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Innovative Concrete Mix Design for Rigid Inclusion Columns: Enhancing Soil Bearing Capacity and Minimizing Settlement

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ABSTRACT: This study evaluates the performance of a Type 1 cement–silica fume mix as an optimal cement–sand mortar for Rigid Inclusion (RI) columns used in aggressive sulfate- and chloride-rich environments, such as the Persian Gulf. Type 5 cement was excluded due to its susceptibility to ion attack, and Type 2 cement was deemed unnecessary because it would require unfavorable grading adjustments. The proposed mix limits C_3A content to below 10% and includes over 7.5% silica fume, enhancing strength, durability, cost efficiency, and environmental sustainability. Given the hot, arid climate and limited freshwater availability, seawater was used for mixing, producing excellent results without compromising performance. The mix achieved a compressive strength of 30–50 kg/cm², using locally sourced materials and Portland cement Type 425-1, in accordance with ASTM C39. Tests showed that the RI columns reached a compressive strength of about 3 MPa, enhancing soil bearing capacity and reducing settlements by 3–8 times. Plaxis modeling and hydrotesting confirmed the mix's reliability, emphasizing the value of optimized mix design for durable and sustainable performance in marine environments.

KEYWORDS: Ground Improvement, Rigid Inclusions, Sand-Cement Mortar, Soil Bearing Capacity.

1. INTRODUCTION

Constructing embankments on weak soils poses significant challenges for civil engineers due to issues like excessive settlement, low bearing capacity, and potential slope instability. Various geotechnical techniques, including preloading and prefabricated vertical drains, have been utilized to mitigate these challenges. Recently, soil reinforcement with rigid inclusions (RIs), or piled embankments, has gained attention for its versatility, cost-effectiveness, and improved performance (Kousik Deb & Sunil Ranjan Mohapatra 2013; Jenck et al. 2006; Jenck et al. 2007; Jenck et al. 2009a; Jenck et al. 2009b; Hassen et al. 2009; Nunez et al. 2013; Girout et al. 2014; Briançon et al. 2015). While raft foundations supported by RIs can alleviate some limitations of traditional methods, they may require increased rebar reinforcement due to the concentration of forces at the RI tops, potentially raising costs. Additionally, cyclic loading can lead to cracking at the connections between inclusions and the raft, creating further structural issues. It is essential to consider the impact of flexible inclusions on foundation stresses during the design phase (Balaam NP, Booker JR 1981; Balaam NP, Booker JR 2011; Deb K, Dhar A 2013). Advancements in RI techniques have evolved soil improvement methods, with materials like vibro-concrete and controlled modulus columns (CMC) being commonly used. A load transfer layer of granular or stabilized soils is crucial, as it redirects most of the load to the more rigid inclusions, reducing the load on the underlying soil (Okyay et al. 2014; Das AK, Deb K 2014). Research by Mahdavi et al. (2015) highlighted the use of CMC to support soft soil embankments for bridges, demonstrating improved settlement control but also increased loads on columns (Mahdavi et al. 2015). Simulations indicated lower estimates of settlement and lateral displacement. Despite advancements in soil reinforcement projects, many overlook crucial performance factors due to complex evaluations, leading designs to focus primarily on deformability and bearing capacity. Huu Hung et al. 2016 highlighted that the sequence of installing new Controlled Modulus Columns (CMCs) affects lateral soil movement and bending moments, emphasizing the need for careful planning. Pham et al. (2019) found a linear correlation between vertical loading on footings and pressure on rigid inclusions, with their numerical analyses mostly aligning with experimental data, despite some underpredictions. Masse et al. (2020) showed that combining vertical rigid inclusions with a load transfer platform effectively enhances settlement control and bearing capacity. Continuing this line of inquiry, Bałachowski and Konkol (2021) investigated Excess Pore Water Pressure (EPWP) around CMC installations and emphasized the importance of monitoring, revealing varying influence zones during installation and static loading tests. Building on this, Nodine et al. (2021) optimized CMCs for a double-sided Mechanically Stabilized Earth (MSE) wall in Syracuse, confirming that predicted settlements closely matched actual measurements, indicating effective load transfer. Furthermore, Sami et al. (2023) demonstrated that incorporating improved soil parameters in Mansoura, Egypt, significantly increased settlement prediction accuracy, reducing error from 74% to 24%. In 2023, Jakub Konkol took the research further by utilizing probabilistic analysis for Controlled Modulus Columns (CMCs) in over-consolidated Poznan clay. He employed Monte Carlo simulations and random field theory to model load-displacement behavior, concluding that factors such as the total stress approach, AUS model, installation effects, and variations in soil and interface parameters could explain discrepancies in CMC performance. Further validating the application of RIs, Ochoa et al. (2024) examined the 3D failure envelope of shallow foundations on soft soil reinforced by RIs, contributing analytical formulas for performance assessment (Colorado et al. 2024). In Bogotá, a significant railway project implemented a 4.1 m embankment supported by 57,000 RIs on soft clay, effectively managing settlement and enhancing ground conditions. Looking ahead, future projects like the 241-acre Tremley Point development in New Jersey plan to employ RIs to mitigate long-term settlement in variable and compressible soils (Towle Taylor; Sanstrom Samantha 2024). Ongoing research into Ground Improvement Techniques emphasizes the efficacy of both the CMC and Rigid Inclusion methods in minimizing total and differential settlement, aligning with industry standards (Vinothkumar 2022). In Singapore, traditional reinforced concrete piles face challenges related to future dismantling needs, prompting a cost-effective proposal to utilize RIs without reinforcement (Chen et al. 2024). Moreover, a recent study by Marco Samy et al. (2023) on floating rigid inclusions in clay deposits revealed substantial reductions in settlement with an average improvement factor of 4.65, thereby enhancing infrastructure design practices. Finally, Bouabdallah et al. (2023) focused on the effects of soft soils on the East-West highway construction in Algeria, employing dynamic analysis to illustrate the significant role of RIs in mitigating settlement and improving overall structural performance.This study emphasizes the critical importance of innovative mix designs in enhancing the structural performance of cement-sand mortar, particularly in the context of Rigid Inclusion (RI) columns subjected to harsh environmental conditions. By investigating the combination of Type 1 cement and silica fume, the research underscores an effective approach to achieving the necessary compressive strength, improved durability, and sustainability for construction applications in sulfate and chloride-rich environments. The results, compliant with ASTM C39 standards, not only demonstrate significant reductions in total and differential settlements but also confirm the reliability of the proposed mix in real-world scenarios. Through continuous monitoring, the study highlights that the actual settlement measurements are closely aligned with the values predicted by numerical modelling, reinforcing the accuracy of our approach. Additionally, the use of ASTM C230 in mixed design further substantiates the effectiveness of the chosen materials and methodologies. This advocacy for strategic material use is in line with environmentally responsible engineering practices. Ultimately, this research showcases the potential for optimized cement formulations to address the dual challenges of structural integrity and environmental sustainability in civil engineering (ASTM C39/C39M-21 ; ASTM C230/C230M-20) .

