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# NUMERICAL INVESTIGATION OF OIL REMOVAL FROM SOIL USING ULTRASOUND EFFECT

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## ABSTRACT

Soil contamination is a big problem facing the whole world as it affects majorly all facets of life. The soil flushing method enhanced by ultrasonic waves is a new, potential and efficient technique for in situ remediation of the ground contaminated by NAPL hydrocarbons. This study investigated the effectiveness of ultrasound enhancement in the soil flushing method for a range of conditions involving treatment time, hydraulic gradient and the discharge velocity. The numerical investigation was performed using MATLAB to develop a program to determine the effectiveness of ultrasound enhancement in soil flushing method. The test result indicated that the rate of the contaminant extraction increased considerably with increasing sonication time up to 120 seconds with 34% contaminant removed without sonication and 64.05% contaminant removed with sonication and started decreasing at the level where cavitation occurred. Increasing the sonication time will increase the contaminant removal up to the level where cavitation occurs. The effectiveness of sonication decreases with hydraulic gradient but eventually becomes constant under higher flow rates and also is highly related with the discharge velocity. It can be concluded from the research work that soil flushing with ultrasound effect can increase the rate of contaminant removal from soil.

**KEYWORDS:** In Situ Remediation, NAPL Hydrocarbons, Ultrasound Enhancement, Soil Flushing, Soil Remediation, Cavitation

## INTRODUCTION

Soil contamination by petroleum hydrocarbon is among the problem facing the oil and gas industry. Petroleum hydrocarbons are mostly found in urban and suburban areas due to possible leakage of gasoline, motor oils and diesel fuel from underground storage tanks. Upon completion of extraction and removal of facilities, many oil and gas lease sites may be left with varying degrees of soil contamination. Such contaminated sites pose great risks to the environment and human health. The polluted ground needs to be cleaned in order to avoid hydrocarbon contamination of ground water aquifer. There are different remediation methods such as replacement, vapor extraction, pump-and-treat and flushing methods. However a method that can be economical and also effective for a broad range of field conditions is not yet available. For development of an effective ground remediation method, there has been considerable research focusing on the technique of enhancing soil-flushing method.

Soil flushing is an extraction process to remove organic compounds from contaminated soil. It removes contaminants by dissolving the liquid, sobbed or vapor phase by mobilizing contaminants existing as free product in soil pores and adsorbed to the soil (Hyman, Norman, and Reidy, 2001). Ultrasound is a sound that has frequency beyond the human hearing from 20 kHz and above. The soil-flushing method enhanced by ultrasonic waves is a new technigues that potentially can become an efficient method for in situ remediation of the ground contaminated by NAPL hydrocarbons. There are data showing that ultrasonic waves are capable of removing non-aqueous phase liquid (NAPL) hydrocarbons from soils. The behavior of a fluid's flow rate through porous media has been well known since Darcy in 1856 formulated an empirical equation from the flow of water through sand. These brought about the use of ultrasound to enhance remediation of soil contaminated with oil. NAPL are non-aqueous phase liquid, examples are DNAPL and LNAPL. While LNAPL on the other hand is a light non-aqueous phase liquid, it is a groundwater contaminant that is not soluble and has a lower density than water. Currently, the two remediation strategies that exist are; *in situ* and *ex situ*. *In situ* remediation techniques are the remediation of contaminated soil which is carried out on the natural place or site. And *Ex situ*, on the other hand requires the extraction of contaminated soils to different locations for treatment. Most physical, chemical and biological modes of non-aqueous phase liquid (NAPL) inducer removal belong to this latter category.

Surguchev and Simkin (1991) attributed the increased extraction of oil (hydrocarbons) to a decrease for water and an increase for oil in the relative phase permeability due to stress waves. Johnson (2004) observed a decrease in the viscosity of polystyrene solution under sound waves. He also reported increase in oil percolation rate through porous medium. Piesio and ooms (2004) developed a theoretical model to predict removal of small particle and fines in porous media. Gadiev (2003) stated that ultrasound can reduce the viscosity of high polymeric liquid by up to 27%. It was reported that ultrasonic excitation can suspend fine particle to which the contaminants are strongly absorbed (Cleveland and Garg, 2003). Also, (Reddi and Challa, 1994) and (Reddi and Wu, 1995) presented that ultrasonic waves can increase not only the mobility of NAPL ganglia but the porosity of the soil as well, resulting in a decrease in viscosity and buoyant pressure. (Kim and Wang, 2003) stated that sonication can enhance pollutant removal considerably and that the degree of enhancement depends on a number of factors such as sonication power, water flow rate and soil type. (Ellen et al, 1995) reported a 30% increase in contaminant extraction due to acoustic excitation. Another study by (Iovenitti et al., 1995) reported a 6-26% improvement in contaminant extraction. Hence the soil-flushing method enhanced by ultrasonic waves is a new techniques that potentially can become an efficient method for in situ remediation of the ground contaminated by NAPL hydrocarbons. The objectives of this research work is to investigate the effectiveness of ultrasound on the soil flushing remediation technique for a range of condition involving soil type, sonication time and flushing rate.

