated soil parameters

Soil Description	Thickness (m)	N_{SPT}	E (kPa)	υ	G (kPa)
Fill material	1.3	*	10000	0.3	3846
Soft clay	2.5	4	8000	0.3	3077
Sandy clay	1	15	12500	0.3	4808
Loose-medium sand	3	11	8426	0.3	3241
Gravel & sand	3	>60	8426	0.3	3241

* Fill Material properties are estimated from DCP Test results

11.2 Results of Steel Tank Assessment After the Water Load Test

The settlement data from the water load test on day 5 (see Table 1) is analyzed using the API 653 [17] method explained in Section 8, resulting in a cosine function shown in Eq. (5) and plotted in Fig. 4.

This curve represents the ideal planar tilt settlement, closely matching the measured data. In Fig. 4, the ideal planar tilt curve is compared to the actual settlement data, and they look almost the same, with a maximum out-of-plane settlement of 3.5 mm. This is lower than the API 653 [17] limit of 13.4 mm, therefore, the settlements are considered rigid body tilting (planar tilt), and there is no need for a stress check to confirm the tank's structural strength.

$$Elev = 36.1 + 39\cos(\theta + 18) \text{ with } R = 0.997 \quad (5)$$

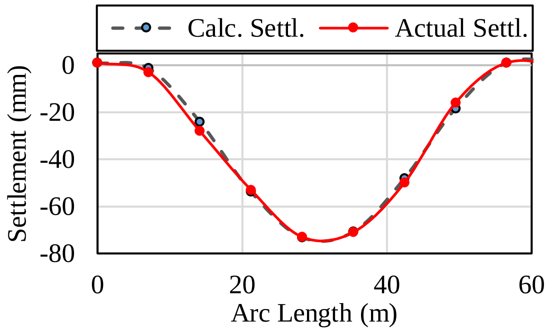

Fig.4 Tank perimeter settlements - actual vs planar

11.3 Final Retrofit Design

After conducting several numerical experiments, it has been determined that a grout area starting from underneath the ring foundation, spread outward with a radius ranging from 4 to 5.5 m, and a minimum unconfined compressive strength (UCS) of 1 MPa, as depicted in Fig.5, yielded satisfactory results that meet the specified criteria.

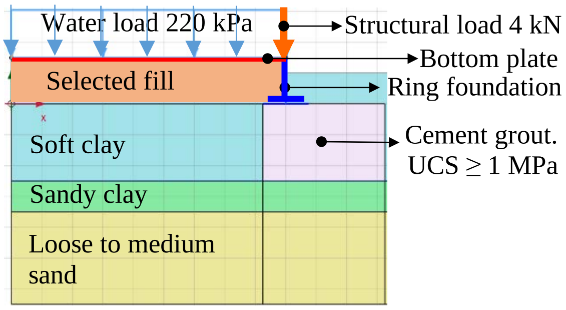

Fig.5 Retrofit by cement grouting scheme

The analysis results for the final retrofit scheme are visually presented in Fig. 6 and Fig. 7, providing insights into the failure circle and potential maximum settlement, respectively. Within the framework of PLAXIS 2D, safety factors and potential slip surfaces were thoroughly evaluated through strength reduction procedures. The analysis showcased that with the implemented foundation retrofit, involving cement grouting beneath the existing ring foundation, the failure surface assumed a circular form (refer to Fig. 6). It is noteworthy that the maximum soil straining occurred beneath the bottom of the cement grouting column, signifying an efficient vertical load transfer mechanism from the tank base to the circular footing and subsequently to the grouting columns.

Examining the results in detail, the global stability safety factor registers at 1.79, surpassing the design requirement of a minimum of 1.5. This marks a significant enhancement compared to the pre-jet grouting analysis, where the global safety factor was only 1.05. The positive shift in safety factors underscores the effectiveness of the implemented retrofit measures in fortifying the structural stability of the tank.