2. PROBLEM STATEMENT AND MATERIAL CHARACTERIZATION

The construction of crude oil storage tanks at Jask Port, Hormozgan Province, Iran, involves three phases, beginning with approximately 20 tanks, each 80 meters in diameter and 18 meters in height, spaced at least 63 meters apart. As shown in Figure 1, geotechnical studies revealed that settlement beneath tank TK-6004 exceeds allowable limits, though differential settlement between the center and edge remains within acceptable bounds. The initial design required 489 reinforced concrete piles (1.2 m diameter, 16 m average depth), consuming nearly 26,000 tons of suitable materials. However, site-specific constraints—including limited access to appropriate construction materials and unavailability of fresh water—posed major challenges. To address these, the project utilized beach sand instead of factory-produced aggregates and substituted seawater for freshwater. This environmentally conscious decision significantly lowered carbon emissions and construction costs. Furthermore, steel reinforcement bars were deliberately omitted from the pile design, further enhancing sustainability. This approach not only ensured environmental benefits but also maintained the structural performance of the system. The overall strategy illustrates the value of innovative, sustainable practices in large-scale infrastructure projects under logistical constraints. Geotechnical investigations (BH-6004-1 and three additional boreholes) revealed layered sand, clay, and fine-grained soils, with groundwater encountered at 3 m depth (Table 1, Table 2, Figure 2). Local materials—including fine sand, untreated seawater, Type 1 cement, and silica fume with over 90% SiO_2—were utilized for Rigid Inclusion columns. The final mix design included a 25% replacement of cement with silica fume to enhance durability, mechanical strength, and resistance to sulfates and chlorides.

