Ground Improvement in Loose Sandy Soils through Dynamic Replacement

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ABSTRACT: The challenge of maintaining the stability and longevity of structures in areas with high fines content soils necessitates effective ground improvement strategies. One such strategy, dynamic replacement, has been successfully implemented in the developing city site of Jaber Al Ahmed, around 25 km west of Kuwait City. The site's soil profile features extensive sand deposits varying from very loose to medium, silty, and clayey, reaching a depth of roughly 10 m. Areas characterized by fines content exceeding 30% were earmarked for improvement. The dynamic replacement technique involves the creation of a crater by dropping a heavy weight, subsequently filled with imported granular material, forming a stiff granular column within the soil. This reduces soil compressibility and settlement significantly while increasing bearing capacity under applied foundation loads. Through an extensive laboratory and field-testing program encompassing an area of 36,000 m^2, soil conditions were assessed using boring and sampling, Standard Penetration Tests, Cone Penetration Tests, and Pressuremeter Tests, both before and after the dynamic replacement. The results were marked improvements in ground conditions, satisfying the specified acceptance criteria with a minimum allowable soil pressure of 300 kN/m^2 for the foundation design of the housing project's structures. This study highlights the impact of dynamic replacement as a ground improvement strategy in terrains rich in fines, establishing a paradigm shift towards resilient, sustainable, and economically viable construction methodologies, with a significant potential to revolutionize infrastructure development in similar geological settings worldwide.

KEYWORDS: Loose Silty Sands, Ground Improvement, and Dynamic Replacement.

1. INTRODUCTION

The rapid pace of urbanization and population growth witnessed globally presents various challenges (Profiroiu *et al.,* 2020). Among these, one of the most critical is expanding and developing infrastructure in regions characterized by complex geotechnical conditions. Engineers and urban planners struggle with various soil types and properties when building new cities, roads, bridges, or other facilities (Shahin 2016). In many instances, they encounter locations with very loose to medium-dense sands, which can pose substantial difficulties for the stability and durability of structures.

Such geotechnical challenges necessitate the use of innovative ground improvement techniques (Daramalinggam and Annam 2019). Among these, dynamic replacement has emerged as a promising solution (Tarawneh *et al.,* 2019). This technique, which involves the substitution of soft or very loose soil with sand columns, has proven effective in enhancing the soil's bearing capacity and reducing its compressibility. This, in turn, facilitates the development of more reliable and cost-effective foundations for structures.

Dynamic replacement has shown immense potential across a wide range of applications (Lo, Ooi, and Lee 1990). Its uses are broad and varied, from improving soft soils to enabling ground improvement in deep waters. However, like any innovative method, it requires careful study and understanding to maximize its potential fully. Detailed investigations into the effectiveness of dynamic replacement under varying geotechnical conditions are of immense importance.

This paper aims to contribute to this crucial area of research. A detailed case study from Kuwait offers an in-depth investigation into the use and effectiveness of dynamic replacement in a real-world context. Through analyzing changes in soil properties and penetration test values, the study provides invaluable insights for geotechnical engineers worldwide dealing with similar challenges. The overarching goal is not just to add to our understanding of dynamic replacement, but also to contribute to the broader efforts aimed at improving infrastructure development practices around the globe.

2. BACKGROUND

Kuwait, a nation enriched by substantial oil revenues and faced with a swiftly expanding population, has embarked on several ambitious infrastructural projects (Biygautane 2017). One such project is the new city, Jaber Al Ahmed City, located 25 km west of the country's capital, Kuwait City. An initial geotechnical investigation of the city's site revealed extensive deposits of very loose to medium-dense silty and clayey sands, extending to depths of 10 meters - a typical soil profile for the region. Such ground conditions, however, present significant engineering challenges for construction, impacting structures' stability and settlement behavior.

In response to these challenges, the Public Authority for Housing Welfare (PAHW) recommended a two-pronged ground improvement approach based on the soil's fines content. Dynamic compaction was suggested for areas where fines were limited to 30%. In contrast, dynamic replacement, a technique that introduces sand columns or 'pillars' within the soil, was advised for areas where fines exceeded 30%, and the soil was particularly loose at the surface.

