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Effect of water temperature on LNAPL contamination saturation reduction using flushing method; A physical modeling

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ABSTRACT: In this study, the efficiency of physical modeling of in situ flushing with water in two different temperatures was evaluated using a geotechnical centrifuge. The centrifugal experiments were made up of two main stages: transport of LNAPL through porous media and remediation of contaminated soil. First, 63 m^3 of LNAPL was infiltrated into a 10m thick prototype layer of coarse grain unsaturated sand. Afterward, continuous flushing of water in temperatures equal to 30 ^oC and 90 ^oC was done to remediate the contaminated soil in 40g acceleration. The efficiency of increasing the temperature on reducing the saturation content of the contaminated soil was investigated in this study. The total volume of injected water on the prototype scale during 19 prototype days was 316 m^3, equal to 1.4 times the soil pore volume between the soil-cement barrier walls. The results showed that when water with a higher temperature was used, the viscosity of LNAPL became more mobile compared to the process in which the temperature was relatively low. Image processing was used to evaluate the migration pattern of LNAPL before and after the injection process and the amount of reduction in saturation content. The test results showed a considerable reduction (65%) of LNAPL content when subjected to high-temperature water; however, the saturation content decrease in the test with lower temperature water was approximately 30%. The results concluded that the described experimental procedure and the geotechnical centrifuge could be used as a design tool for implementing and evaluating this remediation approach's efficiency.

Keywords: physical modeling, contaminated soil, water flushing, high temperature, soil-cement barriers.

1 INTRODUCTION

Fast-growing industrialization, population, and economic growth in different societies have led to an ever-increasing demand for petrochemical products. However, this need for fossil fuels has led to many environmental problems in the past decades. Several researchers have well-reported and well-studied the effects of petroleum hydrocarbons on the environment, like eco-toxicity and its implications on the environment and human health. Much of the contamination resulting from human activities are associated with the exploration, synthesis, and transfer of petrochemical products. The release of these hydrocarbon contaminants, such as light Non-aqueous phase liquids (LNAPLs), is of particular concern due to the high sensitivity of the subsurface environments where these substances enter.

Moreover, the dispersion of these pollutants can negatively affect groundwater quality; thus, various soil remediation methods have been studied to decrease contamination concentration. Nowadays, plans for the LNAPL remediation in soil vastly benefit many infrastructures, such as petroleum extraction and storage facilities, refineries, bulk product terminals, gas stations, and airports. Fortunately, during the past decades, LNAPL remedial techniques have developed from conventional pumping or hydraulic recovery systems to multiple integrated and complicated procedures that can recover the LNAPL in the immobile and residual LNAPL state, as well as LNAPL in the gaseous and dissolved phases. However, adopting the most effective LNAPL remediation technique and quantifying affecting parameters have been controversial yet.