Figure 1. aerial view of the project

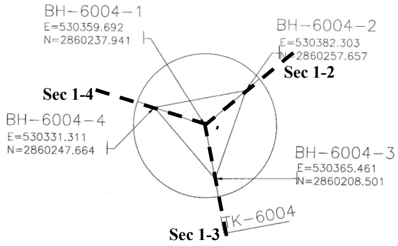


Figure 2. Location of boreholes

Table 1. The results of the tests performed on the sand of the region

Specific Gravity (ton/m^3)	sand equivalent	fineness modulus	Water absorption percentage	Moisture percentage	Passing percentage of sieve #200
2/54	57	0/92	-	-	7/2
-	-	0/47	-	-	4/8
2/67	23	1/17	-	6/9	3/61
2/62	23	0/70	2/5	11/0	5/4

Table 2. Results of Seawater Identification Tests

amount	unit	characteristic
9.8	-	PH
78300	µmohs/cm	Electric conductivity
45300	mg/l	Total Dissolved Solids
6500	mg/l, CaCO3	Total Hardness
23750	mg/l	Cl-
35	mg/l	Carbon
128	mg/l CaCO3	HCO3
14617	mg/l	Na+
530	mg/l	K+
480	mg/l	Ca2+
1272	mg/l	Mg2+
4830	mg/l	Sulphate, SO4

3. MIXING PLANS FOR CEMENT-SAND MORTAR

Three cement-sand mortar mix designs for Rigid Inclusion (RI) columns were developed via laboratory and field trials to optimize compressive strength, elastic modulus, and Poisson's ratio. The first lab mix used Type 1 cement (425 1), 24% silica fume, seawater, and beach sand, achieving an average 28day compressive strength of 280 kg/cm² with mechanical properties per ASTM C469/469M (Table 3, Figure 3). The second field mix (Table 4) reduced silica fume and increased cement to suit site conditions, yielding a 7day elastic modulus of ~2.9 GPa (Table 5) and compressive strengths on various sands; empirical relations (Popa et al. 2018; ASIRI 2012) predicted moduli of 5–6 GPa for 30–50 kg/cm² strengths (Eq 1).

$$E = 3700 f_{ck}^{1/3} \qquad (1)$$

where fck is the concrete compressive strength (MPa) and E is the concrete elastic modulus (MPa).

Integrating these results, the final mix (Table 6) achieves a characteristic strength of 3 MPa and an elastic modulus of 2 GPa, using Type 1 cement with silica fume to enhance durability and cost-efficiency—avoiding Type 5 cement and steel reinforcement—in line with ACI 234R 06. This sustainable design lowers CO_2 emissions and performs effectively in sulfate- and chloride-rich environments.

Table 3. Results of the test to determine the modulus of elasticity for the initial mixing plan.

Compressive strength (MPa)	Poisson's coefficient	Modulus of elasticity E (GPa)	Sample age)day(	Sample number
5/4	0/14	2/36	28	1
6/8	0/16	5/70	28	2
6/1	0/15	4/03	average	

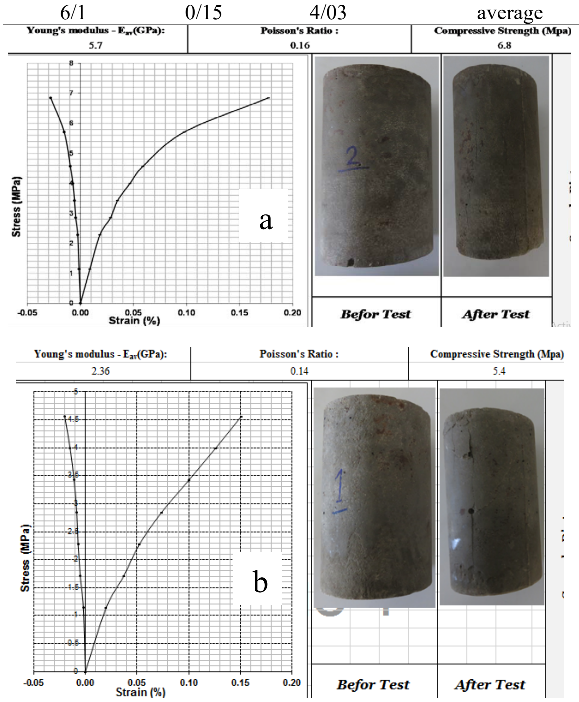


Figure 3. a and b determination of static modulus and static Poisson's ratio of concrete in compressive strength (laboratory)