In the Jaber Al Ahmed City project context, dynamic replacement involved driving sand pillars to a depth of about 7 meters using a weight ranging from 15 to 25 tons. Dropped from a height of 10 to 25 meters, the process aimed to replace the loose soil with denser material, thereby improving the overall soil-bearing capacity and reducing its compressibility.

This study focuses on an area of 36,000 m^2 within the city, divided into six zones. Ground improvement was conducted in three dynamic replacement passes, followed by an ironing pass for surface consolidation. According to the criteria set by PAHW, success is determined by achieving a minimum allowable soil pressure of 300 kN/m^2 - a requirement for the city's foundation design.

By detailing the implementation and outcomes of the dynamic replacement technique used in the Jaber Al Ahmed City project, this paper aims to contribute valuable insights for similar global geotechnical challenges. Engineers dealing with loose sandy soils in coastal regions of the United States or managing similar desert conditions in the Arabian Peninsula and Australia's arid plains could leverage the findings to guide their decision-making processes.

3. METHODOLOGY

This section provides a detailed overview of the methodologies and techniques systematically implemented in this study. The techniques employed in this study can be grouped into four primary categories: site characterization, CPTs, PMTs, acceptance criteria for dynamic replacement.

3.1 Site Characterization and Soil Profile

A detailed plan of the site under investigation is shown in Figure 1. To effectively characterize the initial soil conditions at the site, a series of tests were conducted in each zone. This included one borehole, three CPTs, and one PMT to ensure a comprehensive understanding of the subsurface conditions. The findings are illustrated in Figure 2, which presents the soil profile alongside the SPT values obtained from six boreholes.

The soil profile at the site consists of a very loose surface layer of fine clayey sands (SC), extending to a depth of 2.5 m. Beneath this layer lies loose to medium dense silty sand (SM), transitioning into poorly graded sand with silt (SP-SM) towards the base of the boreholes. The proportion of fines (particles smaller than 0.075 mm) in these layers varied, ranging from 30% to 50% up to a depth of 4 m. During borehole drilling, groundwater was recorded between 2 m and 3 m below ground level.

For this study, the dynamic replacement phases were segmented into six distinct sub-zones. Zones 1 through 5 each covered an area of 6002 m^2, while Zone 6 spanned 6003 m^2. This division resulted in a total study area of 36,013 m^2, allowing for a detailed analysis of the dynamic replacement technique across the various soil conditions and zones.

