Experience of Using Expanding Polyurethane Resin for Ground Improvement Under Existing Shallow Foundations on the Arabian Peninsula

Evgeny N. Zakharin, Bartosz Majewski

***Abstract*—**Foaming polyurethane is a ground improvement technology that is increasingly used for foundation stabilization with differential settlement and controlled foundation structure lifting. This technology differs from conventional mineral grout due to its injection composition, which provides high-pressure expansion quickly due to a chemical reaction. The technology has proven efficient in the typical geological conditions of the United Arab Emirates. An in-situ trial foundation load test has been proposed to objectively assess the deformative and load-bearing characteristics of the soil after injection. The article provides a detailed description of the experiment carried out in field conditions. Based on the practical experiment's results and its finite element modeling, the deformation modulus of the soil after treatment was determined, which was more than five times higher than the initial value.

***Keywords*—**Chemical grout, expanding polyurethane resin, foundation remediation, ground improvement

I. Introduction

THE rapid urbanization and developmental activities carried out in the city of Dubai and other cities within the United Arab Emirates (UAE) have resulted in significant changes to the hydrogeological situation of the region. In particular, the extensive construction and irrigation activities have influenced an elevation in the natural groundwater level. The high rate of construction activities has also led to changes in the natural soil profile and its stress field over a large area. Therefore, it is essential to consider the changing hydrogeological conditions and their impact on the area to avoid unpredicted soil-foundation behavior. Typical reasons that cause defects and failure of the foundations are widely presented in the literature.

The technology of injecting expanding polyurethane foams for ground improvement was developed in the 1980s [1]. However, it is still considered innovative because it is not widely used, especially in Middle East countries. Over the last five years, this method has been applied as an effective solution to remediating foundation differential settlement, controlling structure lifting, and increasing soil bearing capacity on many projects in the UAE. This study aims to summarize the available experience of using this technology on the Arabian Peninsula in terms of geological, technological and climate aspects.

II. Method Description

Numerous studies conducted in various countries, including Germany, Italy, Finland, Spain, the USA, Canada, Australia, Russia, Malaysia, and New Zealand, have explored the use of expanding polyurethane resin for ground improvement [2]-[6]. The key difference between this technology and the conventional mineral grout method is the injection material, which is a fast-reacting foaming resin consisting of two components: polyol and isocyanate. During the chemical reaction, the initial resin can expand up to 30 times in seconds, making it a suitable option for combined hydraulic fracture and compaction soil grouting.

Prior to injection, small-diameter segmented metal lances are rammed into the soil using a hammer drill until the desired level of improvement is reached. If the injection is required under an existing foundation, the lances are installed through 14-18 mm holes drilled in concrete structures or positioned around the footings. After installation, a high-pressure piston grout pump with a separate supply of injection resin components is connected, as is a mixing unit connected to the head of the lance.

A resin mixture is injected into the soil with pressure to create hydraulic fracturing, which compacts the soil around. Due to a chemical reaction, the mixture foams with excess pressure, forming durable inclusions of hard polyurethane foam in the soil. After injection, the soil becomes a composite of compacted soil with reinforcing inclusions of polyurethane foam. This results in low deformability of treated soil, high bearing capacity, and a filtration coefficient that characterizes the soil as waterproof.

This technology utilizes fast-foaming polyurethane, which offers several advantages. It permits better control of the area of soil propagation and reduces the load due to the grout's lightweight nature. This facilitates the enhancement of the condition of the more stressed areas under loaded foundations using minimal material. In addition, this type of material allows for prompt solutions and immediate loading of the structure due to the polymer's rapid strength development. Furthermore, this technology is a proficient method for high-precision and controlled structural foundation lifting using rotating laser-level equipment.

The studies [2]-[6] present numerous case studies of applying this method in cohesive and non-cohesive dispersed soils. Traylen et al. studied the effectiveness of ground improvement using polyurethane grout injection for mitigating liquefaction

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potential [7]. Technology in sandy soils (including siltier sands) increases confining pressures and leads to densification effects in treated areas.

Buzzi et al. confirmed that expanding resin injection reduces the permeability coefficient of clay soils by filling cracks and macropores [2]. The method can be used for the remediation of expansive clay foundations using a treated model of resin-soil composite behavior.