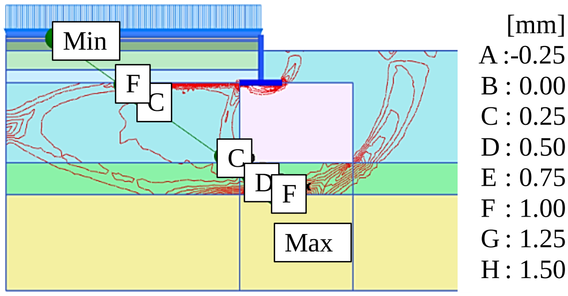

Fig.6 Failure circle of improved soil

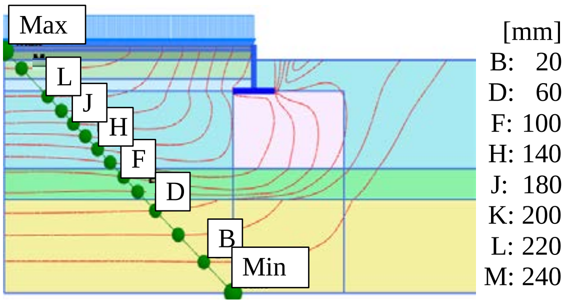

Fig.7 Potential max settlement of improved soil

In evaluating the existing slab footing under the tank base, Winkler's theory, treating it as a beam on an elastic foundation without considering soil compressibility, was employed. This approach, however, is anticipated to result in a notable vertical settlement, estimated to peak at around 250 mm at the center of the tank over the long term (as shown in Fig. 7). Conversely, settlement under the tank perimeter is comparatively lower, approximately 60 mm, indicating a reduced risk of tank tilt. A comprehensive assessment of the tank's structural integrity under these residual soil settlements becomes imperative, emphasizing the need for continued monitoring and analysis to ensure sustained stability.

11.4 FEM Analysis Results of The Tank on Improved Soil

As outlined in Section 10, soil supports are represented by springs model, adjusting stiffness to closely mimic PLAXIS 2D [21] analysis settlement values. Soil spring stiffness is averaged across three zones (see Table 3).

As anticipated, the analysis results from SAP2000 [24] closely correspond to those obtained from the PLAXIS 2D [21] analysis, as illustrated in the displacement contour featured in Fig.8. This alignment in results enhances the reliability of the structural assessments and underscores the consistency between the two analytical approaches.

Furthermore, the assessment of center-to-edge differential settlement (sagging) values reveals a measurement of 130 mm, a reassuring outcome that adheres to the specified guidelines outlined in PIP STE03020 [20]. This value comfortably falls below the allowable limit of 200 mm, demonstrating structural stability and compliance with the prescribed standards. The harmonious agreement between the SAP2000 and PLAXIS 2D analyses, coupled with the adherence to differential settlement requirements, contributes to the overall confidence in the structural integrity of the tank under consideration.

Table 3 Soil Spring Constant

Radius (m)	Settlement (mm)	Vertical Spring ($kN/m/m^2$)
0.0-6.8	-250	833.08
6.8-8.8	-190	1036.47
8.8-9.1	-120	1713.51

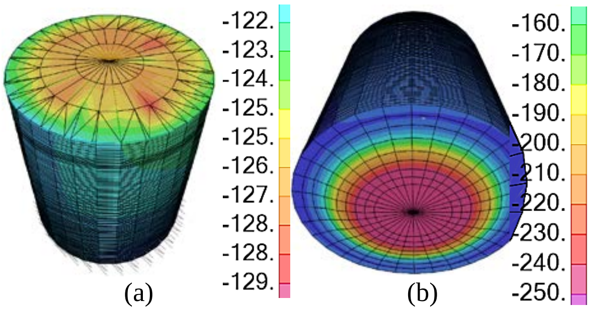

Fig.8 Tank deformation (a) roof view (b) base view
Note: color bars indicate displacement values (mm)

The SAP2000 [24] analysis, illustrated by the Von Mises stress contour in Fig.9, provides crucial insights into the structural behavior of the tank. The maximum stress observed at the base of the tank is measured at 55 MPa, corresponding to a demand/capacity ratio (D/C) of 0.36. On the lower part of the tank wall, the stress typically hovers around 130 MPa, with a D/C ratio of 0.84. Notably, at specific points experiencing differential settlement, stress concentration values can reach up to 149 MPa, reflecting a D/C ratio of 0.97.

It is reassuring to note that the maximum stress developed in both the tank wall and bottom due to operational loads remains well below the permissible stress limit. According to API 650 [18], the allowable stress is set at 154 MPa. This indicates a satisfactory safety margin, underscoring the tank's ability to withstand operational stresses without surpassing the defined structural limits. The detailed analysis provides a comprehensive understanding of stress distribution, ensuring that the tank's structural integrity is maintained within the specified safety parameters.

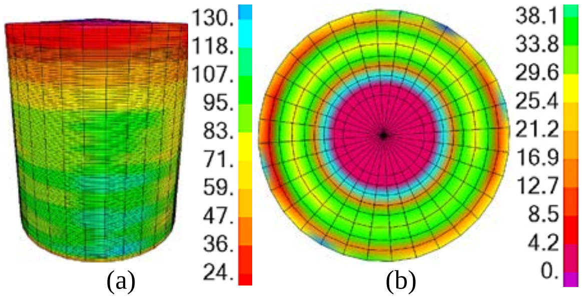

Fig.9 Tank Von Mises stress contour (a) wall (b) base
Note: color bars indicate stress values (MPa)

11.5 Implementation and Post-Retrofit Test

The retrofitting process, employing the jet grouting method in line with the pre-established design, is undertaken with the tank already installed on-site. This presents a unique challenge as the field is characterized by a high density of tanks and other machinery. Fig.10 provides a visual representation of the field conditions during the grouting operation (a) and also shows the pipe injector (b).