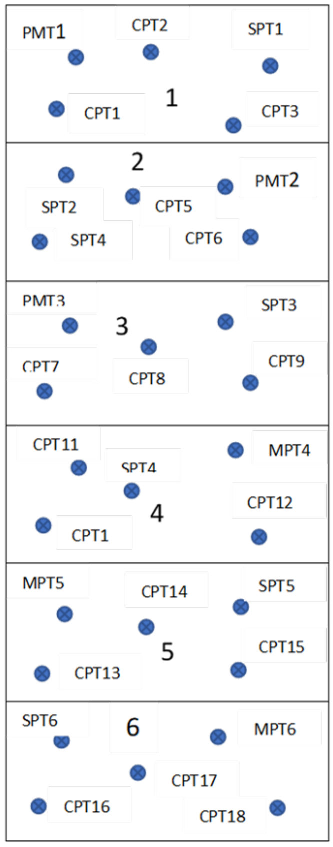

Figure 1 Layout Plan showing the Testing Locations

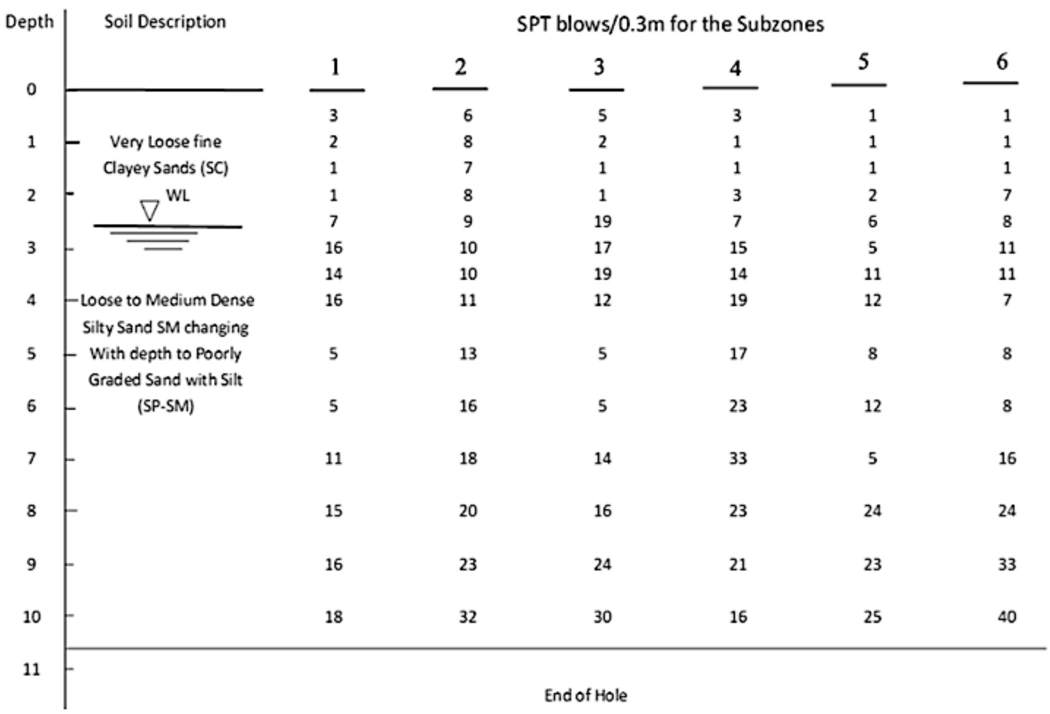

Figure 2 Borehole Logs Showing the Soil Profile and the SPT N Values

3.2 Cone Penetration Tests (CPT)

As per ASTM D-5778, eighteen CPTs were executed across the site, with each zone undergoing three individual tests. These tests provided valuable data, including cone resistance (q_c) and sleeve friction (f_s) at different depths. The study of these parameters across the six zones revealed an average cone resistance (q_c) ranging between 4.25 MPa and 7.78 MPa over the seven-meter depth designated for ground improvement. Simultaneously, the average frictional resistance (f_s) fluctuated between 0.008 MPa and 0.23 MPa over the same depth. Among the zones, Zone 5 registered the lowest average values, with q_c and f_s recorded at 4.25 MPa and 0.008 MPa, respectively, indicating it as the weakest.

3.3 Pressuremeter Tests (PMT)

Following the ASTM D 4719 standard, PMTs were carried out at one location in each of the six zones. These tests revealed average limit pressure (PL) values ranging from 0.61MPa to 1.2 MPa and soil modulus (E_m) values between 5.86 MPa and 9.43 MPa. In line with the CPTs, Zone 5 emerged as the weakest area, with the lowest average P_L and E_m values recorded at 0.61 MPa and 5.86 MPa, respectively.

3.4 Acceptance Criteria and Process for Dynamic Replacement

To meet the requirements for the housing structures and facilities at the Jaber Al Ahmed city site, a specified allowable bearing pressure of 300 kN/m^2 or larger and a settlement not exceeding 25 mm was essential. To achieve this, ground improvement was scrutinized through various penetration tests conducted at two key locations. One location was within the pillar to measure its inherent strength, while the second location was in the area between the pillars, intended to assess the strength of the weaker soil strata. The overall strength of the pillar/improved soil system was gauged by the equivalent composite soil strength, determined by the replacement ratio (n_r), represented by the Equations 1 and 2:

$$n_r = \frac{\pi r^2}{S^2} \quad (1)$$

where r signifies the radius of the pillar, and S denotes the center-to-center spacing between the pillars. The equivalent soil strength was then calculated using the SPT values as per the formula:

$$N_{eq} = n_r N_{pillar} + (1-n_r) N_{soil} \quad (2)$$

where N_{pillar} is the value measured inside the pillar, N_{soil} is the value within the intermediate soil. To adhere to the stipulated acceptance criteria for soils to a depth of 7 m, several key parameters were defined, as shown below.

