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Numerical study of electro-osmotic consolidation effect on pipe-soil interaction

Hakuri Nwen Joshua*, Fuat Kara

School of Water, Energy and Environment, Energy Theme, Cranfield University, UK

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ABSTRACT

Subsea pipelines are laid directly on seabed with further constraining measures to stabilise it against adverse effect of axial walking, upheaval buckling and lateral buckling. Costly mitigating measures are being employed and the need for further investigation to explore more option is considered. Stability of soil depends on the soil strength. Increasing the soil strength has been identified as a possible mitigation against pipeline displacement. Electro-osmotic consolidation process is currently being employed to increase soil strength around offshore and onshore structures, but the effect on pipe-soil interaction has not been fully investigated. This aspect received no attention on numerical model or detail experiment in this regard. The present study numerically investigates the effect of pipe-soil interaction using capabilities of commercial ABAQUS finite element software tool on both Electro-Kinetic (EK) treated and untreated soil to determine their behaviours. Results from this study when compared with non-EK treated soil, indicates remarkable developments, as the force required to displace pipeline increases significantly due to EK treatment.

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1. Introduction

Material strength relates to the greatest stress it can withstand. Low strength of soil may lead to collapse of structures resting on it. The ability of a pipeline to overcome axial displacement depends on the strength of soil in contact with the pipeline. Deepwater consists mostly of very soft clay with high water content, low shear strength and high compressibility [1,2]. Reduction in the moisture content in the soil due to the release of pore water pressure increases the soil undrained shear strength. Shear box testing gives credence to this process of increasing axial resistance due to cyclic hardening of soil [3]. Another concept at improving soil shear strength is Electro-Kinetic (EK) process. This concept is similar to the above in such that all involves a decrease in pore water pressure from the soil and one important advantage is that the time taking for soil to consolidate is highly reduced. This method find it application at increasing soil-bearing capacity of onshore and offshore structures. As obtained in the other processes, the EK process helps to reduce the pore water pressure in the soil. Applying the EK method to a pipeline which is susceptible to buckling and walking has been carried out experimentally by Eton [4]. The phases involve electro-osmotic consolidation process followed by stress displacement analysis of the pipe-soil interaction. Results from the experiment indicates remarkable developments as the soil shear strength increases significantly due to EK treatment. Numerical investigation of EK process on the pipe-soil interaction to a very soft soil has received almost no attention. The present study investigates numerically the impact in which treated soil will have on pipe-soil interaction using ABAQUS, a commercially available software package. With proper design and configuration of electrodes around the pipe, the EK approach on pipe-soil interaction will result in significant increase in soil shear strength thereby mitigating against pipeline displacement.

1.1. Electro-Osmotic concept

Electro-osmosis process to increase the strength of soil is conducted by applying electrical voltage to electrodes. Due to voltage flow, the soil pore water pressure tends to move from the anode to cathodes as shown in Fig. 1 [5]. The electric potential applied to soil will lead to the generation of negative pore pressure where the drainage condition is being determined by the anode and cathode of the electrode. Pore water pressure being generated lead to an increase in the effective stress of the soil with the total stress experiencing no changes and subsequently, leading to consolidation due to soil compartment [6]. The induced water flow due to ion migration can also lead to movement of other contaminant in

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* Corresponding author.
E-mail address: h.n.joshua@cranfield.ac.uk (H.N. Joshua).

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Nomenclature

Notation

A	Surface area (m^2)
A_c	Area of contact
b	Body force vector (N)
C_p	Electrical capacitance per unit volume
C_v	Soil coefficient of consolidation
D	Diameter (m)
F	Force (N)
F_e	Effective axial force (N)
F_w	Axial force on pipe wall (N)
L	Length (m)
k_{eo}	Electro-osmotic permeability m^2/Vs
k_w	Hydraulic conductivity m/s
$k_{\sigma e}$	Electrical conductivity (S/m)
j	Electrical current density (A/m^2)
L_0	Original length (m)
p_e	External pressure (Pa)
p_i	Internal pressure (Pa)
s	Solid particle
S_u	Undrained shear strength, (Pa)
t	Time (s)
u	Pore water pressure (Pa)
v	Velocity (m/s)
v^s	Soil particle velocity (m/s)
$\bar{v}$	Relative velocity (m/s)
V	Vertical load (N/m)
x	Particle position (m)
X	Particle reference configuration
z	Elevation (m)
α	Coefficient of thermal expansion
α'	Adhesion factor
β	Intermittent power supply
σ	Total cauchy stress (Pa)
σ'	Effective cauchy stress (Pa)
ϕ	Mapping function
π	Moving particle phase
γ_w	Soil unit weight
φ	Electric potential (V)
θ	Temperature (°C)
I	Electrical current (A)
υ	Poisson ratio