Numerous attempts have been performed to investigate different methods' scope and efficiency using different approaches, including numerical simulations, field tests, and physical modeling. The numerical exercises have been confirmed to be highly challenging and uncertain because of sophisticated and known input parameters. On the other side, in-situ investigations can be costly and time-consuming. Therefore, experimental approaches, particularly the physical modeling using the geotechnical centrifuge, are invaluable substitutions providing advantages. (Behdad, Moradi and Afshari Aghajari, 2021) Jeong & Charbeneau (2014) developed an analytical model to estimate the recovery and distribution of LNAPL in heterogeneous aquifers and practiced multiple scenarios to recover LNAPL using LDRM, such as water trenches, skimmer wells, and air-enhanced wells. (Jeong and Charbeneau, 2014) In experiments done by Francisca & Montoro (2015), the effects of mineralogy, wettability, and fine-grain content on the displacement of LNAPL in sandy soils were analyzed by mixing coarse sand with zeolite, silt, and hydrophobic. (Francisca and Montoro, 2015) Shiota et al. (2016) studied a verification for the air injection method in remediating contaminated sand with LNAPL. A micro x-ray CT scanner was utilized to investigate the efficiency of this mechanism. (Shiota and Mukunok, 2015) Pasha et al. (2011) performed centrifuge tests to determine the LNAPL shape and its leakage rate from the USTs in various consolidation conditions. (Pasha *et al.*, 2011) Qiao et al. (2018) investigated an optimum surfactant that enhanced electro osmotic flushing effectively. Bi et al. (2018) focused on the dispersion of LNAPL under the influence of DNAPL. Sharma *et al.*, 2020 investigated the effects of a micellar flood process on a full-scale field application to recover and mobilize an LNAPL phase. A recovery rate of 90% was reported in their study. (Sharma *et al.*, 2020) A.Abdelhafeez et al. (2021) studied numerous methods for chemical and physical remediation techniques. They investigated green remediation techniques for heavy metals and hydrocarbons polluted sites. (Abdelhafeez *et al.*, 2022) Kaveh Sookhak et al. (2017) validated a new computational framework against sequential field pilot trials. (Kaveh *et al.*, 2017) Trulli et al. (2016) studied a combined treatment in contaminated alluvial soil due to an accidental LNAPL spill. (Trulli *et al.*, 2016) Despite all of the advantages of centrifuge testing, which are well studied and well recognized, the number of studies applying this modeling is limited. Nevertheless, several researchers have recently tried to incorporate the LNAPL remediation techniques in centrifuge modeling. Soga et al. (2003) conducted centrifuge tests equipped with the image processing method in different soil types to observe the LNAPL movement and entrapment in the unsaturated zone. (Soga *et al.*, 2003) The results were compared with numerical analysis. Krishna R.Reddy et al. (2004) investigated the remediation of DNAPL source zone in groundwater using the air sparging method. The spatial effects of different air injection rates were evaluated in the study. (Reddy and Tekola, 2004) Stroud et al. (2007) investigated Microbe-aliphatic hydrocarbon interactions in soil. Their research aimed to consider the physiochemical properties of aliphatic hydrocarbons and highlight mechanisms that control their behavior and fate in soil. (Stroud, Paton and Semple, 2007) K.Henderson et al. (2009) simulated the effect of remediation on EDB plumes at sites polluted by leaded gasoline. (Henderson, Falta and Freedman, 2009) Pasha et al. 2011 utilized the in-situ flushing of water containing a surfactant. The efficiency of this technique was simulated in centrifuge tests. (Pasha *et al.*, 2011) Among the various physical and chemical approaches of soil remediation, soil-cement barriers in the flowing and non-flowing groundwater conditions were simulated using centrifuge tests by Kererat et al. (2013). The aim of inserting these barriers is to confine the lateral spread of the LNAPL plume. (Kererat, Soralump and Sasanakul, 2013) The efficiency of these barriers with different depths was investigated by Behdad et al.(Behdad, Moradi and Afshari Aghajari, 2021). This manuscript aims to simulate one of the practical techniques of the LNAPL remediating in the soil using geotechnical centrifuge. The effectiveness of the combination of soil-cement barriers with pumping the heated water for LNAPL extraction was assessed through two centrifuge tests. The data for quantifying the key variables were analyzed and processed using the image processing method.

2 CENTRIFUGE MODELING TESTS

2.1 Model configuration

The C67-2 ACTIDYN geotechnical centrifuge at the University of Tehran was used for the tests. Tests were performed at 40 times the Earth's gravity. The soil chamber used for tests was a steel-made strongbox with a net weight of 195 kg. This strongbox is 0.3 m in width, 0.6 m in length, and 0.8 m in height, equal to the prototype dimensions of 12m? 4m? 2m. Table 1. Briefly displays the overall features of the tests.

Table 1. Overall features of the tests.

Test ID	Soil type	LNAPL volume (Lit)	Injected Water Volume (Lit)	Centrifuge Acceleration (g)	Temperature
No 1.	Firuzkoh sand #No 161 & 131	0.9	5	40	30
No 2.	Firuzkoh sand #No 161 & 131	0.9	5	40	90

2.2 Experimental Materials

Three different grain-sized sand, including Firuzkoh sand No. 131, No. 161, and No. 141, were used for the experiment. Detailed information for soil types is presented in Table 2.

Table 2. Soil Information.