3.4.1 SPT Acceptance Criteria

The average N value along the depth of acceptance criteria in the intermediate soil should be no less than 8, and the average equivalent N value should be 15 or larger.

3.4.2 CPT Acceptance Criteria

The average cone resistance (q_c) along the depth of the acceptance criteria in the intermediate soil should be 1.5 MPa or larger, and the average equivalent cone resistance should be 10 MPa or larger. The equivalent cone resistance (q_{cequiv}) can be calculated by replacing N_{pillar}, N_{soil} in Equation 2 by $q_{c\ pillar}$ and $q_{c\ soil}$. These values were required by the project specifications which satisfy the foundation design criteria of this project.

3.4.3 PMT Acceptance Criteria

The average limit pressure (P_L) along the depth of the acceptance criteria in the intermediate soil should be 0.25 MPa or larger, and the average equivalent P_L should be 1.0 MPa or larger. These values fulfill the project's design requirements.

4. DYNAMIC REPLACEMENT PROCEDURE DETAILS

Dynamic replacement was used for thick, loose layers with high fines content, ideal when fines exceed 30% and F_r exceeds 2%, where F_r is the friction ratio defined as f_s / q_c. This method consolidates fine soil and boosts its strength by embedding a stiff element. The designed pillars were 6 m long, 2 m in diameter, spaced at 4.25 m, using granular materials with under 10% fines. Before large-scale improvements, a 2500 m^2 test section trialed dynamic replacement to validate the design and production phase parameters. Figures 3 and 4 depict sand column formation and compaction phases. Table 1 details the production work in three phases, with phase 3 having four passes. A 15-ton pounder measuring 1.6 m x 1.6 m was dropped from a height of 14 to 20 meters. For the ironing cycle, the pounder with a surface area of 1.8 m x 1.8 m was dropped 2 to 4 blows from a height of 12 to 14 meters.