Table 4. The second plan of mixing sand and cement mortar

specific weight (ton/m^3)	Amount (kg)	Consumables
3/15	260	Type 1 cement (425-1)
2/2	20	Silica fume
1/0	380	Sea water (contains 4% dissolved salt)
2/65	1330	Unsaturated beach sand (dried in the beach sun)

Table 5. Elastic Modulus Test Results of the Secondary Design

Compressive strength (MPa)	Modulus of elasticity E (GPa)	Sample age (day)	Sample number
1/8	2/92	7	105

Table 6. The Final plan of mixing sand and cement mortar

specific weight (ton/m3)	amount (kg)	Consumables
3/15	250	Type 1 cement (425-1)
2/2	25	Silica fume
1/0	380	Sea water (contains 4% dissolved salt)
2/65	1330	Unsaturated beach sand (dried in the beach sun)

4. RESERVOIR SETTLEMENT ASSESSMENT (UNIMPROVED RI COLUMN)

The study evaluates total and differential settlements at a construction site by modeling three soil sections using 2D Plaxis software under load conditions of 75 kN/m on the tank shell and additional loads ranging from 177 kPa (hydro-test) to 157.5 kPa (operation). Long-term consolidation was analytically calculated throughout construction phases. Results (Figure 4, 5 and Table 7) reveal uneven settlement near tank 6004, necessitating soil improvement. The proposed solution employs Rigid Inclusions (RI), cement-based elements that enhance soil bearing capacity and reduce settlement. RI is cost-effective, removes the need for costly load transfer platforms, and suits various structures such as buildings and storage tanks, reducing settlement by 3–8 times with minimal disruption. A schematic illustrating the RI foundation and load distribution system is provided in Figure 6 (ASIRI 2013).

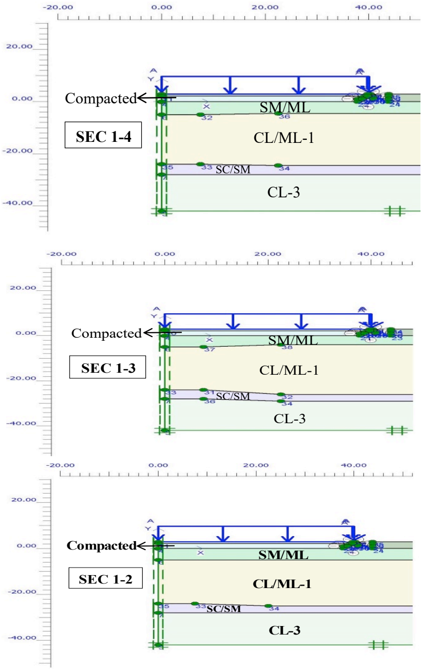
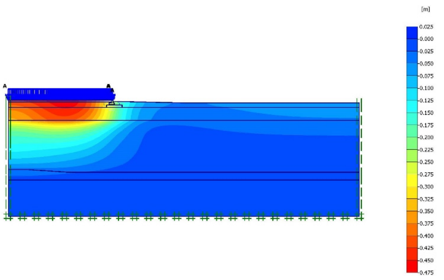
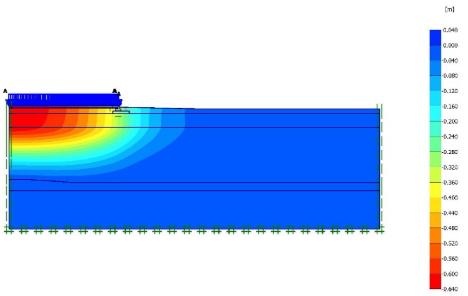


Figure 4. Soil modeling without improvement in sections 1-2, 1-3, 1-4



(a)



(b)

Figure 5. a) settlement in the last phase of the hydrotest test b) total settlement in the long term with regard to the consolidation settlement in the operational load

Table 7. Summary of settlements calculated in three assumed sections (before improving the soil under the tank)

section	*Maximum settlement hydrotest (cm)*		*Long-time settlement operation (cm)*	
	Center of the tank	*edge of the tank*	*Center of the tank*	*edge of the tank*
2-1	42/3	26/0	63/6	32/2
3-1	40/2	28/3	67/6	36/7
4-1	41/0	27/3	63/3	33/1