**Numerical Analysis**

Darcy's law is a derived constitutive equation that describes the flow of a fluid through a porous medium. It shows that the volumetric flow rate is a function of the flow area, elevation fluid pressure and proportionality constant. The law was formulated by Henry Darcy based on the result of experiments on the flow of water through beds of sand. It also formed the scientific basis of fluid permeability. For these equations, these assumptions were made

**Basic Assumptions**

- It is assumed that the flow is steady throughout.
- The flow is laminar.
- The sand is saturated with the NAPL contaminant.
- There is uniform or constant NAPL permeability within the soil.

**Basic Governing Equations**

The basic equations for modeling soil remediation using soil flushing method enhanced by ultrasonic waves are presented below:

- Determination of external pressure

$$P_{ext=}GL_v + \Delta P_g L_v \tag{1}$$

Where, G is the Pressure gradient

$\Delta P$ is Density different between water and the NAPL

$L_v$ *is* the Vertical Length between interface indicated by K and i

While, G can be expressed as;

$$G = \rho g i \tag{2}$$

$$i = Hydraulic\ gradient$$

$$v = ki \tag{3}$$

$$i.e\ P_{ext} = \frac{V_{uw}}{K} L_v + \Delta\rho_g L_v \tag{4}$$

$$q = \frac{Q}{QP} \tag{5}$$

Where $Q = \frac{1}{T}\int_0^T Q(t)dt$

T=Period of oscillations

$$Q_p = \frac{\pi R^4}{8\mu} G \tag{6}$$

$Q_p(G)$ is the Poiseuille flow rate

Determination of hydraulic conductivity

$$\mathrm{K} = \frac{\mathrm{k\rho g}}{\mu} \tag{7}$$

Where, K is the hydraulic conductivity

k is Permeability

$\rho$ is the Fluid density ($kg/cm^3$)

$\mu$ is the Fluid viscosity

$g$ is the Gravitational constant ( 9.81m/s )

- Flow rate under effect of vibration

$$W = a^{ei\omega t} \tag{8}$$

Where; W is the Flow rate with vibration

$a$ is the Displacement Amplitude

$\omega$ is the angular frequency of Vibration.

- Determination of permeability

$$K = \frac{Q\mu L}{A\Delta P} \tag{9}$$

Where K is the Permeability (Darcy)

Q is the Total discharge ($cm^3/s$)

$\mu$ is the Viscosity (cp)

L is the length of cell (cm)

A is the cross sectional area ($cm^3$)

$\Delta$P is the Pressure drop

- Determination of porosity

$$P=\frac{V_r}{V_b} \tag{10}$$

Where P is the porosity of soil

$V_r$ is the Volume of the reservoir

$V_b$ is the Bulk Volume (cross sectional area $\times$ Length)

- Percentage of oil recover

$$\text{\% of oil recovery} = \frac{Total\ volume\ of\ oil\ removed}{Initial\ volume\ of contaminant\ in\ the\ soil} \times 100 \tag{11}$$

- Contaminant flow rate

$$\text{Contaminant flow rate} = \frac{RecoveryVolumeofsoil}{Time} \tag{12}$$

- The flow rate of oil in the reservoir to total volume of fluid

$$Q_{r=}\ ((1-\alpha)Q_{oil})/(\alpha Q_w+\ (1-\alpha)Q_{oil}) \qquad (13)$$

Where $Q_r$ is the flow rate of oil in the reservoir to total volume of fluid

$Q_{oil}$ is the flow rate of oil

$\alpha$ is the fraction volume of reservoir occupied with water

$Q_w$ is the flow rate of water

- Increase in flow rate due to vibration

$$J_{(q_o)}=\frac{q-q_o}{q_o} \qquad (14)$$

Where J is the increase in flow due to vibration

$q_o$ is the steady flow rate (no vibration)

$q$ is the steady flow rate with vibration

- The percentage of contaminant removed is given as;

$$\%\ \text{of contaminant removed} = \frac{Total\ volume\ of\ oil\ removed}{Initial\ volume\ of\ contaminant\ in\ the\ soil} \times 100 \qquad (15)$$

**Soil Sample and Contaminant**

The soil sample used was sandy soil of grain sizes between 0.45mm-1.10mm. The contaminant chosen for this research work is Diesel which is produced from the fractional distillation of crude oil between 200$^o$c and 350$^o$c at atmospheric pressure thereby resulting in a mixture of carbon chains that typically contain between 8 and 12 carbon atmosphere molecule. It has a density of 0.918g/mol at 20$^o$c and viscosity of 65cst at 20 $^o$c.