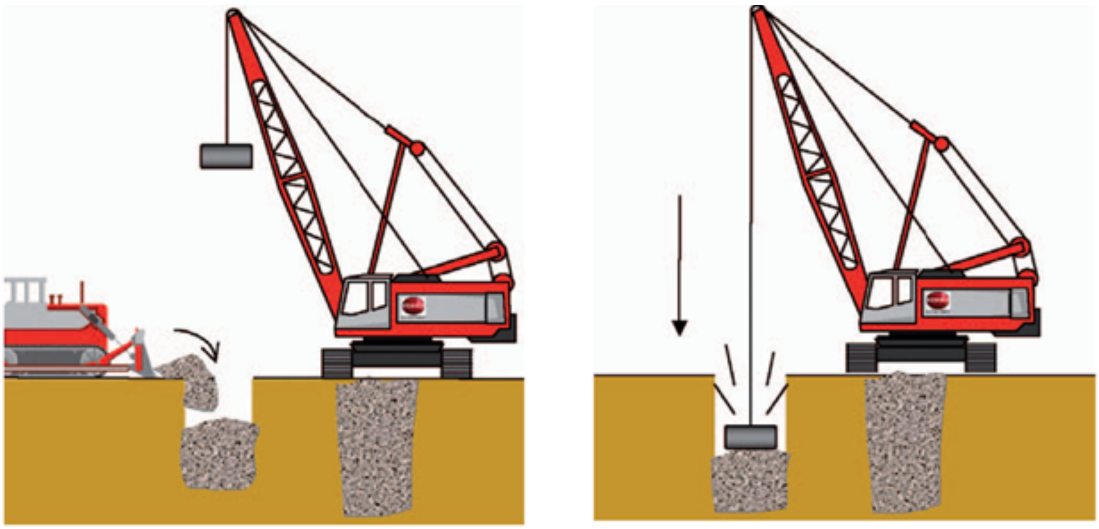

Figure 3 Dynamic Replacement at the Site

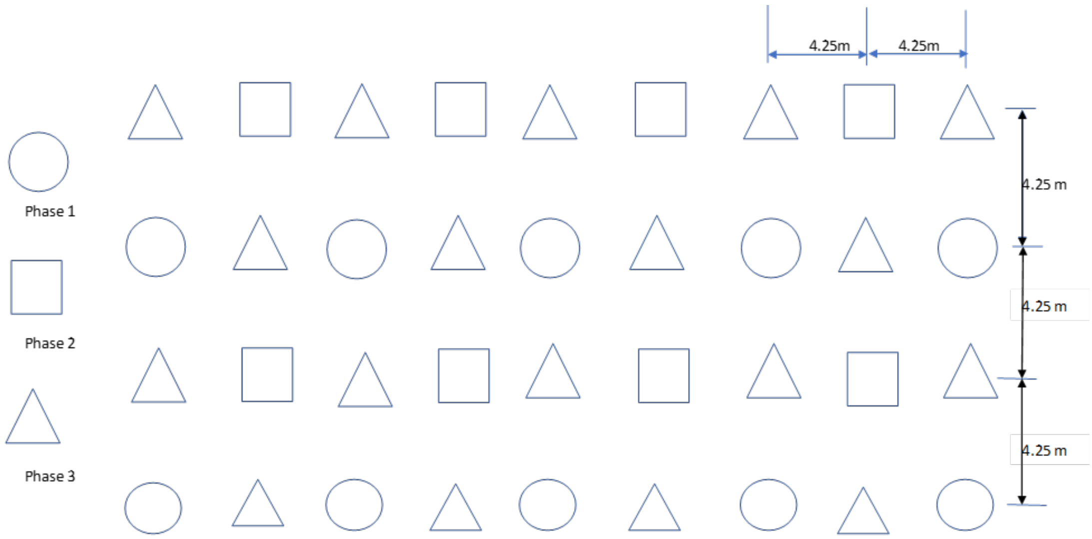

Figure 4 Plan of the Impact Points and Phases of Dynamic Replacement

Table 1 Summary of the Dynamic Replacement Phases

Phase 1							
	Pass 1		**Pass 2**		**Pass 3**		**Ironing**
Pounder		Pounder		Pounder		Pounder	
Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.8m x 1.8m
Weight	15 t	Weight	15 t	Weight	15 t	Weight	15 t
Blows	8 to 10	Blows	10 to 12	Blows	8 to 12	Blows	2 to 4
Height	14 to 16 m	Height	16 to 18 m	Height	16 to 20 m	Height	12 to 14 m
Phase 2							
	Pass 1		**Pass 2**		**Pass 3**		**Ironing**
Pounder		Pounder		Pounder		Pounder	
Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.8m x 1.8m
Weight	15 t	Weight	15 t	Weight	15 t	Weight	15 t
Blows	6 to 10	Blows	8 to 12	Blows	8 to 12	Blows	2 to 4
Height	14 to 18 m	Height	16 to 20 m	Height	16 to 20 m	Height	12 to 14 m
Phase 3							
	Pass 1		**Pass 2**		**Pass 3**		**Pass 4**
Pounder		Pounder		Pounder		Pounder	
Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.6m x 1.6m	Surface	1.6m x 1.6m
Weight	15 t	Weight	15 t	Weight	15 t	Weight	15 t
Blows	8 to 10	Blows	8 to 12	Blows	6 to 10	Blows	6 to 10
Height	14 to 18 m	Height	16 to 20 m	Height	16 to 18 m	Height	16 to 20 m
	Ironing						
Pounder							
Surface	1.8m x 1.8m						
Weight	15 t						
Blows	2 to 4						
Height	12 to 14 m						