It is important to consider the potential drawbacks of the soil injection method. One significant challenge is the absence of a verified technique for determining soil parameters after injection, which is contingent upon the soil type and the quantity of material utilized. Consequently, to evaluate the effectiveness of the approach, establish the material consumption, and identify the necessary installation grid of injection lances, a test site that simulates a construction environment must be employed.

Moreover, in-situ estimation of soil foundation parameters under existing facilities can be difficult due to the unpredictable nature of technogenic soils and limited access. Thus, determining the actual material consumption can only be achieved once the work has been completed. A compromised solution to this problem is proposed to use the isolated foundation load test method, which is a modification of the Plate Load Test (PLT) procedure according to ASTM D 1194 [8]. In this case, it is proposed to use a reinforced foundation slab instead of a round rigid stamp to transfer stress to the ground from the load.

III. Experience of Application in UAE

According to the Dubai Building Code, a major characteristic of the ground in Dubai is its calcareous origin for sand and rock [9]. Groundwater has a high chlorite and sulfate content, which makes it very aggressive to underground concrete structures and foundations.

The expanding polyurethane injection method has been successfully utilized to stabilize over 20 structures in Dubai since 2019. The primary objective was to stabilize foundations with differential settlement, increase the deformation modulus of the soil and its bearing capacity, and protect against suffusion processes. The method successfully stabilized shallow-type foundations with a subsoil load of up to 300 kPa and a maximum injection depth of 8 m.

The expanding polyurethane produced by MC-Bauchemie and metal lances with a 13-14 mm diameter were used to inject resin into the soil. During the application process, the injection is performed from the bottom up, with a gradual rise of the lance. The Dynamic Cone Penetration Test (DCPT) evaluates relative soil compaction before and after injection, providing quick data in the area a few cm away from the existing foundation. A comparative assessment before injection and after by DCPT for the strip foundation of a pumping station building located in Jebel Ali District in Dubai is presented in Fig. 1.

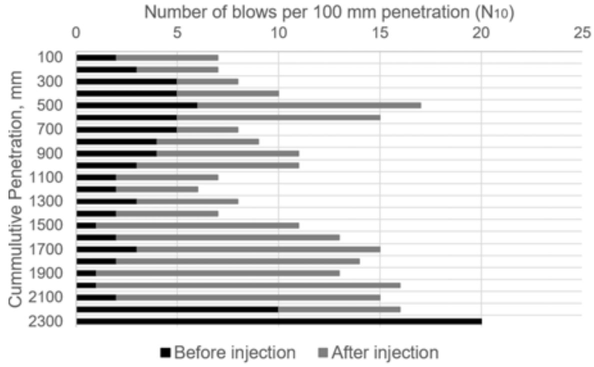

Fig. 1 The DCPT chart, comparing results before and after injection for silty, fine to medium sand

The speed of the chemical reaction of polyurethane resin is dependent on the temperature of the components and the surrounding environment. This factor must be considered when carrying out work in open spaces, particularly during summer. Executing work at temperatures above 30°C does not adversely affect the quality of the polymer in the soil.

However, it is necessary to consider the correction of the reaction rate due to temperature to avoid a rapid polymerization reaction that may clog the injection lance and the pump mixing unit. To regulate the reaction rate of the composition, a reaction retarder can be added to the polyol component of the resin. Alternatively, the canisters of materials can be cooled in containers with ice for delaying chemical reaction (Fig. 2).

Fig. 2 Expanding resin injection application during hot temperature with storing the components in ice boxes

The cooling method with controlled separate resin components has been working well and can be recommended for application in countries with hot climates.

IV. Trial Foundation Load Test

The injection of foaming polyurethane resin into soil can result in polymer inclusions that may reach a thickness of 10 mm or greater. The presence of these inclusions makes the use of standard laboratory test methods unapplicable, as the post-treatment soil becomes a heterogeneous composite material. For an objective evaluation of soil strengthening outcomes, the suggestion is to conduct a trial foundation load test in accordance with the statements of [8]. This process involves casting a reinforced rigid foundation slab with a minimum size of 1 m x 1 m. The presence of this foundation is essential to offer support on the soil surface for the injection of foaming resin. This is necessary as the reaction results in the development of chemical pressure, and back pressure from the soil surface is required. The testing consists of the following steps: a. A rigid concrete slab is poured at the selected experimental site. If necessary, a load is applied to simulate the conditions of a real object, b. The soil is then injected using foaming polyurethane injection technology. c. Static load tests are conducted to determine the deformation modulus and bearing capacity of the soil composite, which consists of the original compacted soil and polymer inclusions. The modulus of elasticity E_s can be determined using the following expression, based on the theory of elasticity

$$E_s = \frac{(1-\nu_s{}^2)}{\Delta p/\Delta q_p} B_p I_w \quad (1)$$

where, ν_s is Poisson's ratio, Δp is foundation pressure increment; Δq_p is foundation settlement increment, B_p is least lateral dimension of footing, I_f is influence factor.