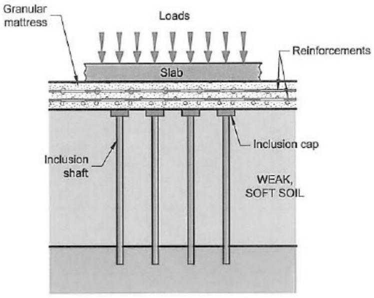
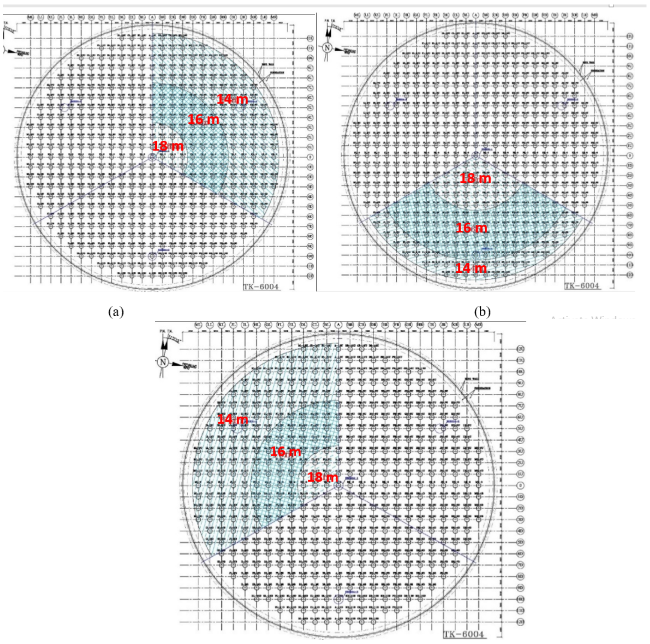


Figure 6. Different components of improved soil with RI columns

5. SOIL COLUMN COMPOSITE SYSTEM.

Most existing theories on settlement in composite systems predominantly address scenarios involving rigid loading and uniform strain. These theories enable the determination of the equivalent elastic modulus (Eeq) of the soil-column composite system by considering a modified area ratio. In this context, Es and Ec represent the elastic moduli of the soil and column, respectively, while the modified area ratio (as) accounts for the areas of both the column (Ac) and the surrounding soil (As) (Equation 2-6). A new soil improvement plan utilizing RI column aims to mitigate settlement under tanks by applying these theoretical underpinnings, particularly focusing on the soil-column interaction and area ratios. The implementation includes RI columns with a diameter of 1.2 meters and a spacing of 3 meters, analyzing options for soil-cement columns of varying lengths (14m, 16m, and 18m) for effective improvement (Figure.7).



(a) (b)

(c)

Figure 7. a) section 1-2, b) section 1-3, c) section 1-4 with improvement depths equal to 18, 16 and 14 meters

The project features RI columns designed with mortar characterized by a strength of 3 MPa and an elastic modulus of 2 GPa, with parameters for adhesion and internal friction angle derived based on the compressive strength. The relevant design parameters utilized for settlement analysis of the composite system are summarized in Table 8. (Pulko & Majes 2005; McCabe & Egan, D. 2010; Cooper & Rose, 1999; Abusharar, & Han, 2011).

$$a_s = \frac{A_c}{A_c + A_s} \tag{2}$$

$$E_{eq} = E_s(1 - a_s) + E_c a_s \tag{3}$$

$$\gamma_{eq} = \gamma_s(1 - a_s) + \gamma_c a_s \tag{4}$$

$$c_{eq} = c_s(1 - a_s) + c_c a_s \tag{5}$$

$$tan\phi_{eq} = tan\phi_s(1 - a_s) + tan\phi_c a_s \tag{6}$$

$$C_c = \beta\, f_{ct} \tag{7}$$

$$\mu = tan\, \emptyset_c \tag{8}$$

$$f_{ct} = 0.3.\frac{(f_{ck})^{\frac{2}{3}}}{1.5} \tag{9}$$

Table 8. Mechanical parameters of soil and soil-column system

Soil Layer	γ (kN/m^3)	C$'$ (kPa)	ϕ' (°)	E_{50}^{ref} (MPa)
Compacted Fill	20	10	35	50
Traffic Compacted Fill	20	5	30	20
SM/ML	19	5	35	40
With RIC		20	35	285
CL/ML-1	19	10	26	2.3
With RIC		24	27	252
SM/SC-SM	20	30	26	20
CL/ML-2 (CL-3)	21	10	27	35

6. SETTLEMENT PERFORMANCE OF RI COLUMNS: NUMERICAL AND FIELD VALIDATION

Plaxis numerical modeling (Figure 8, 9) indicated center settlements of 19.3–19.9 cm and wall settlements of 0.19–19.1 cm across tank sections 1-2, 1-3, and 1-4, revealing uneven deformation. Following RI column installation and depth optimization, total and differential settlements fell within allowable limits: central settlement improved from ~40.2–42.3 cm to 17.9 cm, and consolidation settlement from 63.3–67.6 cm to 19.3–19.9 cm. A 188-day hydrostatic test (reservoir height ~18 m; daily center readings) showed a long-term settlement of 160 mm (Figure. 10), matching model predictions and confirming RI efficacy in settlement mitigation.