4.1 Preparation and Execution of Dynamic Replacement

Before improvement, the site was cleared to 0.5 m depth to remove vegetation and topsoil. Post dynamic replacement, craters were filled with specific granular materials, then the ground was releveled for the next compaction. An 'ironing pass' compressed surface soils after compaction, as detailed in Table 1. During the dynamic replacement procedure, the application of energy was ceased when any of the following conditions were observed:

1. Groundwater appeared in the crater: Upon occurrence, the crater was backfilled, and the compaction process resumed.

2. Ground surface exhibited heave or swelling before reaching the required number of drops: In such cases, compaction was paused to allow time for dissipation of pore water pressure before resuming.
3. The crater's depth exceeded the thickness of the drop weight by 0.3 m: In this situation, the crater was backfilled, and the compaction process continued.

5. RESULTS

Following the completion of the dynamic replacement process, the initial field tests were reconducted to assess the effectiveness of the soil improvement. This was essential to accurately assess the extent and effectiveness of the soil improvement achieved. In this phase, all tests were carried out, focusing on both the dynamically replaced pillars and the surrounding intermediate soils. This approach provided a comprehensive understanding of the improvements made to the soil's structure and properties, thereby enabling an effective evaluation of the overall impact of the dynamic replacement technique.

5.1 Standard Penetration Tests (SPT) Results

Table 2 summarizes the average SPT N values observed within a depth of 7 m following the dynamic replacement. The table details average N values inside the pillars, the surrounding soil, and the average equivalent N value, N_{eq} (Equations 1, 2), alongside their corrected values considering the effect of overburden pressure, as described by B. P. Peck *et al.* (1974) (Peck, Hanson, and Thornburn 1974):

$$N_{corrected} = C_N * N_{field} \quad (3)$$

where C_N is a correction factor for the effect of overburden pressure is given by:

$$C_N = 0.77 \log\left(\frac{20}{\sigma\upsilon'}\right) \quad (4)$$

Here, $\sigma\upsilon'$ is the effective overburden pressure in ton/ft^2 (equivalent to 95.76 kN/m^2).

Table 2 Summary of the SPT Post-Dynamic Replacement

Sub Zone	^{N} Field			^{N} Corrected		
	Avg. N Pillar	Avg. N Soil	Avg. N eq	Avg. N Pillar	Avg. N Soil	Avg. N eq
1	22	23	23	28	30	30
2	27	25	26	36	33	33
3	17	24	22	23	31	29
4	26	18	19	34	24	26
5	21	20	20	29	27	28
6	24	19	20	31	24	26

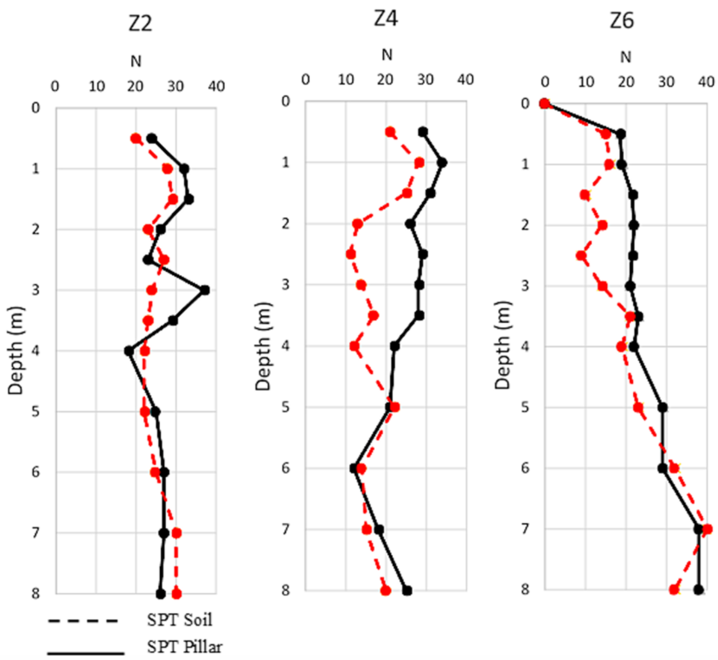

Figure 5 N Values Depth-wise in Zones 2, 4, 6 post Dynamic Replacement.