## RESULTS AND DISCUSSIONS

The results of the numerical investigation carried out are presented below in Table 1-3. Before the contaminant can be flushed out on the soil, the soil/contaminant bond have to be broken first. Inside the soil mass, the contaminant can be trapped within the pore formed by the interlocked soil particles or absorbed on the surface of individual particles or both. Regardless of the nature of bond, the breakdown of the contaminant/soil bond is time-dependent process.

**Table 1: Percentage of Contaminant Removed with Respect to Time**

| Treatment (Sonication) Time (Seconds) | Contaminant Removed Without Sonication (%) | Contaminant Removed with Sonication (%) |
|---|---|---|
| 20 | 19.9824 | 49.9824 |
| 40 | 23.6242 | 53.6242 |
| 60 | 26.4879 | 66.4879 |
| 80 | 28.2241 | 58.2241 |
| 100 | 29.6812 | 59.6812 |
| 120 | 21.2401 | 61.2401 |
| 140 | 30.7812 | 60.7812 |
| 160 | 30.2890 | 60.2890 |
| 180 | 29.6210 | 59.6210 |
| 200 | 29.4214 | 59.4214 |

**Table 2: Contaminant Removed with Respect to Hydraulic Gradient**

| Hydraulic Gradient (Cm) | Contaminant Removed Without Sonication (%) | Contaminant Removed with Sonication (%) |
|---|---|---|
| 5 | 36.2130 | 66.2131 |
| 10 | 33.1461 | 63.1461 |
| 15 | 30.7112 | 60.7112 |
| 20 | 28.4581 | 58.4581 |
| 25 | 27.9811 | 57.9811 |
| 30 | 26.6432 | 56.6432 |
| 35 | 26.0346 | 56.0346 |
| 40 | 25.8378 | 55.8378 |
| 45 | 25.6311 | 55.6311 |
| 50 | 24.7181 | 54.7181 |

**Table 3: Contaminant Removed with Respect to Discharge Velocity**

| Discharge (/S) | Contaminant Removed Without Ultrasound (%) | Contaminant Removed with Ultrasound (%) |
|---|---|---|
| 1.5 | 33.5335 | 64.5935 |
| 2.5 | 26.3558 | 57.8535 |
| 3.5 | 23.5479 | 54.4321 |
| 4.5 | 22.3494 | 52.9761 |
| 5.5 | 22.9124 | 52.8124 |