the soil, which depends on factors such as the soil and pore water conductivity [7].

EK process found its application on both saturated and unsaturated soil. Electro-osmosis offers great benefit such that, the time taken for soil consolidation is highly reduced and surcharge loading avoided [9]. A normally consolidated soft clay has shown to be over-consolidated when treated and the over-consolidated ratio can be achieved in the range of about 1.2 and 1.7 while the soil shear strength can witness an increase of about 100%–200% [10]. As stated by Al-Hamdan and Reddy [10], the undrained soil shear strength increases further after the EK treatment mainly due to the soil hardening as a result of ionic diffusion and is permanent. Considerable increase in the soil shear strength around the anodes [11] has been observed. A recent approach by Eton [4] of which the soil modification was applied to pipelines on soft clay soil indicated a considerable improvement in the soil strength.

A three-dimensional (3-D) model was analysed by Micic, Shang and Lo [12] considering the material behaviours and boundary conditions. HU and WU [13] also presented a two-dimensional (2-D) and 3-D numerical analyses of the field test conducted by Bjerrum, Moum and Eide [14]. Yuan, Hicks and Jommi [15] also conducted a numerical study based on the field test reported by Bjerrum, Moum and Eide [14] in 2-D considering large strain and constitutive elasto-plastic behaviour of the soil. Yuan and Hicks [16] presented numerical analyses of a multi-dimensional model based on field data given by Burnotte, Lefebvre and Grondin [17]. The complex geometry with multiple electrodes and intermittent current were determined. Other conditions such as the material nonlinearity and the soil elasto-plastic behaviour were considered.

1.1.1. *Constitutive equations*

As given by Yuan and Hicks [16] mass conservation of water is given by the equation:

$$\nabla.\left(v^s + \bar{v}\right) = 0 \tag{1}$$

where the soil particle velocity is given as v^s and the water filtration velocity relative to the soil skeleton is$\bar{v}$. The fluid flow due to electrical and hydraulic gradient can be coupled to give a total flow [18–20]:

$$\bar{v} = -\frac{k_w}{\gamma_w}\left(\nabla p + \gamma_w z\right) - k_{eo}\nabla\phi \tag{2}$$

where the hydraulic conductivity, soil unit weight and the elevation is given by k_w, γ_w and z respectively, the electro-osmotic permeability is k_{eo} and electric potential given as φ.

Assuming a charge conservation with steady state current, the electrical field governing equation is given as Yuan and Hicks [16]:

$$-\nabla \cdot j = \boldsymbol{C_p}\frac{\partial\phi}{\partial \boldsymbol{t}} \tag{3}$$

where the electrical current flux is given as j, the electrical capacitance per unit volume as, C_p. Assuming C_p is negligible and based on ohms law, the electrical flow can be represented as:

$$\boldsymbol{j} = -\boldsymbol{k_{\sigma e}}\nabla\phi \tag{4}$$

where the electrical conductivity is $k_{\sigma e}$.

For a constant hydraulic pressure, the excess pore water pressure u_e can be obtained from equation [18–20]:

$$\nabla^2\boldsymbol{u_e} + \frac{\boldsymbol{k_{eo}}}{\boldsymbol{k_h}}\boldsymbol{\gamma_w}\nabla^2\phi = -\frac{1}{\boldsymbol{C_h}}\frac{\partial \boldsymbol{u_e}}{\partial_{\boldsymbol{t}}} \tag{5}$$

Fig. 1. Electro-kinetic phenomena: electro-osmosis.

adapted from Ref. [8].

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