Figure 5 shows the depth-variation of N values in pillars and intermediate soils for zones 2, 4, and 6 after dynamic replacement. Pillar values are typically higher. Table 2 reveals average equivalent N values between 19-26, surpassing the minimum criterion of 15. Corrected values range from 26-33. Thus, using Bowles (1977) (Bowles 1977), the permissible soil pressure for foundation design, with a 25 mm max settlement, exceeds 300 kN/m2, meeting PAHW specifications.

5.2 Cone Penetration Tests (CPT) Results

A total of 36 CPTs were conducted at three initial test locations in each zone – one inside the pillar and another in the intermediate soil, performed until refusal. Average cone resistance (q_c) was assessed for each 7m depth test, as detailed in Table 3. All q_c values met the 1.5 MPa soil and 10 MPa equivalent criteria. Pillars showed 10%-54% higher strength than intermediate soil. Post dynamic replacement, average q_c values doubled, indicating increased strength and stiffness.

Table 3 Cone Resistance $q_{c\ average}$ and $q_{c\ equivalent}$ after Dynamic Replacement

Sub Zone	$q_{c\ field}$ (MPa)		
	Avg $q_{c\ pillar}$	Avg $q_{c\ soil}$	Avg $q_{c\ equivalent}$
1	17.76	14.93	15.53
	17.42	14.55	15.16
	18.58	14.92	15.69
2	18.55	14.65	15.47
	17.54	15.96	16.29
	19.47	14.34	15.42
3	17.07	13.02	13.87
	19.53	12.67	15.71
	15.94	12.28	13.05
4	15.19	11.27	12.09
	15.77	11.29	12.23
	14.87	10.53	11.44
5	12.54	9.76	10.34
	18.36	11.89	13.25
	11.86	10.74	10.98
6	15.15	12.51	13.07
	14.2	11.32	11.93
	15.54	11.95	12.71

5.3 Pressure Meter Tests (PMT) Results

Twelve PMT tests were executed. Two boreholes were drilled for testing in each zone's vicinity, one inside the pillar and the other in the intermediate soil. The average value of the limit pressure (P_L) was calculated up to a depth of 7 m. Table 4 summarizes these results, including the average P_L values for the pillar, the soil, and the equivalent P_L values for each zone. All values met the minimum acceptance criteria of average $P_{L\ soil} > 0.25$ MPa, $P_{L\ equivalent} > 1$ MPa. Generally, the average P_L values in the pillars were larger than the corresponding values in the intermediate soil. Upon comparing these values with the initial ones, it was observed that the range of P_L values in the soil increased from 0.4 – 1.2 MPa to 1.79 – 2.6 MPa post-dynamic replacement, indicating a considerable increase in strength and bearing capacity.

Table 4 Average Limit Pressure and Equivalent Pressure Values from the PMT

Sub Zone	P_L (MPa)		
	Avg. $P_{L\ Pillar}$	Avg. $P_{L\ Soil}$	Avg. $P_{L\ equivalent}$
1	3	2.12	2.11
2	2.02	2.28	2.16
3	2.76	2.61	2.35
4	2.34	2.1	2.11
5	2.7	1.79	1.84
6	2.2	1.96	1.92

6. DISCUSSIONS

Ground improvement techniques are crucial for infrastructure development in regions with sub-optimal soil conditions (Kamal, Korulla, and Meenu 2020). The new Jaber Al Ahmed city in Kuwait presented such a challenge, requiring the application of a dynamic replacement technique to address the issue. Field tests and laboratory investigations were carried out before and after the implementation, generating comprehensive data on basic soil properties and assessing the technique's efficacy.