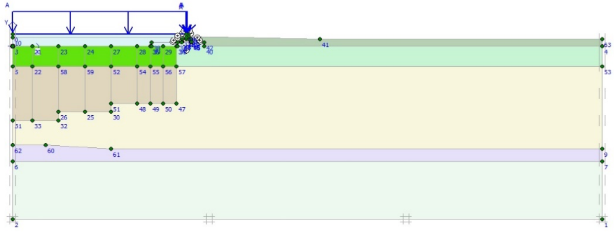


Figure 8. Numerical model of subsidence analysis of improvement

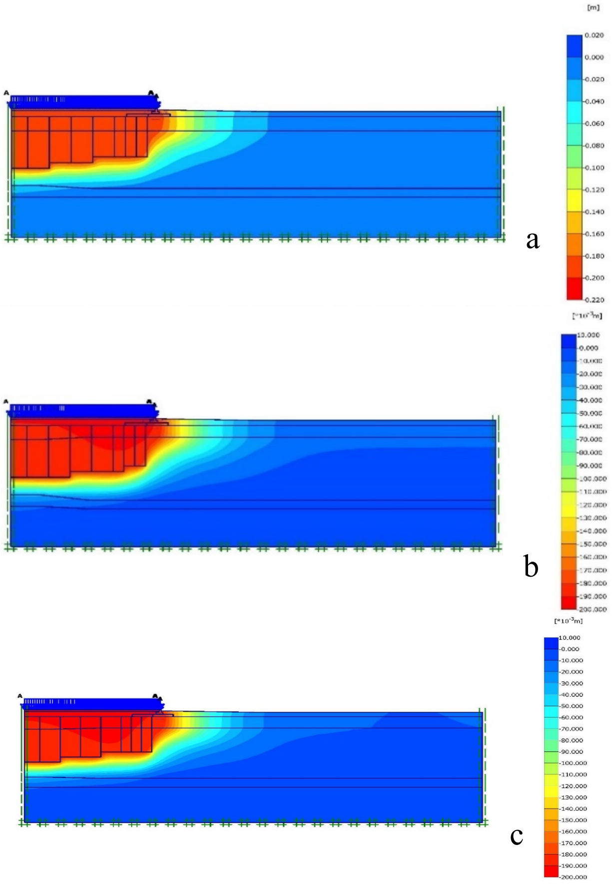


Figure 9. The contours of displacement and total settlement in the long term with regard to consolidation settlement during operation in reservoir a) section 1-2 b) section 1-3 c) section 1-4

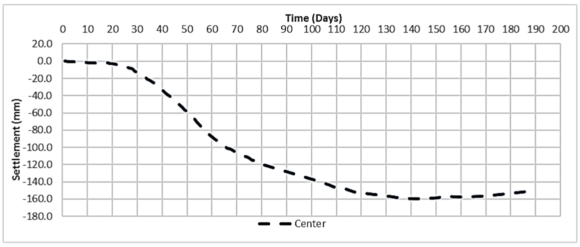


Figure 10. The reading of the center and corners of the tank after improving with the RI column method

7. CONCLUSION

The study outlines the development of three distinct mix ratios for cement-sand mortar through trials and material modifications, focusing on compressive strength, elastic modulus, and Poisson's ratio. The final proposed mix design achieves a characteristic strength of 3 MPa and an elastic modulus of 2 GPa, recommending the use of Type 1 cement combined with silica fume due to its cost-effectiveness and performance advantages, particularly in sulfate and chloride-rich environments. Additionally, the research includes a detailed settlement analysis using Plaxis software, which assessed the impact of Rigid Inclusions (RI) columns on reducing total and differential settlements in various tank sections after hydrotesting, showing significant reductions in both center and wall settlements. Hydrotesting of a reservoir confirmed the adequacy of bearing capacity, with a recorded long-term settlement of 160 millimeters after 188 days. Overall, the findings support sustainable practices in civil engineering by enhancing material efficiency and minimizing environmental impacts while ensuring structural integrity.

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