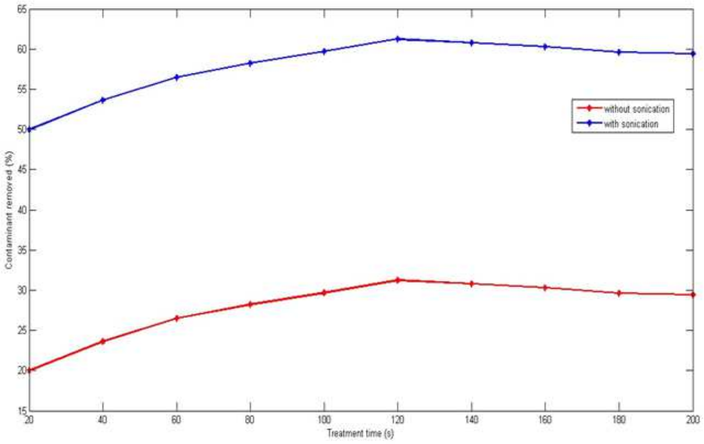


**Figure 1: Relationship between Treatment Time and Contaminant Removal (%)**

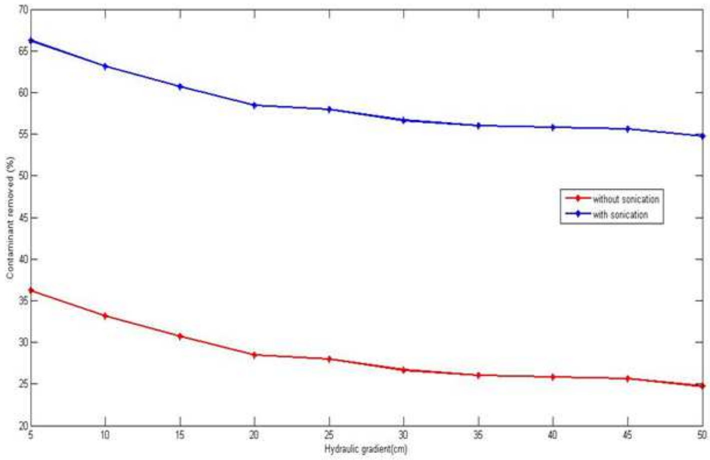


**Figure 2: Relationship between Hydraulic Gradient and Contaminant Removal (%)**

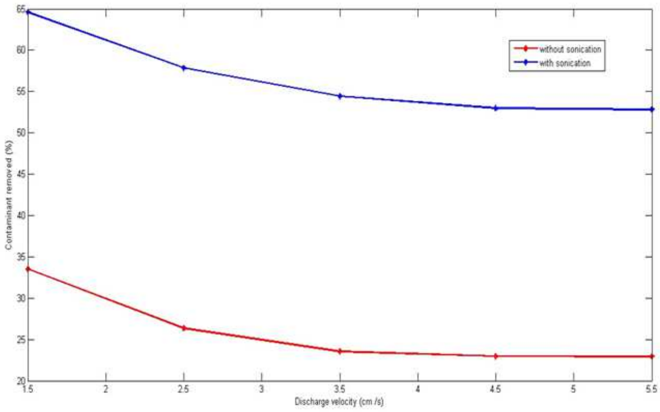


**Figure: 3: Relationship between Discharge Velocity (Cm/S) and Contaminant Removal (%)**

From the Figures above, it is obvious that numerous factors may influence the percentage of contaminant removal. Major factors investigated were sonication time, hydraulic gradient, and discharge velocity. The effect of these factors on contaminant removal was investigated on the sandy soil specimens that were prepared. Figure 1 presents the graphical relations between treatment time and percentage of contaminant removed for the numerical investigation. The effect of treatment time on contaminant removal was carried out at hydraulic gradient of 20cm. It was observed that for a constant hydraulic gradient, the percentage of contaminant removed increases with the treatment time for both ultrasonic enhanced soil flushing and the soil flushing processes to a maximum around 120 seconds of treatment then decreases. The treatment time beyond 120 seconds yielded decreased percent contaminant removed. It is evident that if the treatment time increases further, the reduction will increase further. The reduction in contaminant removal after 120 seconds is due to the effect of cavitation. Cavitation is the formation and then immediate implosion of cavities in a liquid i.e. bubbles that are the consequence of forces acting upon the liquid. The graph also shows the effectiveness of ultrasound in contaminant removal in a porous medium as it increases the percentage of contaminant removed all other factors being kept constant.

Figure 2 presents the graphical relations between hydraulic gradient and percent contaminant removed for the numerical investigation, carried out with hydraulic gradients interval of 5cm with a fixed treatment of 60seconds. It is evident that at low hydraulic gradient, there is higher percentage of contaminant removed. It is observed that the percent contaminant removal decreases with increasing hydraulic gradient. The explanation is that, increasing the hydraulic gradient will increase discharge velocity and flow rate, therefore reducing the time for the flushing water to interact with the soil/contaminant system. For low hydraulic gradient, the water has longer time to interact with the system, which makes it more efficient to remove the contaminant than fast flushing under high hydraulic gradient.

Similarly, Figure 3 shows the percent contaminant removed vs. discharge velocity in the numerical investigations respectively. It can be deduced from the relationship between the hydraulic gradient and discharge velocity which is linearly proportional that the higher the hydraulic gradient the higher the discharge velocity. At lower discharge velocity, more percentage of contaminant was removed due to low flushing time for long interaction between the flushing water and the soil/contaminant system.

## CONCLUSIONS

The research work numerically investigated the effectiveness of sonication in the soil-flushing method. The test soil was sand and the contaminant was Diesel. The results indicated the following:

- Sonication increases the efficiency of soil flushing in soil remediation by enhancing contaminant removal considerably.
- Increasing the sonication time will increase the contaminant removal up to the level where cavitation occurs.
- The degree of enhancement depends on factors such as soil type and water flow rate.
- The effectiveness of sonication decreases with hydraulic gradient but eventually becomes constant under higher flow rates and is highly related with the discharge velocity.

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