An experiment was conducted in an open field in Dubai, with the coordinates 24°59'58.6"N 55°15'04.9"E. The objective was to perform static load tests, for which a site was prepared with the necessary equipment (Fig. 3).

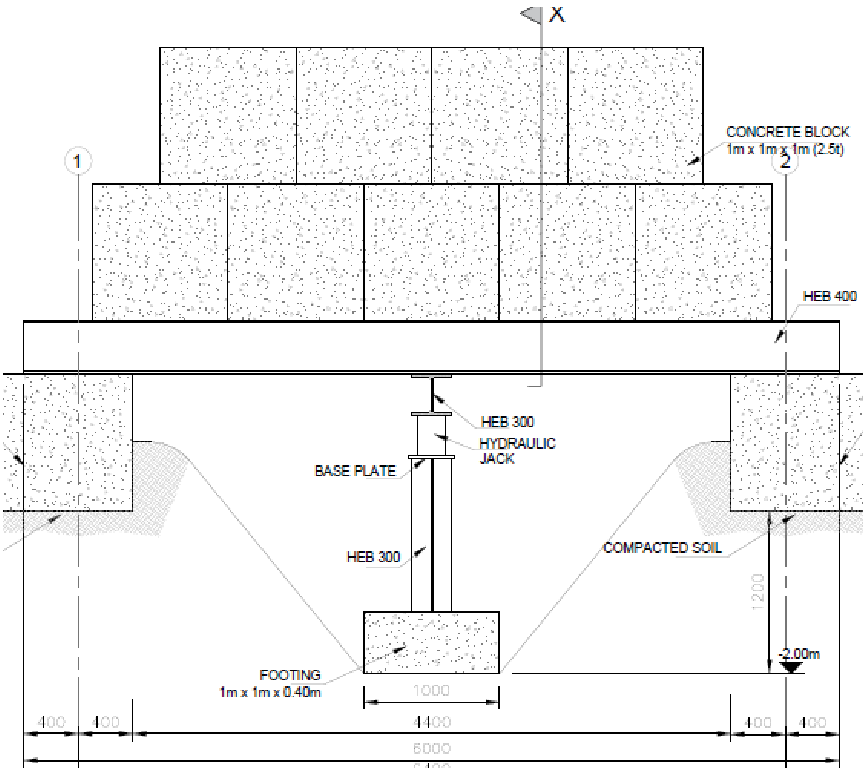

Fig. 3 Static load test detail

The foundation was a reinforced concrete slab, with dimensions 1 m x 1 m and 0.4 m thick, installed in the excavated pit at a depth of 1.7 m. The load was transferred to the foundation through the centrally placed column. A platform was constructed over the column for the gravity load method, and the load was applied to the platform using concrete blocks. The hydraulic jack was placed between the column and loading platform to apply gradual loading.

The area below the foundation was injected in two locations through the foundation (Fig. 4). Lances were installed 1 meter deep below the bottom face of the footing. The area was loaded with a seating load of 50 kPa and injected with resin consumption of 10 liters per m^3 of soil.

The load test started the day after the injection was finished. After increasing the load, settlement should be observed after 1, 4, 10, 20, 40, and 60 minutes and then at hourly intervals until the settlement rate is less than 0.02 mm per hour.

After collecting data for a particular load, the next load increment was applied, and readings were noted under the new load. This increment and data collection were repeated until the maximum load was applied.

Four dial gauges placed on a metal plate tightly pressed against the concrete foundation took the displacement measurements. A specialized geotechnical laboratory, invited for the purpose, carried out the static tests and measurements.