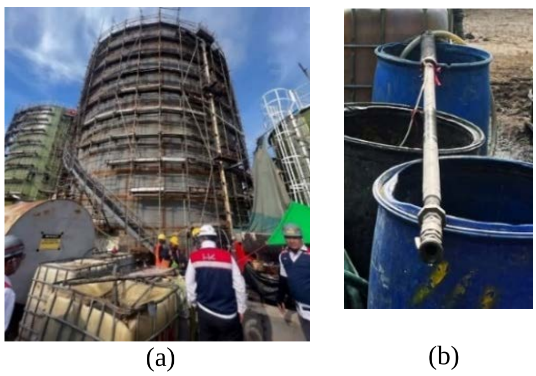

Fig.10 Grouting operation: (a) tank field condition (b) injection pipe

The grouting equipment comprises a mixer, a storage and agitation agitator, a pump, and a pipe injector. In the mixer, binder, water, and other essential materials are blended to produce a uniform grout. The agitator maintains continuous agitation to prevent sedimentation and segregation within the grout. The pump is responsible for generating the necessary pressure to inject the grout into the ground, while the injector, equipped with packers, openings, or nozzles, facilitates the entry of the grout into the ground.

The grouting operation commences with the drilling of a small-diameter hole up to the final injection depth, and the grout pipe is then inserted into the predrilled hole. The equipment injects the grout at approximately 0.5 bar pressure, allowing the material to penetrate and mix with the surrounding soil.

The grout is composed of water and cement in a ratio of about 1:1, considering the predominant subsurface soil type as silty to sandy soil. This grout composition is anticipated to achieve an unconfined compressive strength (UCS) value of 1 MPa.

After the completion of the retrofit, a soil investigation and a water load test were conducted. The purpose of the soil investigation was to assess the condition of the grouted soil. It revealed a significant improvement in the SPT numbers, which increased from 4 or lower (indicating soft soil) to a range of 18 to 25 (indicating stiff to hard soil). This indicates a substantial enhancement in soil strength and stability.

In addition to the soil investigation, a second load test was performed, measuring the settlement along the tank perimeter. The results were quite remarkable, as the settlement measured during the second load test was only 3 mm. This demonstrates the effectiveness of the retrofit in minimizing settlement and maintaining the stability of the tank structure. The combined findings from the soil investigation and load test confirm the successful outcome of the retrofit, providing a solid foundation for the continued safe operation of the tank.

12. CONCLUSIONS AND RECOMMENDATIONS

The following sub-sections present conclusions and recommendations, providing insights and practical guidance for future actions.

12.1 Conclusions

The conclusions derived from the assessment and retrofitting design process for the steel water tank encompass several key findings. Firstly, the assumption of uniform soil data across a large area is identified as a potential source of significant design flaws and safety risks for the constructed infrastructure, pinpointing it as the root cause of the case problem. Secondly, API 653 [17] proves to be a robust and straightforward method for assessing the safety of tilted tanks, categorizing settlement types to confirm the tank's safety post-tilting. Additionally, cement grouting emerges as a highly effective retrofitting method for existing structures, especially those in soft soil, offering the notable advantage of eliminating the need to dismantle the structure during the retrofitting process. The retrofit by cement grouting not only significantly improves the load-bearing capacity of the soil but also minimizes settlement, thereby enhancing the overall structural integrity of the tank.

12.2 Recommendations

Based on the conclusions drawn from the assessment and retrofitting design process for the steel water tank, several recommendations for further research can be identified:

1. Explore innovative retrofitting techniques beyond cement grouting. Investigate alternative methods or combinations of methods that can further enhance the stability and integrity of existing structures. This could include the use of advanced materials, novel construction technologies, or eco-friendly retrofitting solutions.
2. Conduct long-term performance monitoring of retrofitted structures to assess the effectiveness and durability of the applied retrofitting methods. This research could involve continuous monitoring of settlement patterns, structural deformations, and soil conditions over an extended period to ensure the sustained safety and reliability of the retrofitted tank.
3. Investigate the environmental impact of different retrofitting techniques, with a focus on cement grouting. Assess the ecological consequences of material usage, energy consumption, and waste generation associated with various retrofitting methods. This research can inform the development of sustainable retrofitting practices.
4. Conduct comprehensive cost-benefit analyses comparing different retrofitting strategies. Assess the initial costs, ongoing maintenance expenses, and potential long-term savings associated with each method. This research can aid decision-makers in selecting the most economical and sustainable retrofitting approach for specific projects.

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