Firuzkoh Sand Types	e_{min}	e_{max}	G_s	D_{50} (mm)	*Hydraulic Conductivity (cm/s)*
#No.131	0.629	0.924	2.68	0.5	9×10^{-2}
#No.141	0.675	0.917	2.63	0.43	9×10^{-2}
#No.161	0.658	0.91	2.66	0.27	4.5×10^{-2}
#No.181	0.64	0.902	2.65	0.23	3.5×10^{-2}

3 LNAPL SATURATION ANALYSIS AND TESTS' RESULTS

A comparison between the LNAPL Saturation content along the centerline before and after the injection is demonstrated in figure 1. All time frames are calculated in the prototype scale. The results of the first test is shown in Figures 1 and 2, respectively.

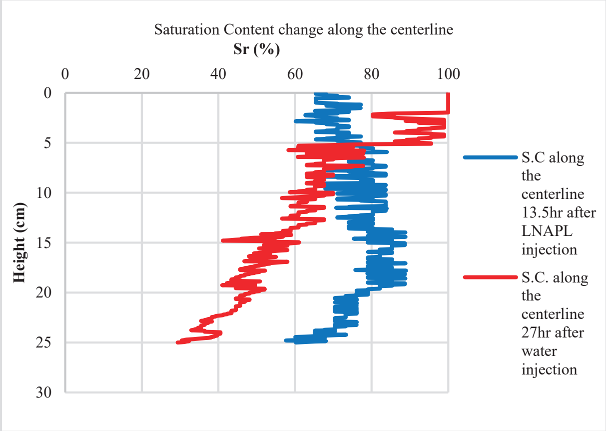

Figure. 1. LNAPL saturation content change before and after water injection for the 1st test.

Figure1. illustrates the effects of water injection by comparing the LNAPL saturation at the end of the LNAPL release and the end of the water injection. The maximum recovery rate occurred near the bottom layers, with approximately 30%. For upper layers because the LNAPL was forced upward, it was accumulated in those layers as time passed, and the saturation content increased.

In the second test, along with the jet flushing, the mechanism of viscosity reduction was applied using water with a higher temperature. Previous researchers observed the effects of increasing the temperature on lowering the LNAPL's viscosity. Results showed a drastic decrease in the saturation content, especially for bottom layers. Figure 2.

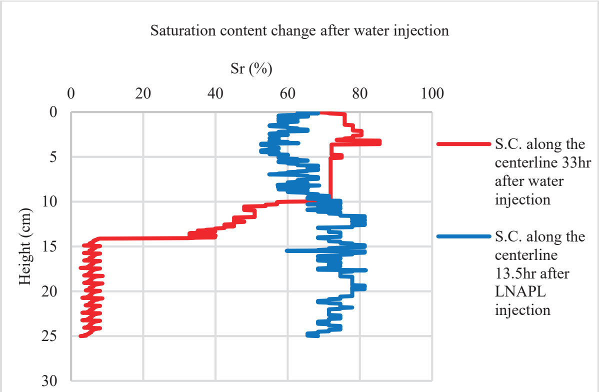

Figure. 2. LNAPL saturation content change before and after water injection for the 2nd test.

It can be inferred from the figures mentioned above that increasing the water temperature can enhance the method's efficacy up to 30%; however, it should be noted that the practicality of this method would be considered for the lower half of the barriers' height. In fact, to achieve a more homogeneous reduction along with the barriers' height, additional provisions, such as inserting another injecting device in the half elevation of the walls, could be considered.

4 SUMMARY AND CONCLUSION

In this study, two centrifuge tests were performed under different conditions. The main aim of these tests was to find out how efficient it is to inject water with varying temperatures into contaminated soil to remediate it. The following conclusions can be drawn from the present study:

- ✓ As water was injected upward, the saturation content of the LNAPL plume decreased. Results showed a 30% decline in saturation content.
- ✓ Injecting heated water, as expected, weakened the internal bond between LNAPL's molecules and lowered its viscosity, which decreased the saturation content up to 65%.
- ✓ Due to the soil's porosity, the more the water was injected, the more the saturation content decreased.

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