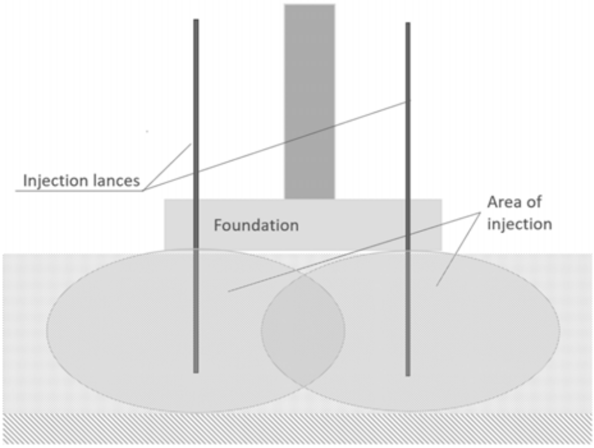

Fig. 4 Schematic view of injection below the mock-up foundation

Table I shows the soil profile according to a series of boreholes conducted in the experimental area. The groundwater level was determined at a depth of 7.25 m.

TABLE I
TRIAL AREA SOIL PROFILE

Depth, m	Description	Profile symbol
0-2.0	Light brown to brown, slightly silty to silty, fine to medium SAND	A1
2.0-3.0	Very dense, light brown to brown, silty fine to medium SAND with cemented pieces	A2
3.0-6.0	Extremely weak, light brown to brown, thickly laminated to very thinly bedded, fine to medium grained SANDSTONE	B1
6.0-8.0	Extremely weak, light brown to brown, thickly laminated to very thinly bedded, fine to medium grained, slightly conglomeratic, slightly gypsiferous SANDSTONE	B2

The geotechnical laboratory determined sandy soils' physical and mechanical characteristics using an isotopically consolidated drained triaxial test. Table II summarizes the soil parameters.

TABLE II
SOIL PROFILE PARAMETERS

Parameter	Top sand (A1)	Middle sand (A2)	Sandstone (B1,B2)
Unsaturated unit weight, γ_{unsat}, kN/m^3	17.7	17.8	19[1]
Void ratio, e_{int}	0.68	0.52	0.5[1]
Young's modulus at peak deviator stress E_{50}, MPa	55	80	n/a
Young's modulus E_{ref}, MPa	n/a	n/a	700[1]
Poison's ratio, ν_s	0.3[1]	0.3[1]	0.2[1]
Cohesion, c	0	0	n/a
Friction Angle, φ, grad	35	38	n/a

[1]Theoretical values

The results of static load tests carried out according to standards [8] in the pressure range of 0-200 kPa are presented on Fig. 5. Additionally, the results of the experiment's modeling for soil parameters before injection, as listed in Table II, using the Hardening Soil model for sand in Plaxis 3D, are also included for comparison.

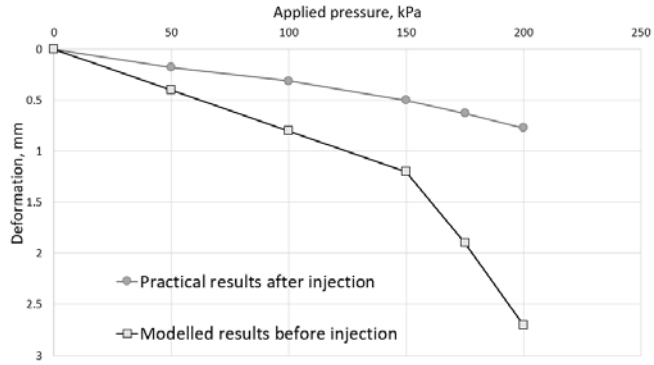

Fig. 5 Static load test results in comparison before and expanding resin injection

The elasticity modulus was calculated based on the test results. For a load in the range from 150 kN to 200 kN, according to (1), the elastic modulus before injection is 27.3 MPa; after injection, it is 151.7 MPa, which indicates a significant reduction in the deformability of the soil base after treatment with expanding injection resin.

V. CONCLUSION

Completed shallow foundation stabilization projects on sandy soils of the Arabian Peninsula show the high efficiency of the soil strengthening method by expanding polyurethane injection. DCPT method confirms an increase in the relevant resistance of the soil to cone penetration under dynamic load after treatment. When performing work, it is necessary to consider climatic conditions, especially in countries with hot climates, since temperature significantly affects the reaction rate of the composition. A trial foundation static load test was carried out, and as a result, it was possible to achieve the modulus of elasticity of silty sand increased from the initially calculated value of 27.3 MPa to 151.7 MPa according to the test results. This technique can be recommended for use as an effective method for assessing the deformative properties of soil after expanding resin injection method.

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