The initial soil profile of the site, characterized by very loose clayey sands transitioning to loose to medium silty sand and poorly graded sand at a depth of 2.5 m, was problematic for construction. With the fines ranging from 30% to 50% and the presence of groundwater at a depth of 2 to 3 m, the ground conditions were notably sub-optimal for supporting large structures. This concurs with numerous studies highlighting the challenges posed by such soil conditions for construction purposes (Dafalla 2012; Jebelli, Meguid, and Sedghinejad 2010; Matanovic, Cikes, and Moslavac 2012). However, the application of dynamic replacement offered a promising solution. The process involved dropping a 15-ton weight from varying heights in multiple passes, leading to the installation of granular pillars. This transformation drastically increased the soil's strength and stiffness, echoing findings from other research highlighting the efficiency of dynamic replacement in ground improvement (Sękowski, Kwiecień, and Kanty 2018).

The ground improvements were quantitatively evaluated through SPTs and CPTs. The former revealed a change in ground conditions from very loose to medium dense to dense, a significant improvement that enhances the soil's load-bearing capacity. The CPTs also indicated a more than doubled average cone resistance after dynamic replacement. The pillars exhibited 10 to 54% higher q_c than the intermediate soil, highlighting the remarkable success of the dynamic replacement process.

This technique not only met the specified design acceptance criteria but also exceeded the allowable soil pressure based on the permissible settlement of 25 mm. This finding has significant implications for the stability of future structures built on the site, allowing for more ambitious architectural designs and larger load-bearing structures. Furthermore, after dynamic replacement, soil stiffness notably increased, with the soil modulus rising from 10 MPa to 30 MPa, and limit pressure PL values jumping from the 0.4 MPa-1.2 MPa range to 1.79 MPa-2.6 MPa, indicating enhanced soil bearing capacity. This highlights dynamic replacement's efficacy in ground improvement. These findings highlight dynamic replacement's broad applicability and effectiveness as a cost-efficient ground improvement solution for areas with loose sands and clayey sands, suitable for new city or large structure developments globally (Mishra 2016).

7. CONCLUSIONS

The results of this study demonstrate the successful application of dynamic replacement as a ground improvement technique in the challenging soil conditions of the new Jaber Al Ahmed city in Kuwait. The technique effectively addressed the inherent issues associated with the loose and clayey sands, transforming the sub-optimal ground conditions into a more robust and construction-ready state.

Not only were the specified design acceptance criteria met, but they were significantly exceeded, with the soil pressure tolerance surpassing the initial expectations. The combination of on-site tests and laboratory-based examinations provided a comprehensive assessment of the soil properties, demonstrating a significant increase in the soil's strength and stiffness following the implementation of dynamic replacement. These findings are a significant contribution to the body of knowledge surrounding ground improvement techniques, particularly in regions that present similar challenges (N. F. Ismael *et al.,* 1986).

From the behavioral perspective, the success of this project can motivate engineers and construction stakeholders to be more conscious of sustainable practices (D. Ismael and Shealy 2018). Behavioral interventions can include the promotion of techniques like dynamic replacement through workshops, seminars, and professional development programs. Recognizing the potential for professional acclaim and the intrinsic rewards of environmental stewardship can encourage more engineers to adopt these sustainable techniques (D. Ismael and Shealy 2018; 2019).

Based on these results, it is recommended that dynamic replacement be considered for future projects globally, especially regions where very loose sands and clayey sands extend to depths of up to 10 m. The technique has demonstrated both effectiveness and economy, making it a highly viable solution in these contexts. It is particularly suitable for open desert areas where new cities or large structures will be under construction and where no surrounding structures exist.

The broader impact of this research extends beyond the immediate context of Kuwait. Ground improvement techniques like dynamic replacement have global relevance, particularly with increasing urban expansion into areas with challenging soil conditions. Future research can build upon this study by examining the stability of dynamically replaced soil and exploring this technique in various geographical and geological conditions.

8. ACKNOWLEDGMENTS

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